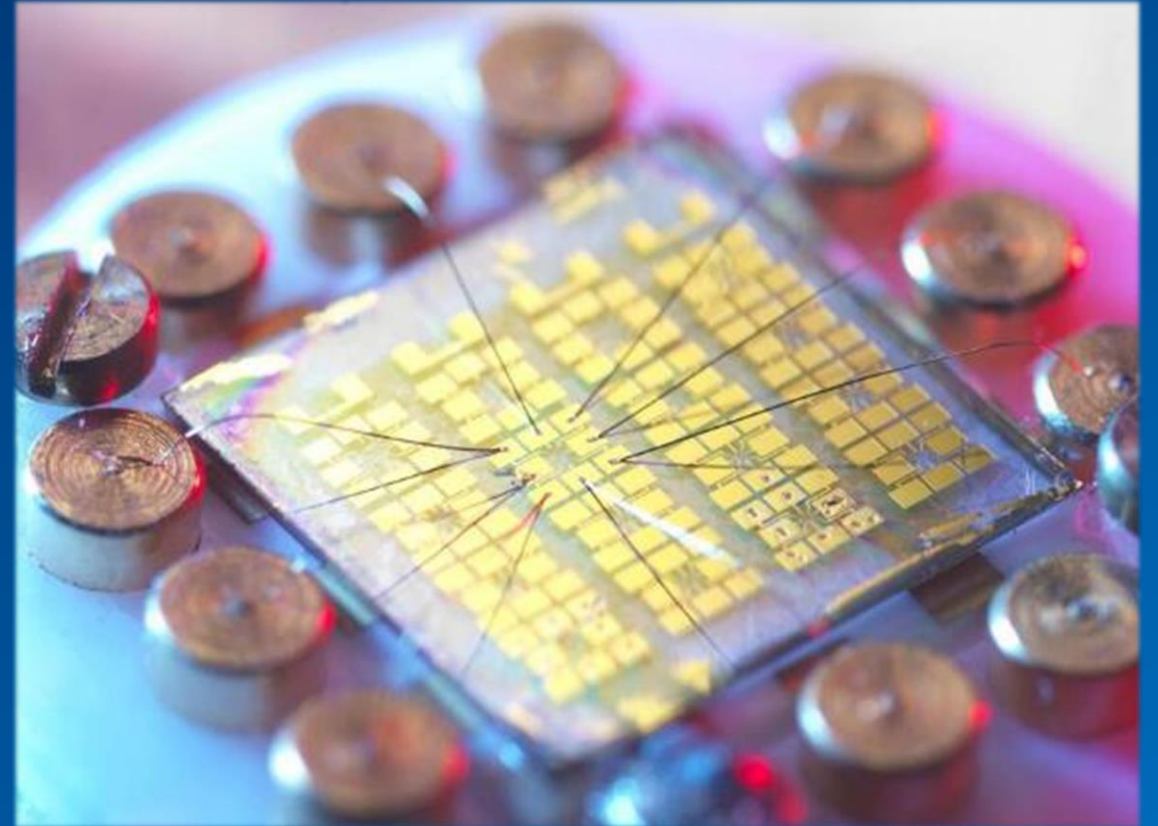


Quantum Sensing & Metrology: The next frontier

Jan-Theodoor (JT) Janssen

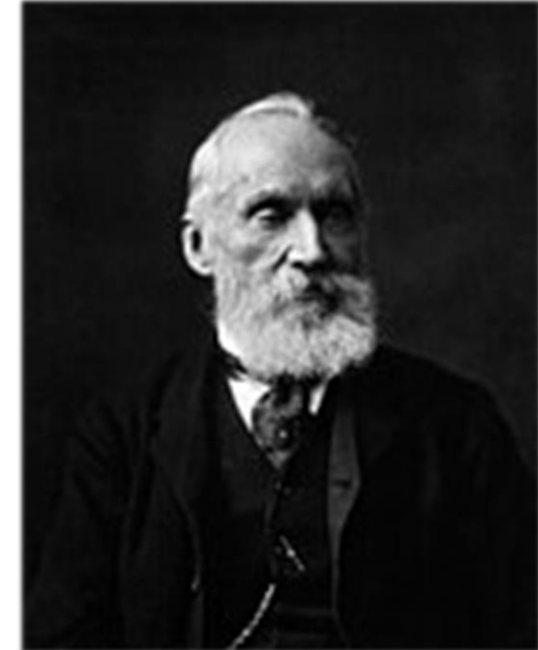
Chief Scientist, National Physical Laboratory (NPL)

United Kingdom



The measure of everything

- Why measure?



If you can't measure, you can't make it better.

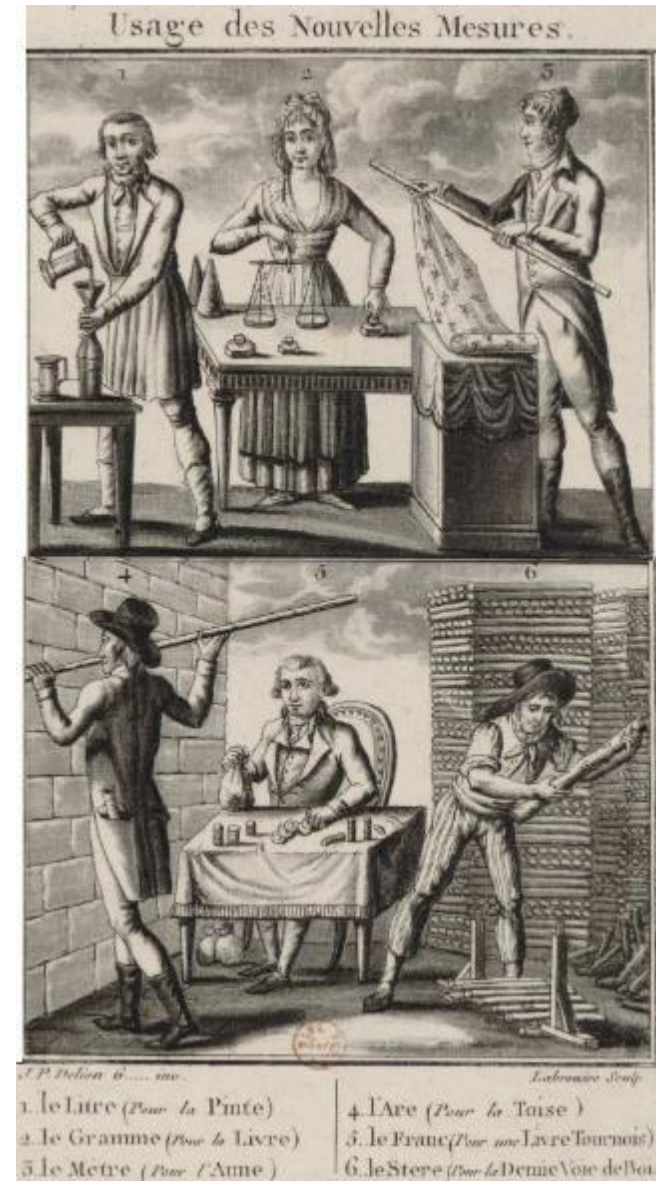
"Arguably, the ability to measure physical properties accurately has tremendous survival value that gives humans an adaptive evolutionary advantage"
Lord Kelvin (1883)

What is 'Metrology'?

- Metrology is “the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.”
- Almost all of science, industry and commerce involves making and interpreting measurement – **why is metrology special?**



The Proclamation Regarding Weights and Measures, 1556 by Ford Madox Brown (1889)



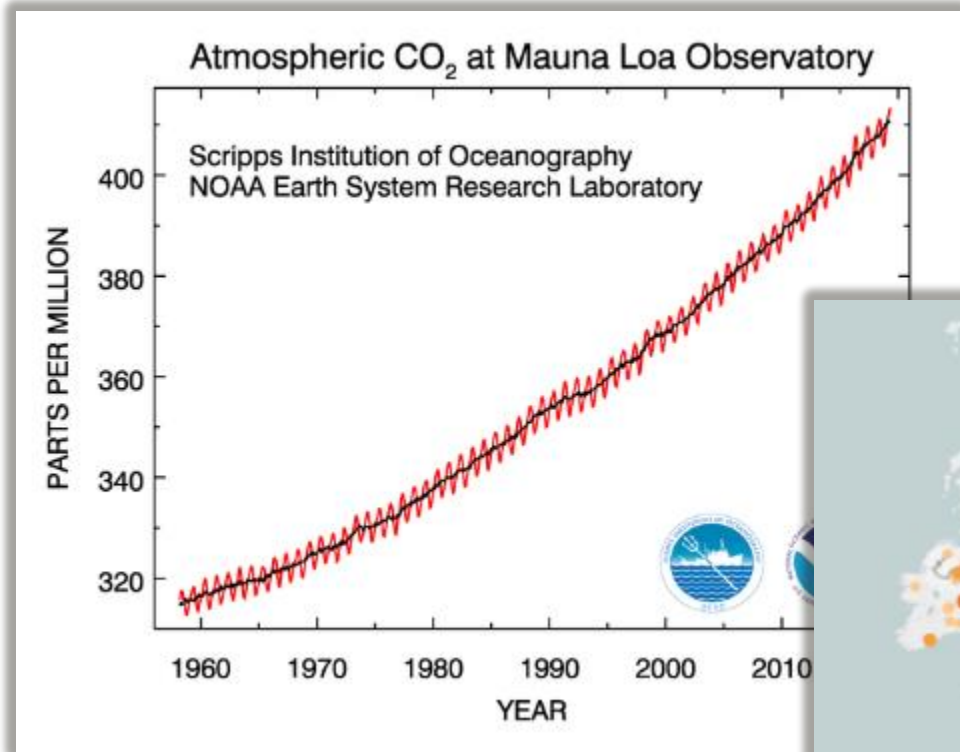
Woodcut dated 1800 illustrating the new decimal units which became the legal norm across all France in 1800

Metrology's main activities

- The **definition** of internationally accepted units of measurement, e.g. the kilogram
- The **realisation** of units of measurement by scientific methods
- The establishment of **traceability** chains by disseminating and documenting the value and accuracy of a measurement
- Traceability implies the calculation of an associated **measurement uncertainty**



stable



comparable



universal

improving certainty in measurement



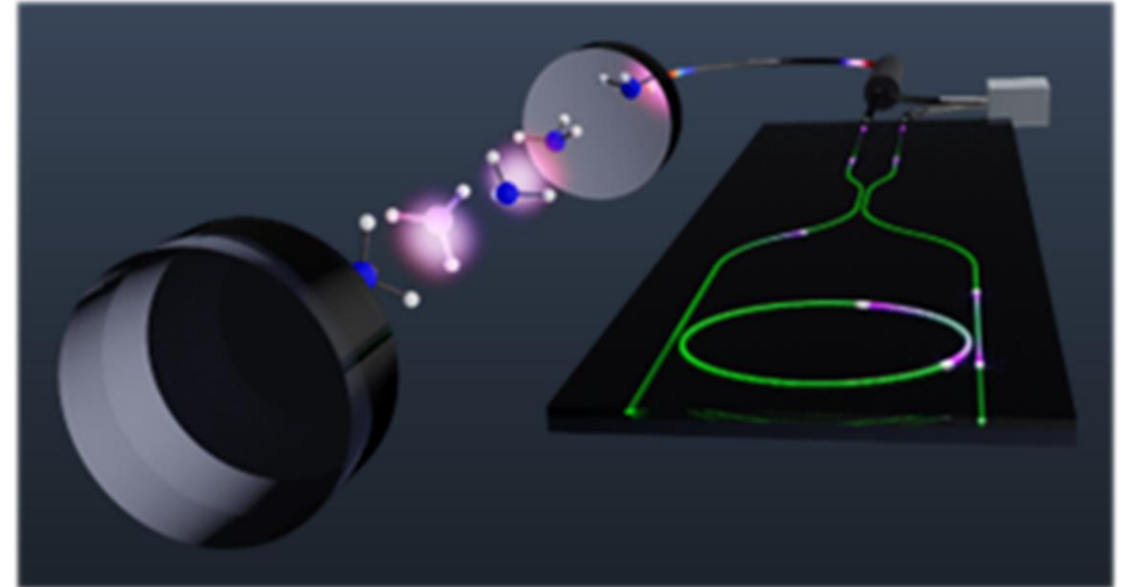
Confidence in measurement



- Stable
- Comparable
- universal

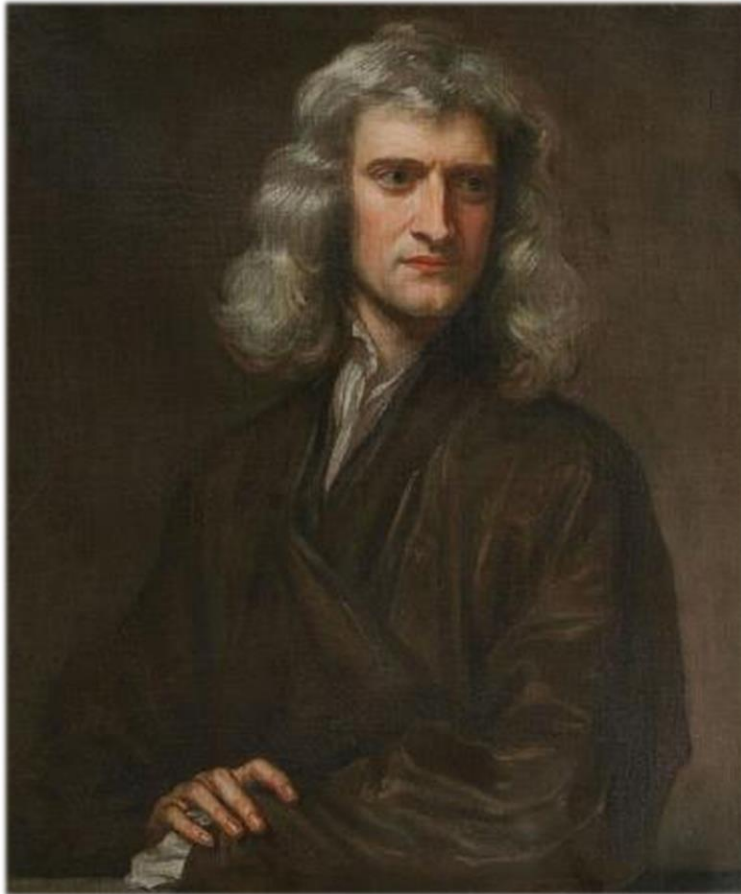
Coming up:

- Quantum mechanics – what is it?
- Quantum technology today
- What made quantum possible?
- Quantum technology tomorrow
 - Magnetometry
 - Gravimetry
 - Quantum imaging



Classical mechanics

Gravity, light & calculus



Isaac Newton
1642-1726



$$F = \frac{GM_1M_2}{r^2}$$

$$F = gm$$

Classical mechanics

- **Johannes Kepler**

Three laws of planetary motion



- **Joseph-Louis Lagrange**

Differential equations, Lagrangian mechanics etc.



- **Leonhard Euler**

Calculus of variations, analytical number theory etc.



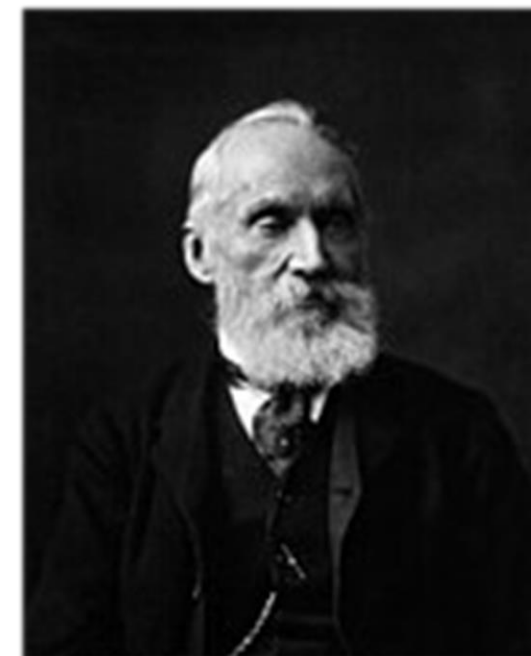
- **Gottfried Leibnitz**

Differential & integral calculus



- **Michael Faraday**

Electromagnetism



“There is **nothing new to be discovered in physics** now. All that remains is more and more precise measurement.”
Lord Kelvin (1900)

Unexplained observations

- Blackbody radiation
- Photoelectric effect
- Energy spectrum of Hydrogen
- ...

Hydrogen Absorption Spectrum



Hydrogen Emission Spectrum



Quantum mechanics founders



Planck



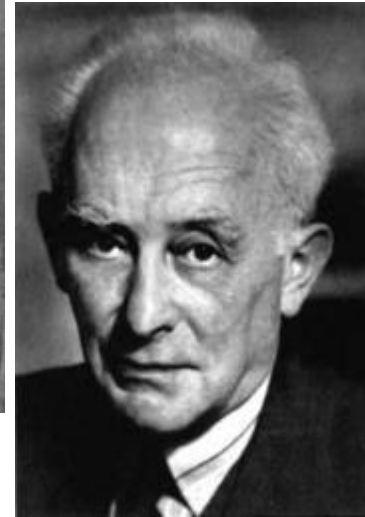
Einstein



Bohr



Heisenberg



Born



Dirac

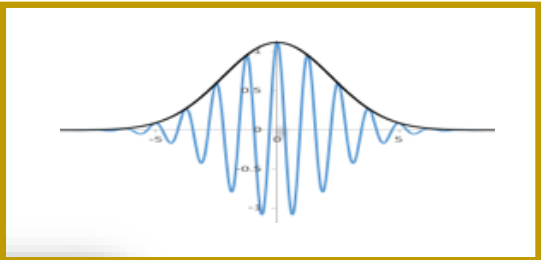


Schrodinger

The strange world of quantum is highly counter-intuitive!

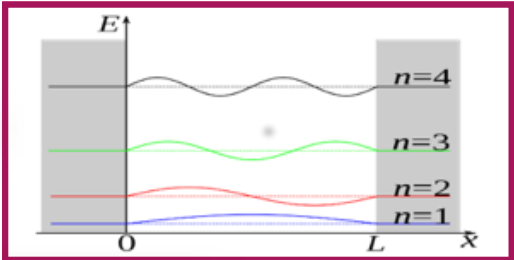


Wave Nature of Matter

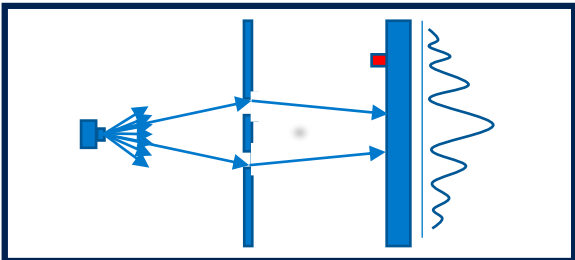


$$\lambda = \frac{h}{p} \text{ and } h \approx 6.6 \times 10^{-34} \text{ Js}$$

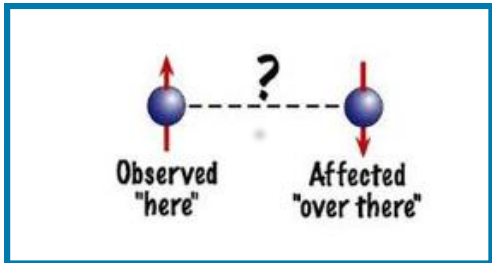
Quantization



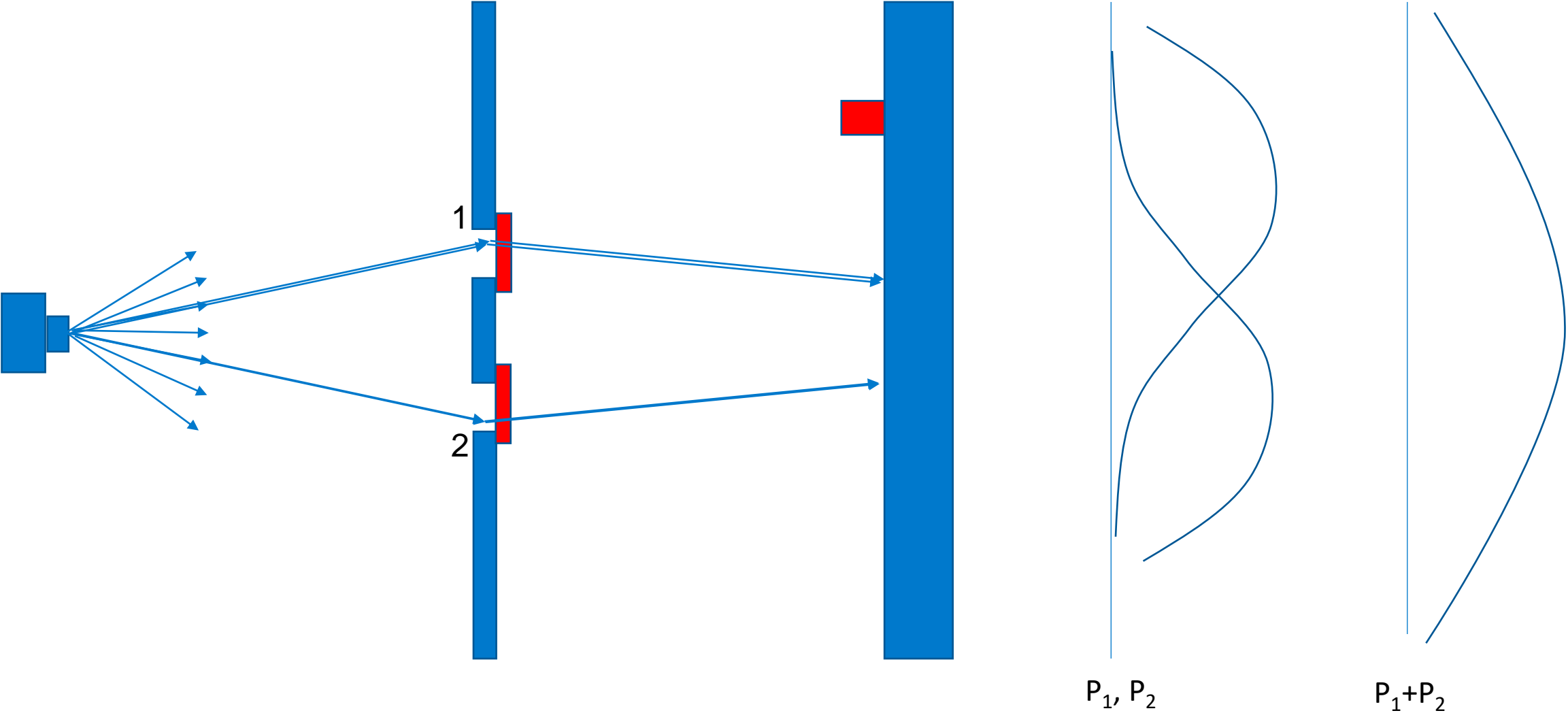
Superposition



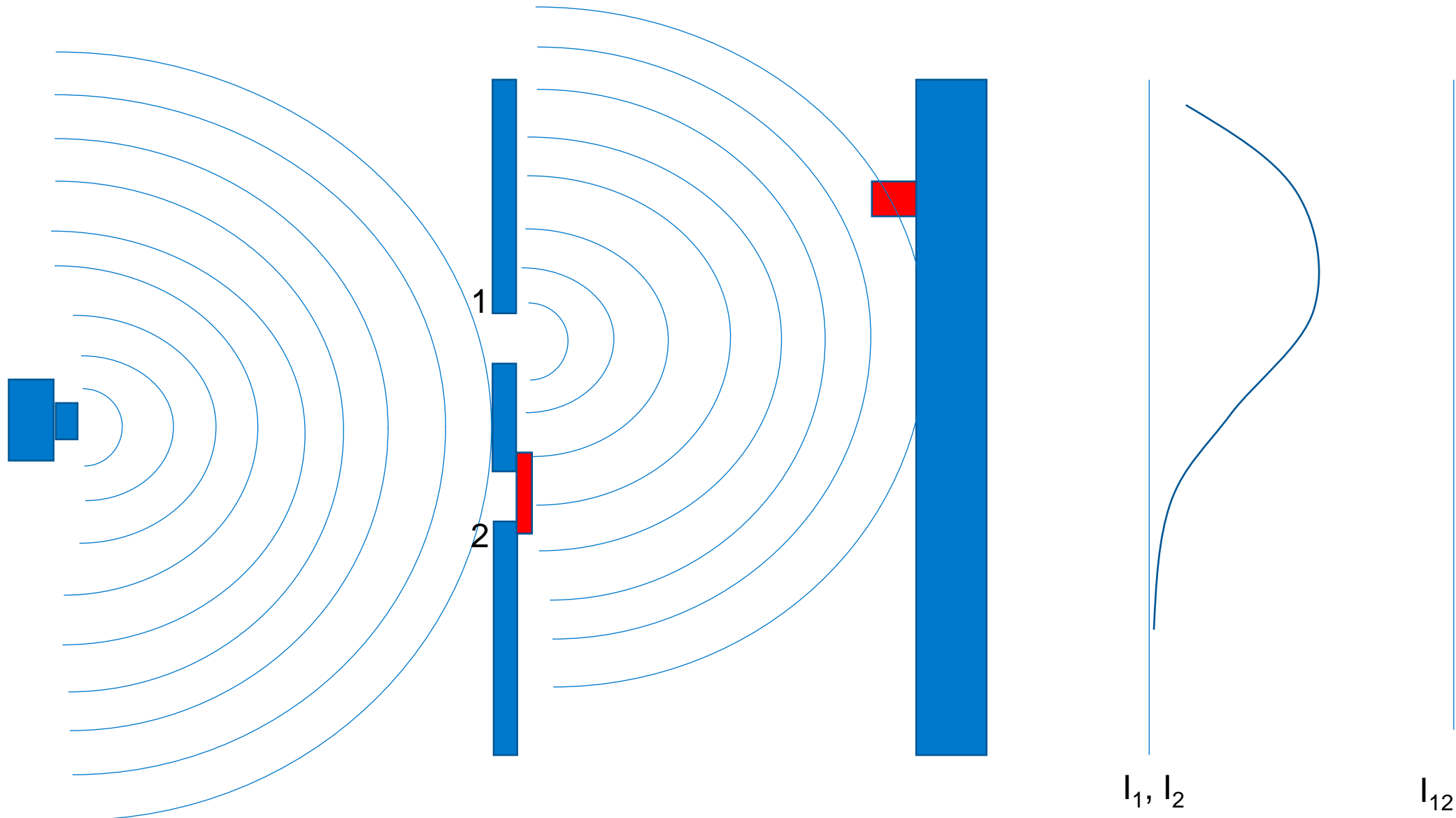
Entanglement



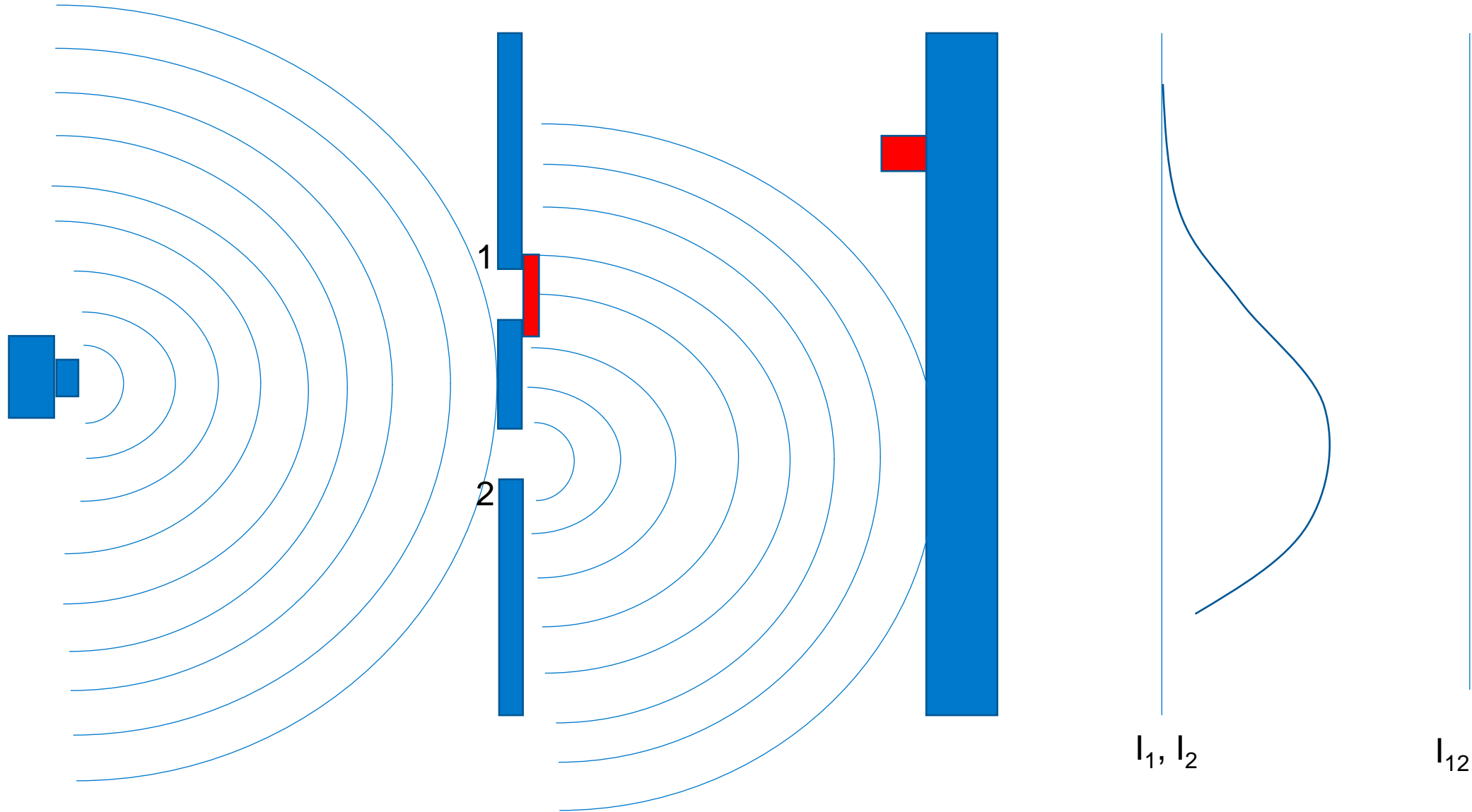
Young's Double Slit Experiment: Bullets



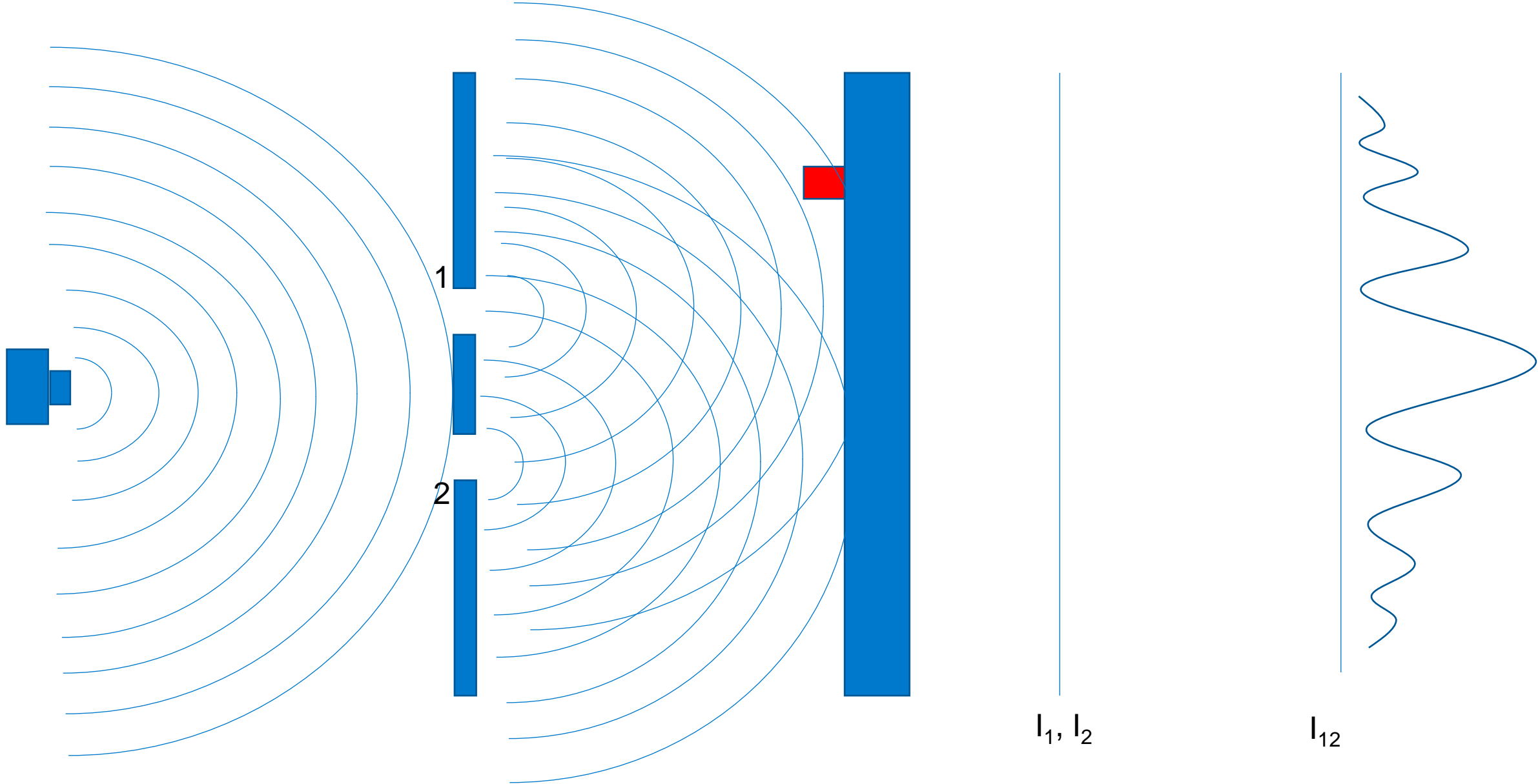
Young's Double Slit Experiment: Waves



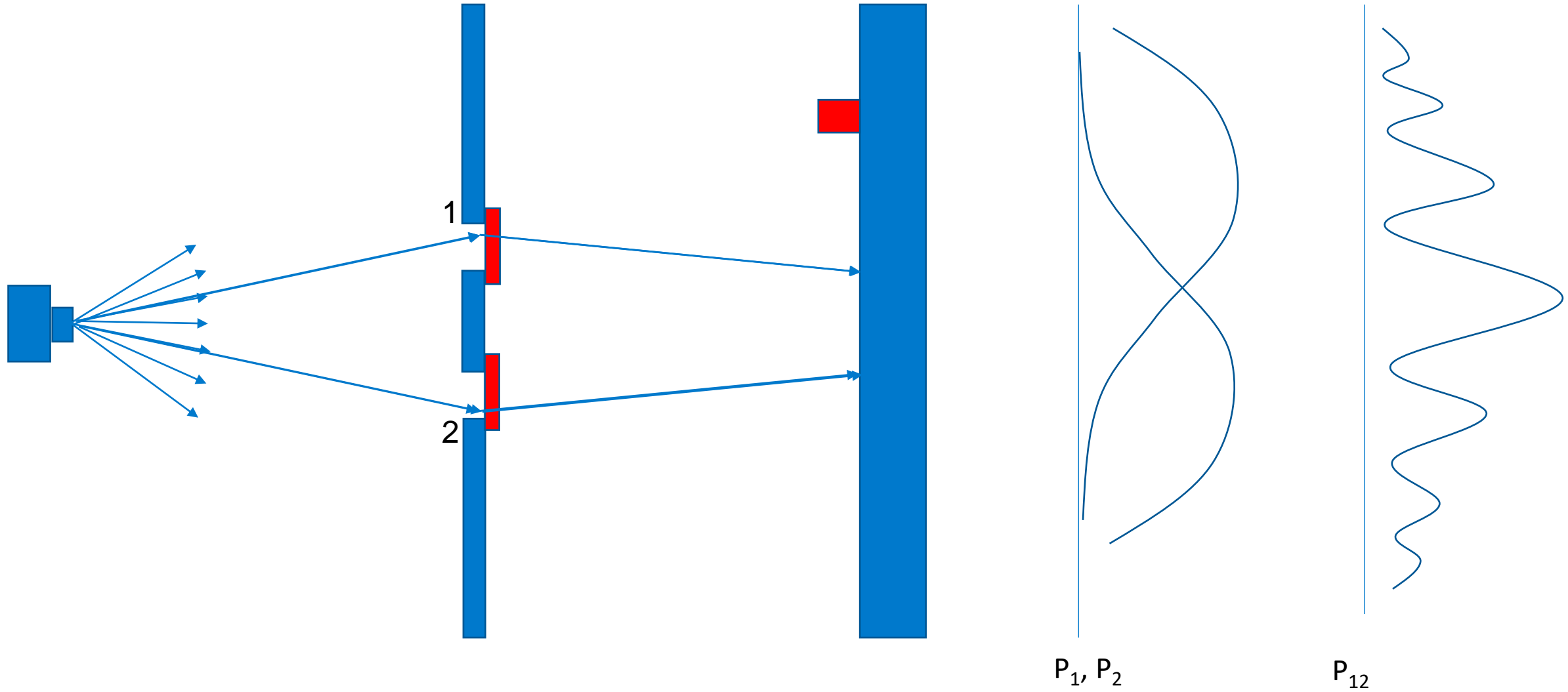
Young's Double Slit Experiment: Waves



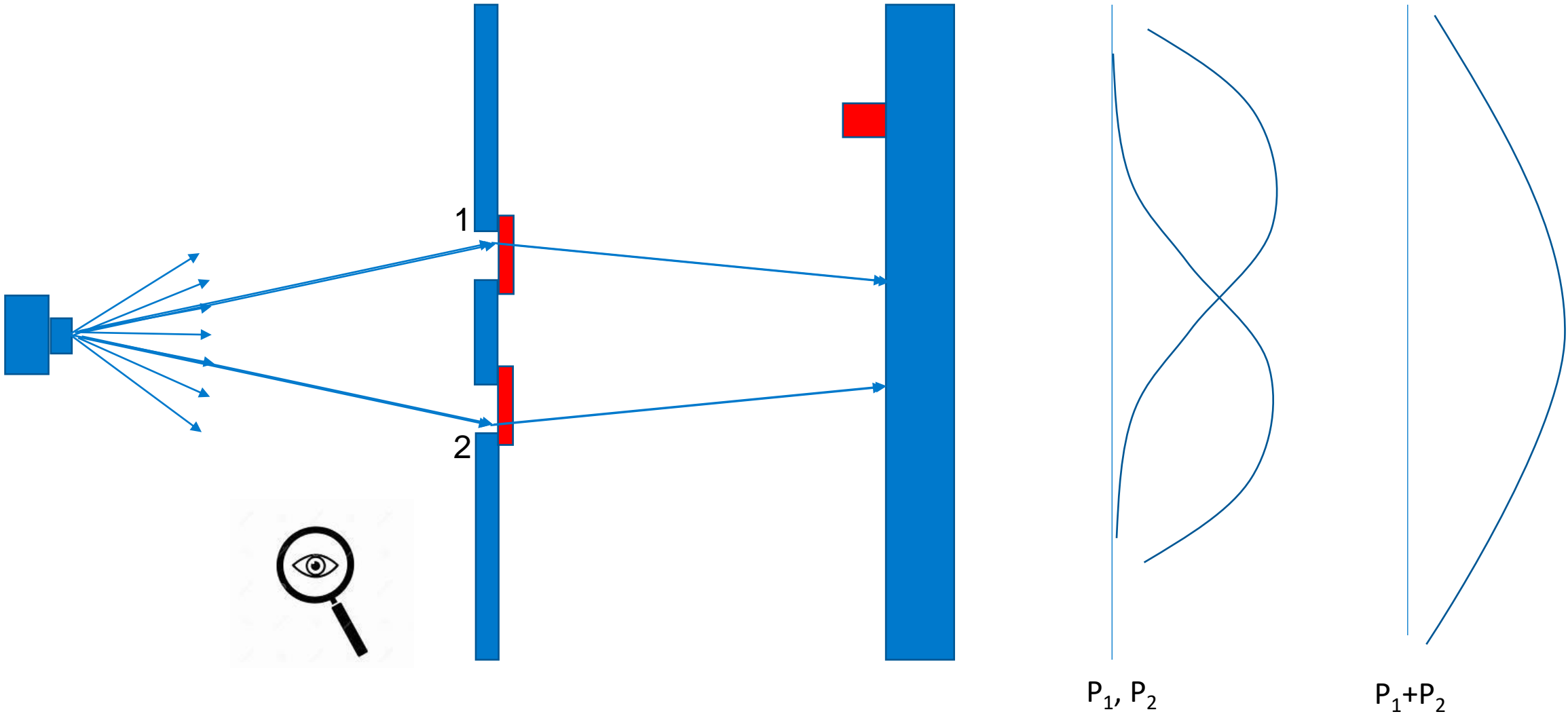
Young's Double Slit Experiment: Waves



Young's Double Slit Experiment: Electrons



Young's Double Slit Experiment: Electrons



Quantum Summary

- Things can be in two states at the same time
- Things are described by probabilities
- The act of measurement has a profound effect
- Things can interact non-locally
- It's impossible to know all things exactly

Yet, quantum mechanics is the most successful theory which describes nature with unprecedented precision

Quantum Applications today

Loads of modern technology is underpinned by quantum technology



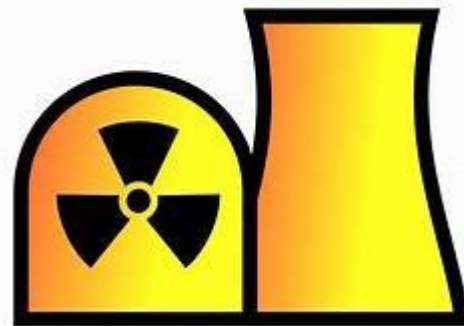
NMR



Lasers



Semiconductors



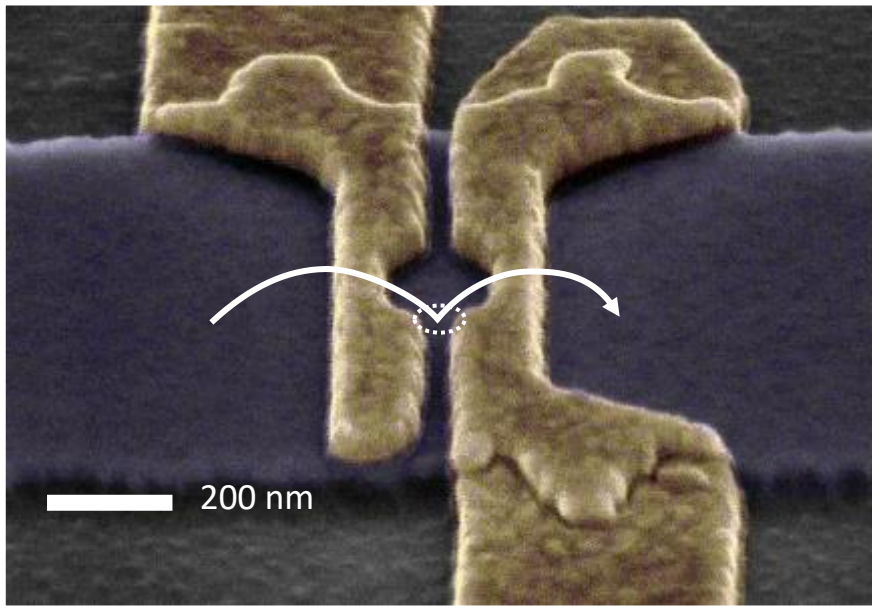
Nuclear power



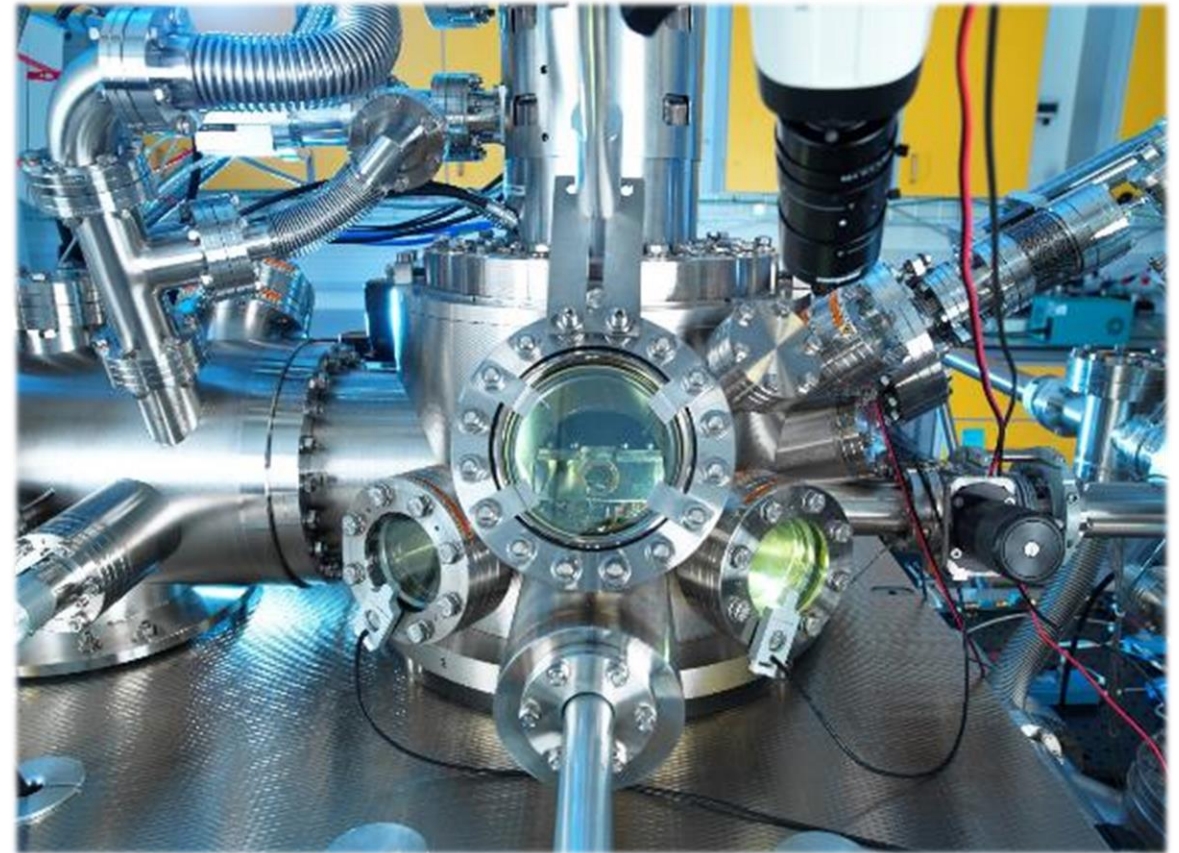
Atomic clocks

Nanotechnology

- Semiconductors
- Lithography
- Microscopy



Top-down

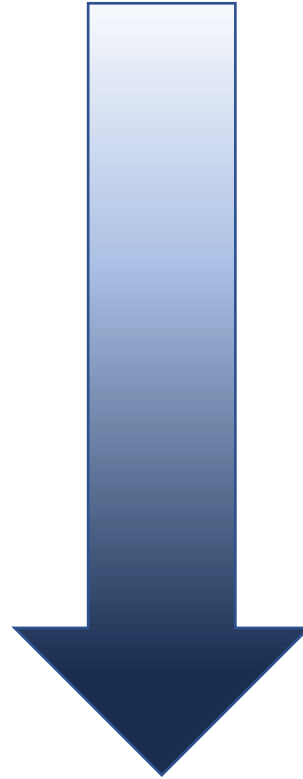


Bottom-up atom by atom

Cryogenics

Coldest place on earth	-65 °C or 210 K
Liquid Oxygen	-180 °C or 90 K
Liquid Nitrogen	-200 °C or 77 K
Liquid Hydrogen	-240 °C or 33 K
Liquid Helium	-269 °C or 4 K
Outer Space	-270 °C or 3 K
Absolute zero	-273 °C or 0 K

Classical

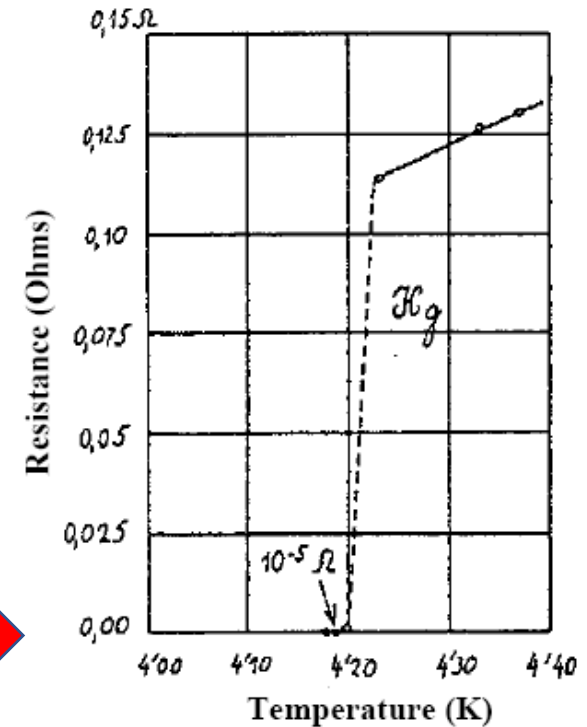


Quantum

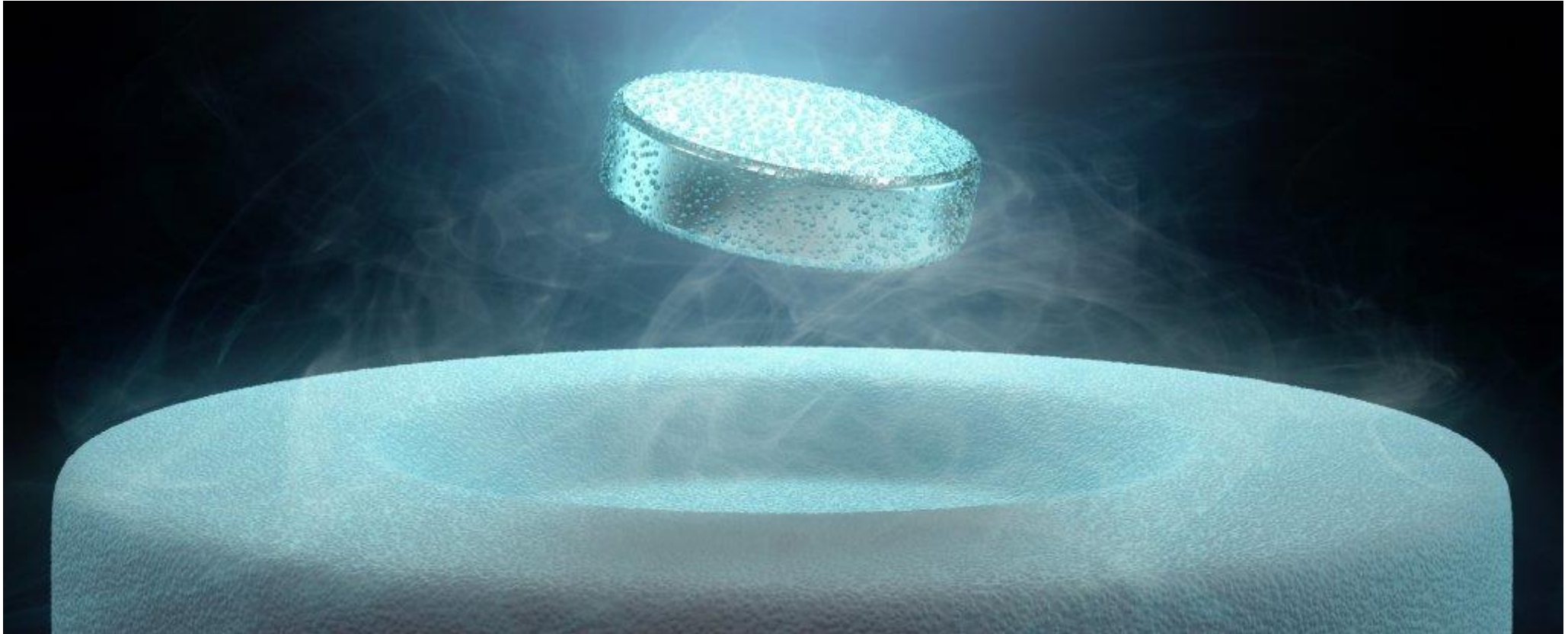
Superconductivity



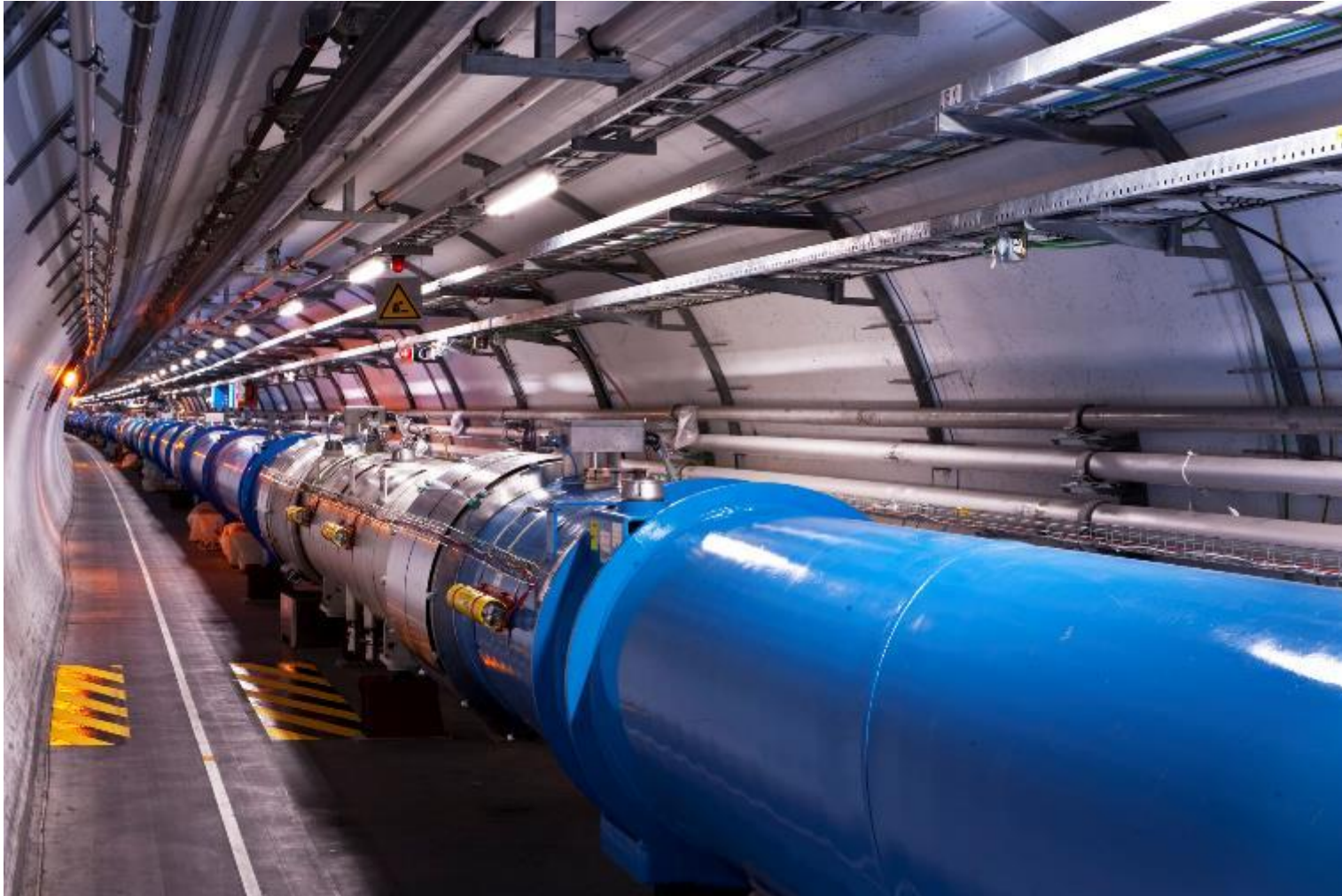
Kamerling Onnes, 1911



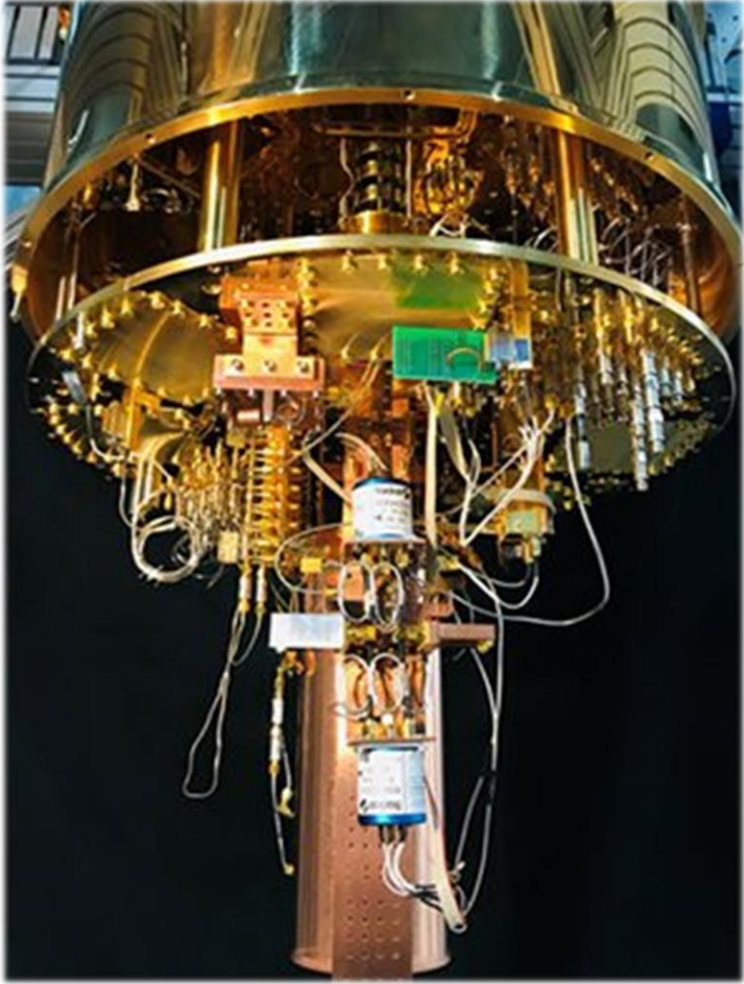
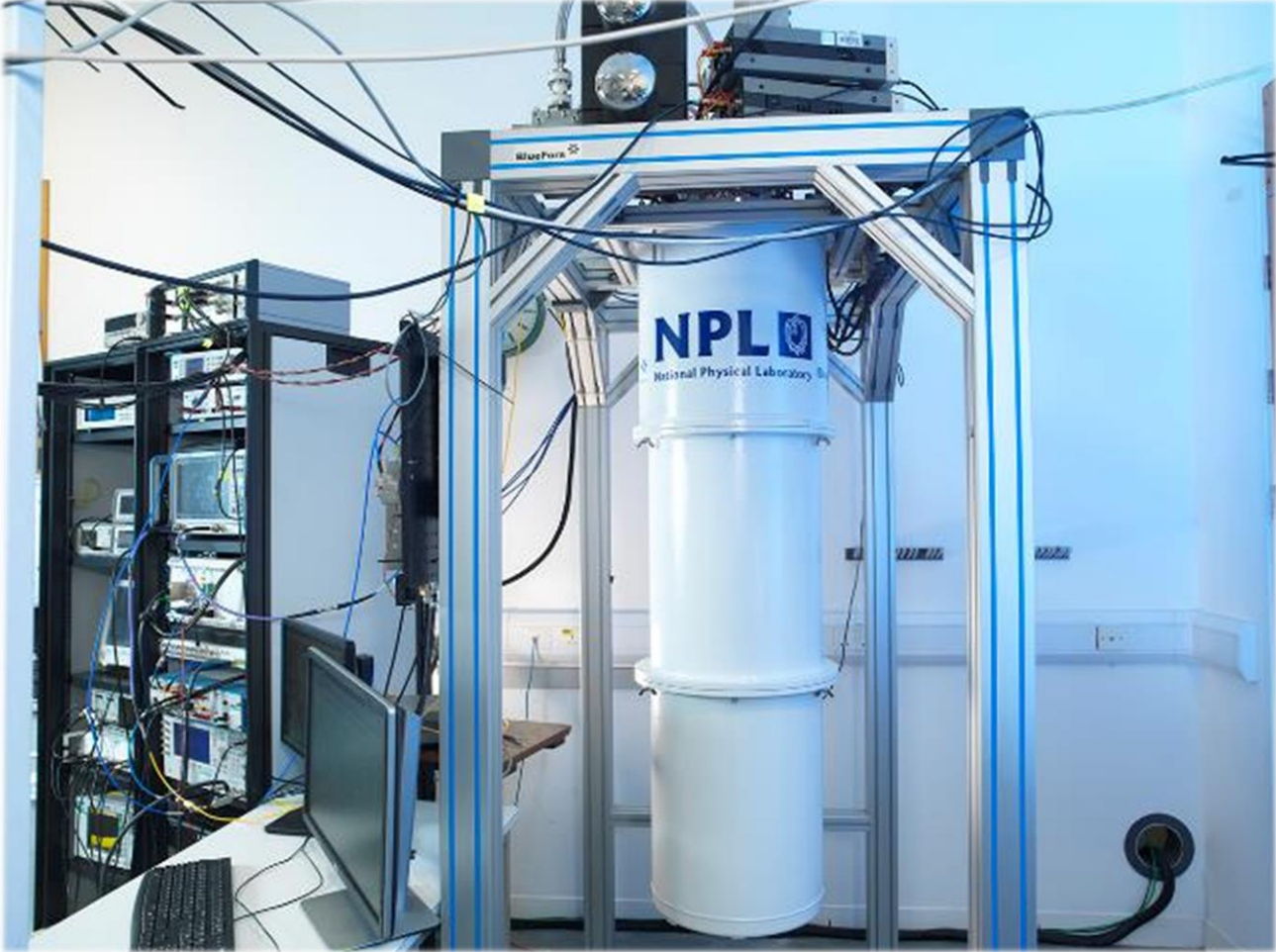
Superconductive Levitation



LHC Magnets

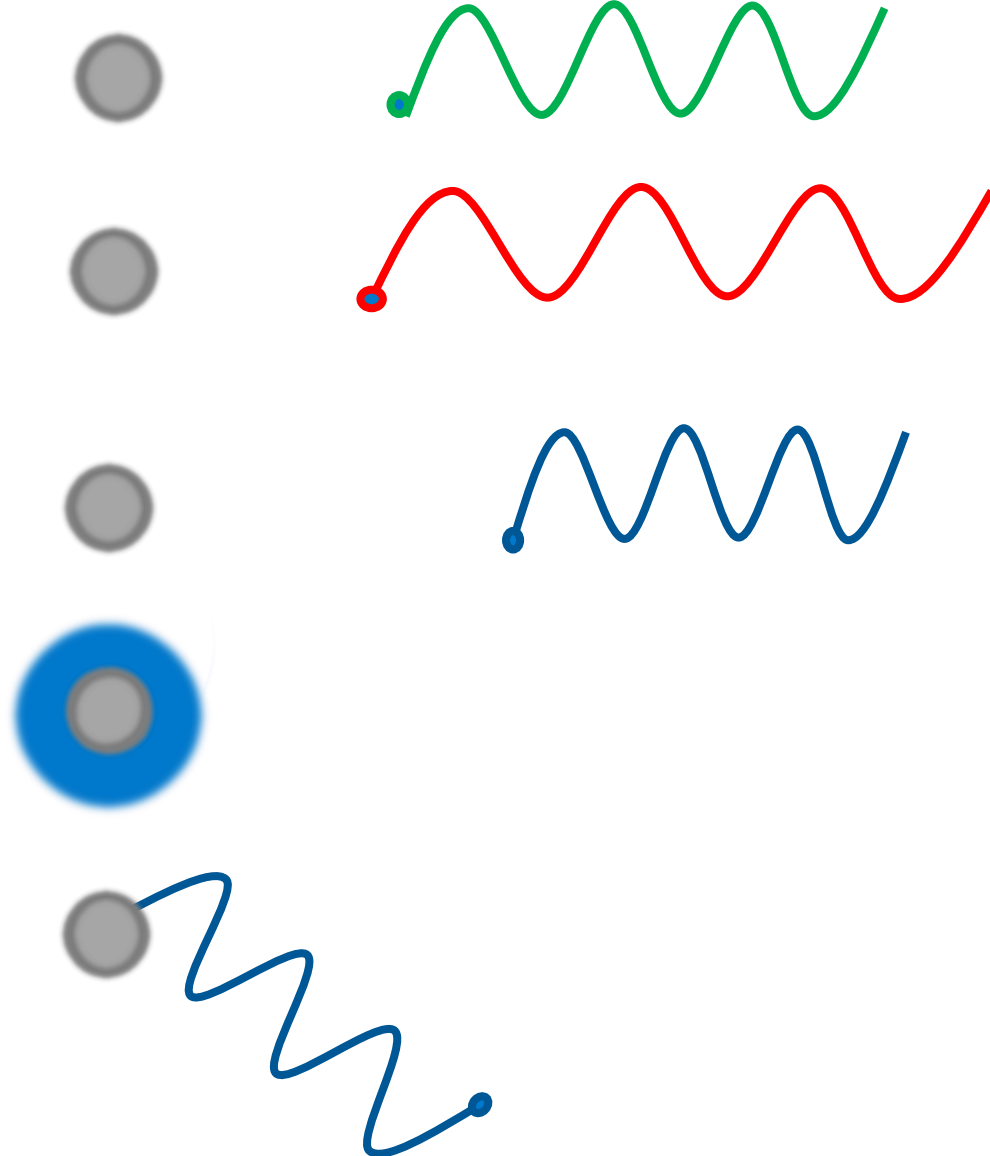
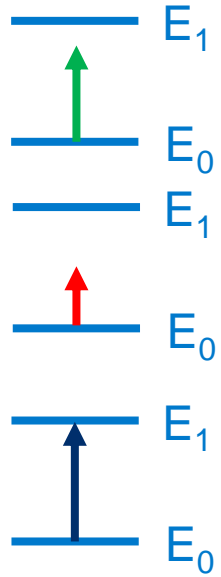


Modern Cryogenics



← ~ 10 mK
 ~ 1 meV

Laser Cooling



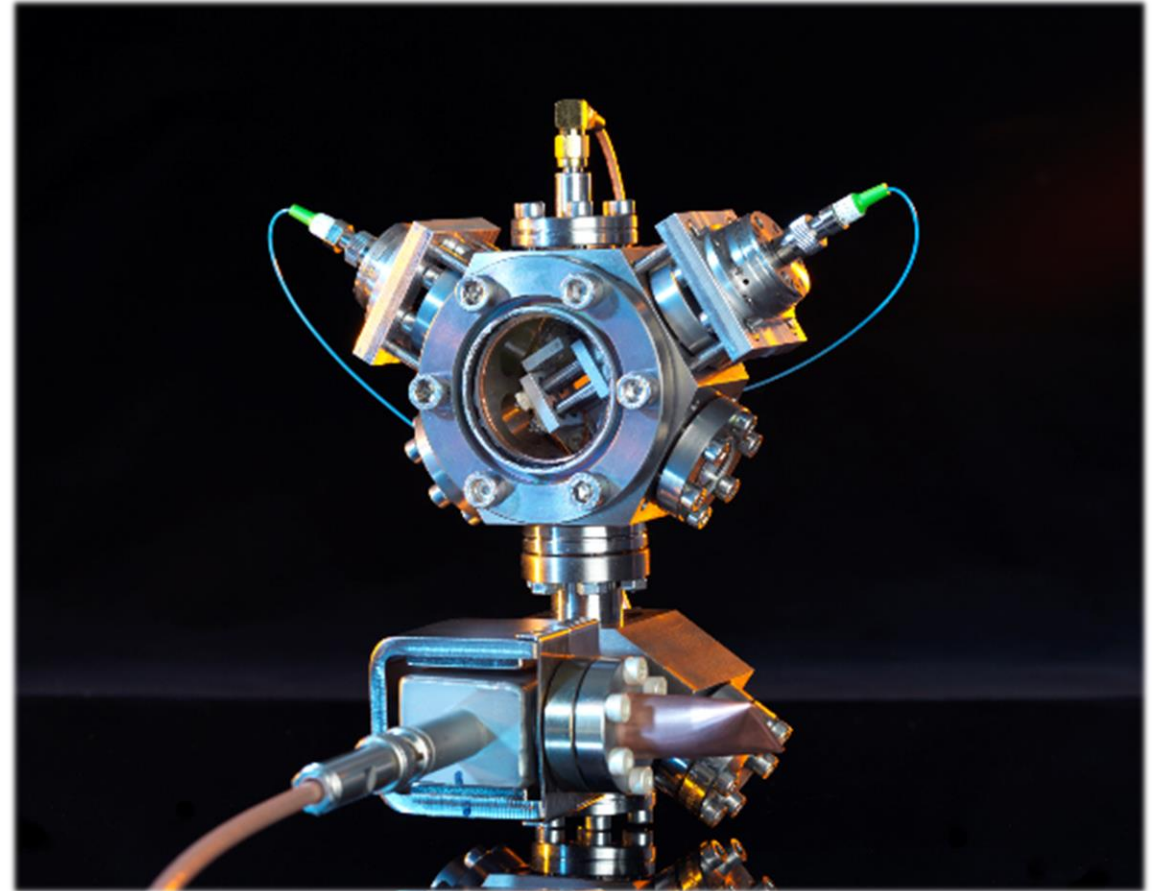
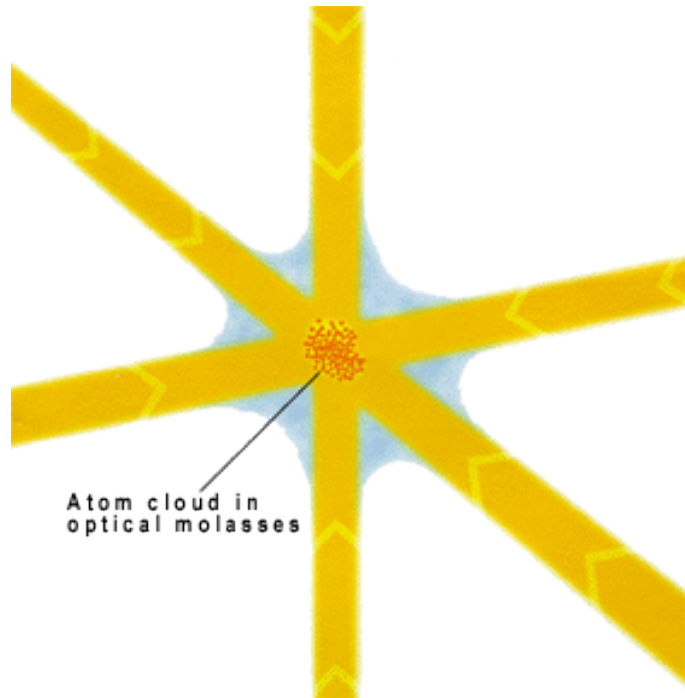
Plane = Atom



Balls = Photons

Atom trapping

- If you can **cool** atoms with lasers, you can **trap** them...



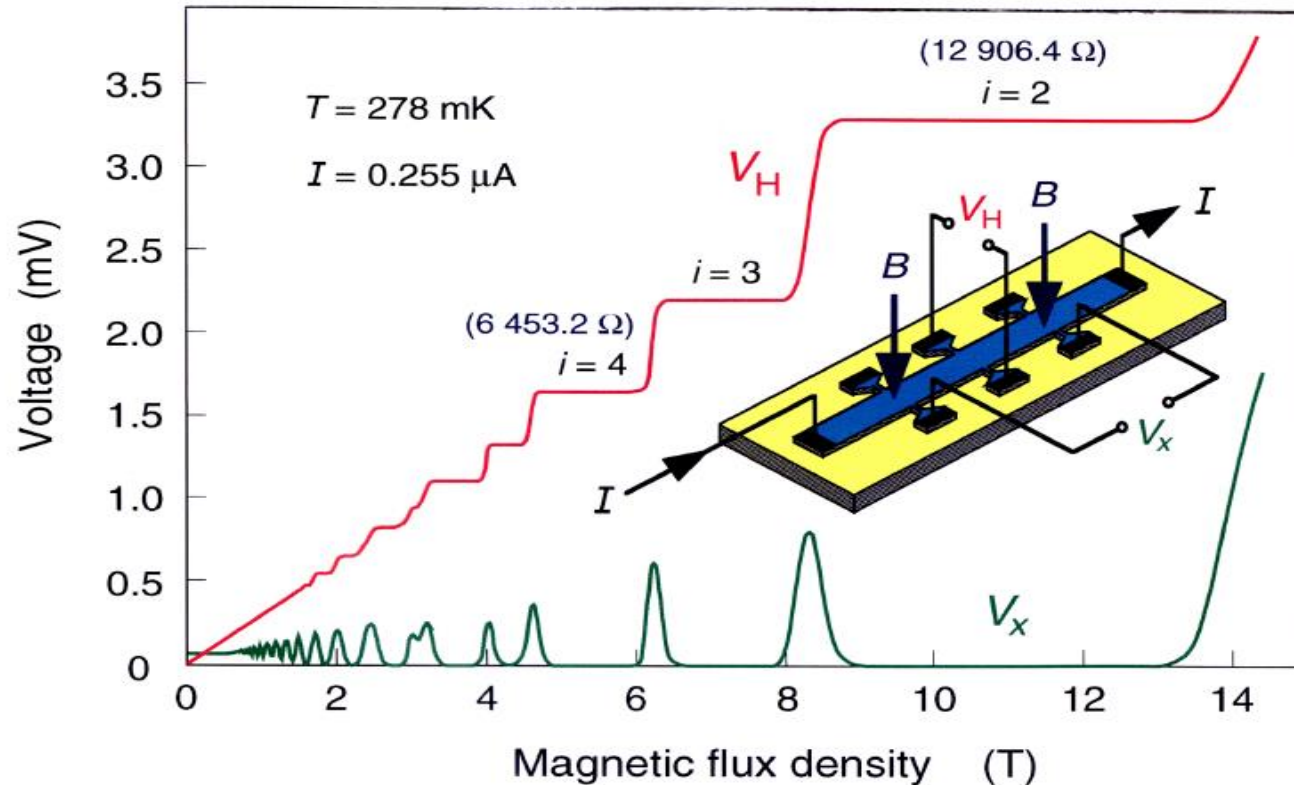
Quantum Electrical Metrology and the SI

The quantum Hall effect



Discovered in 1980 by Klaus von Klitzing
Nobel Prize in Physics in 1985

$$R_H = \frac{h}{e^2} \cdot \frac{1}{i}$$



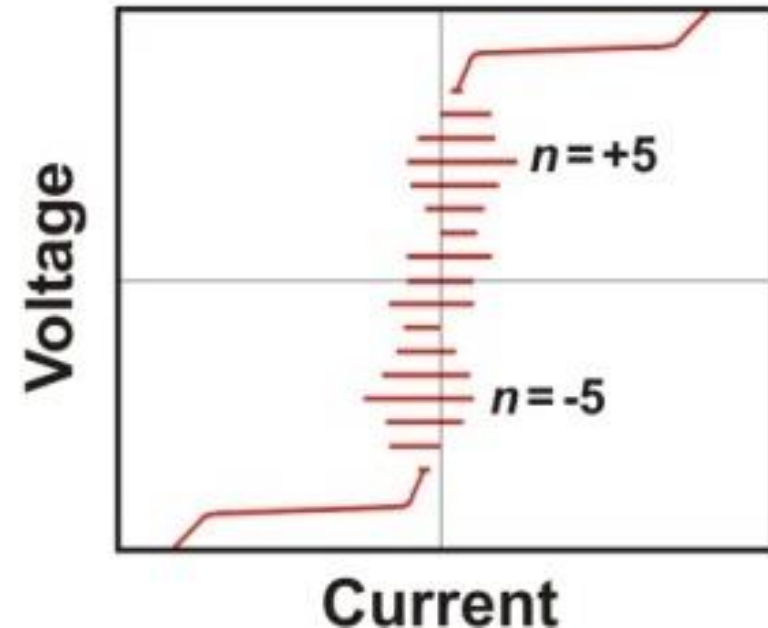
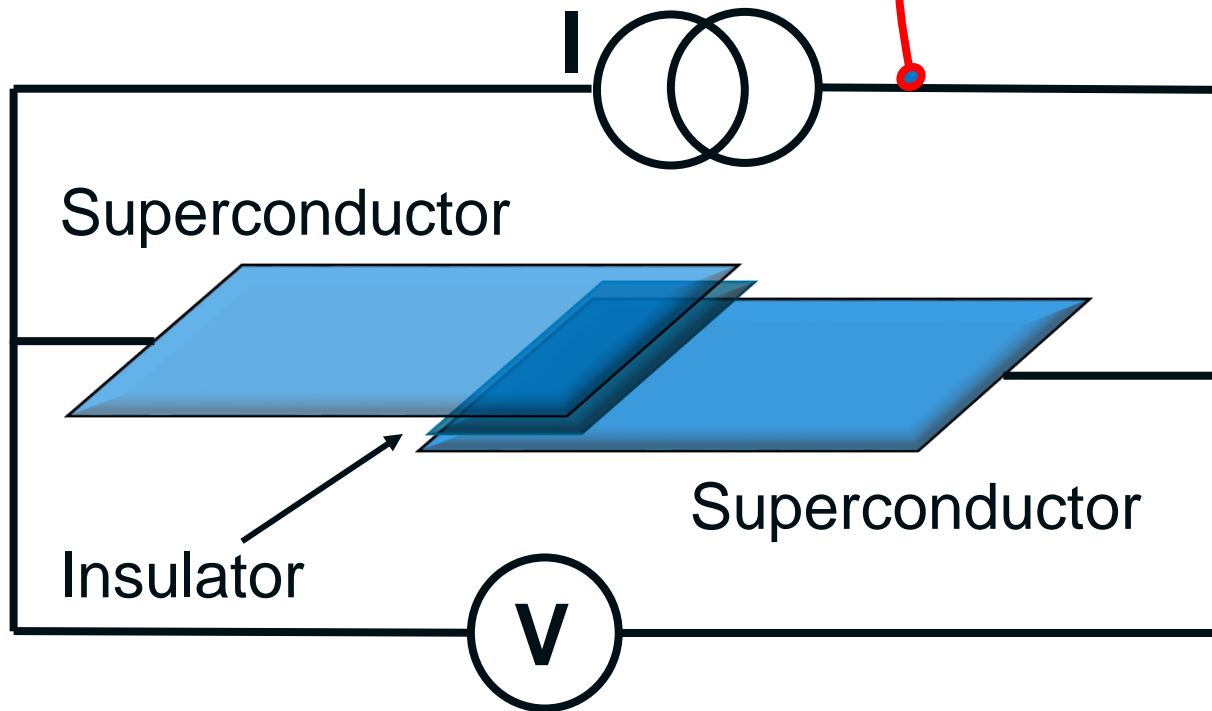
Josephson effect



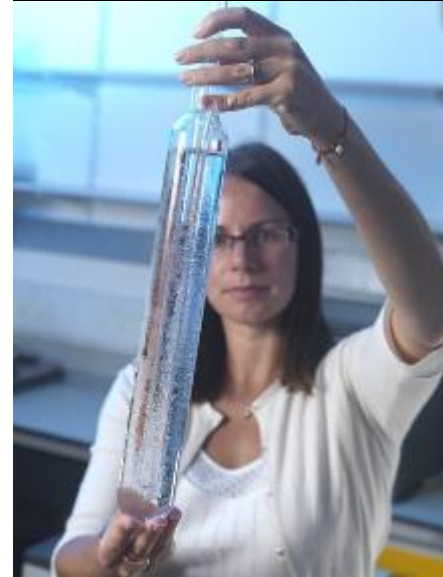
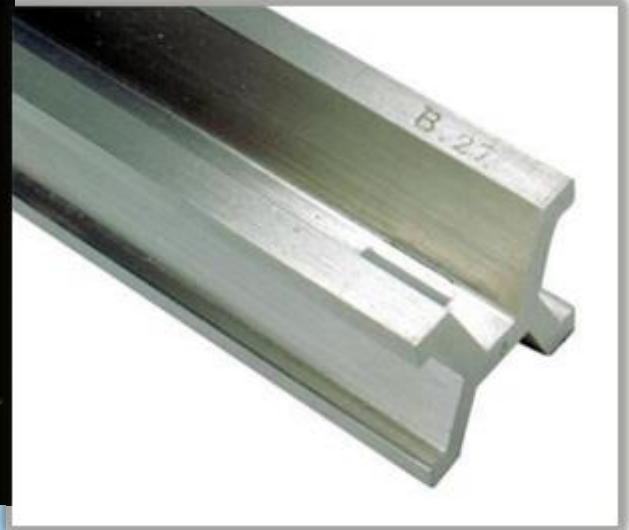
Predicted in 1962 by Brian Josephson

Nobel Prize in physics in 1973

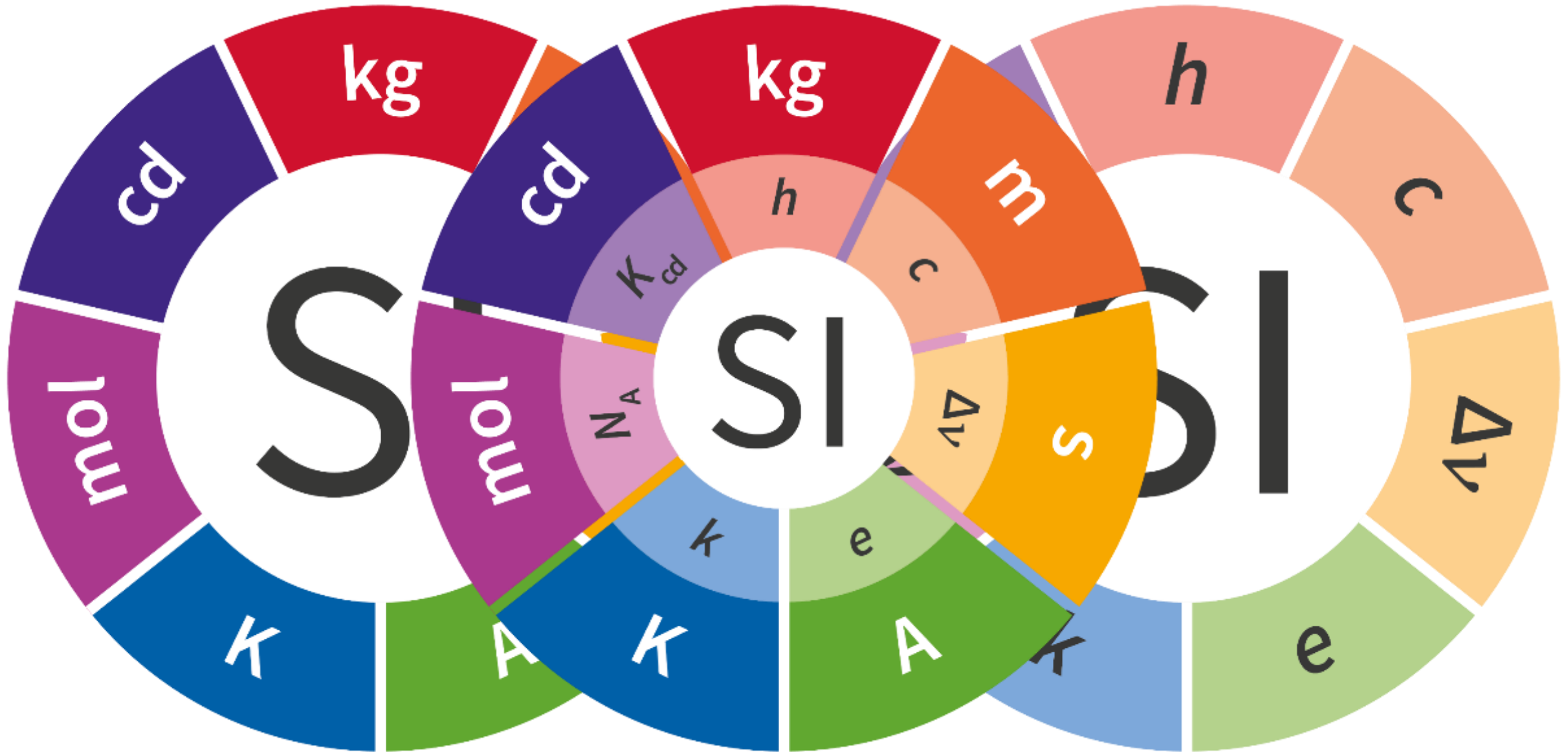
$$V = n \cdot \frac{h}{2e} \cdot f$$



The SI Base Units Pre-2019

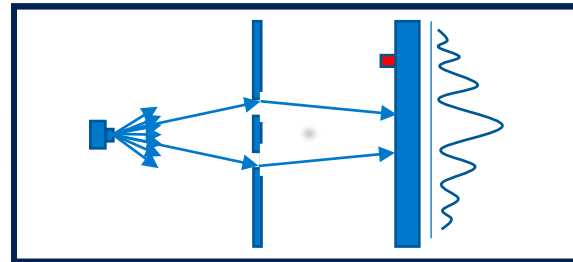


The New International System of Units

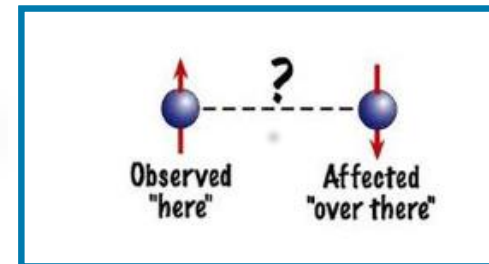


Quantum Revolution #2

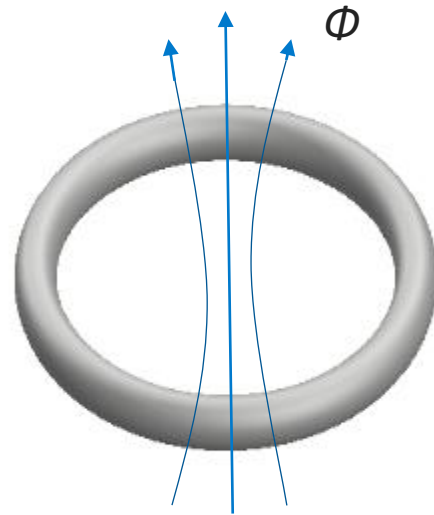
Superposition



Entanglement



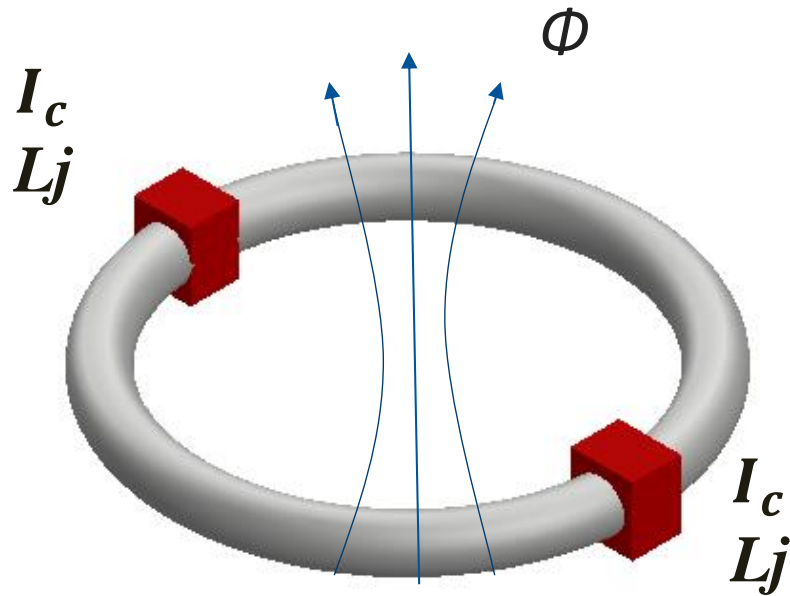
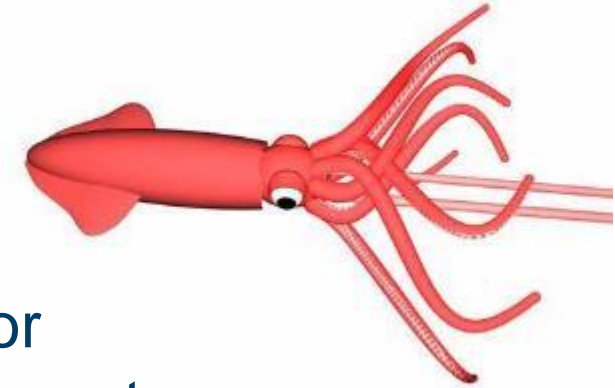
Flux quantisation in a superconducting ring



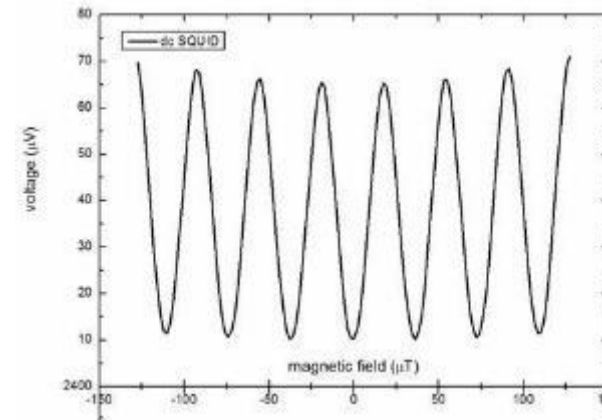
$$\Phi = \frac{h}{2e}$$

The SQUID

Superconducting Quantum Interference Device



An interferometer for superconducting current



$$\delta B \sim 1-10 \text{ fT} / \text{Hz}^{1/2}$$

Field produced by the brain ~1 pT 0.0000000000001	Earth Magnet field 30 microT 0.000030	Fridge magnet 5 mT 0.005	Loudspeaker magnet 1 T 1.0	Neutron Star ~MT 1,000,000
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Quantum Magneto Encephalography



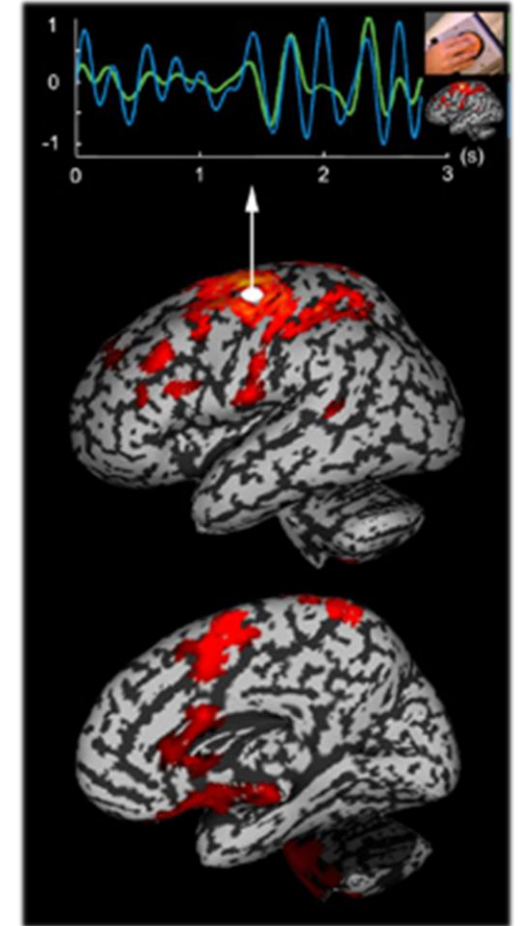
Courtesy CTF MEG systems

Epilepsy: 60M people world-wide

Dementia: 1% GDP

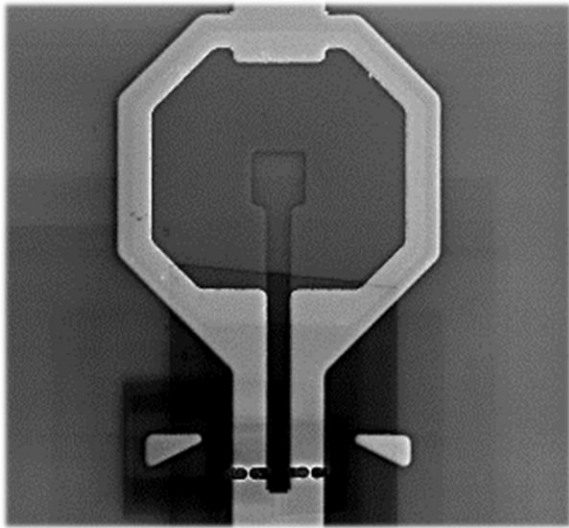
Schizophrenia: 1% of population

Trauma: 100,000 / year in the UK

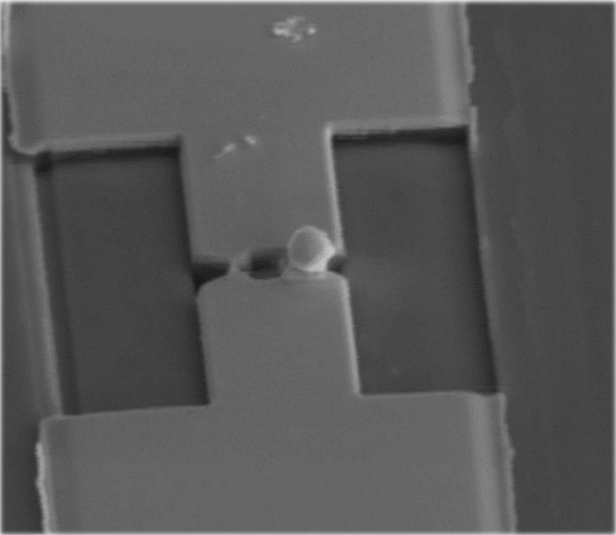


NanoSQUIDs for Quantum Sensing

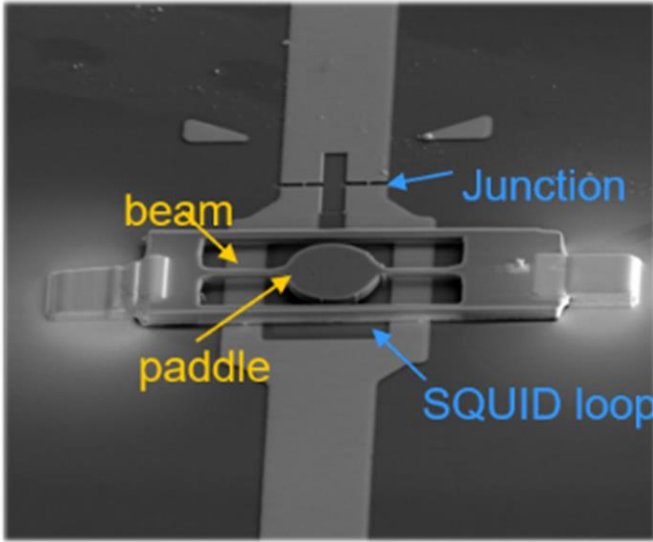
NanoSQUIDs for single photon detection



NanoSQUIDs for spin detection



NEMS resonators readout with nanoSQUID



Big Science



Nasa Image

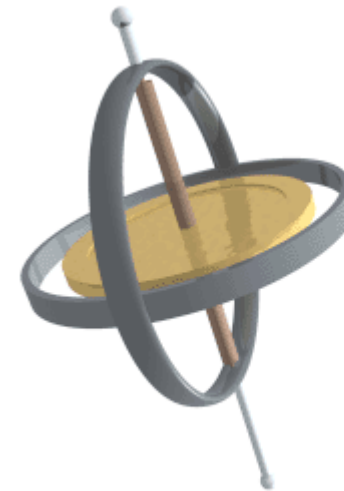
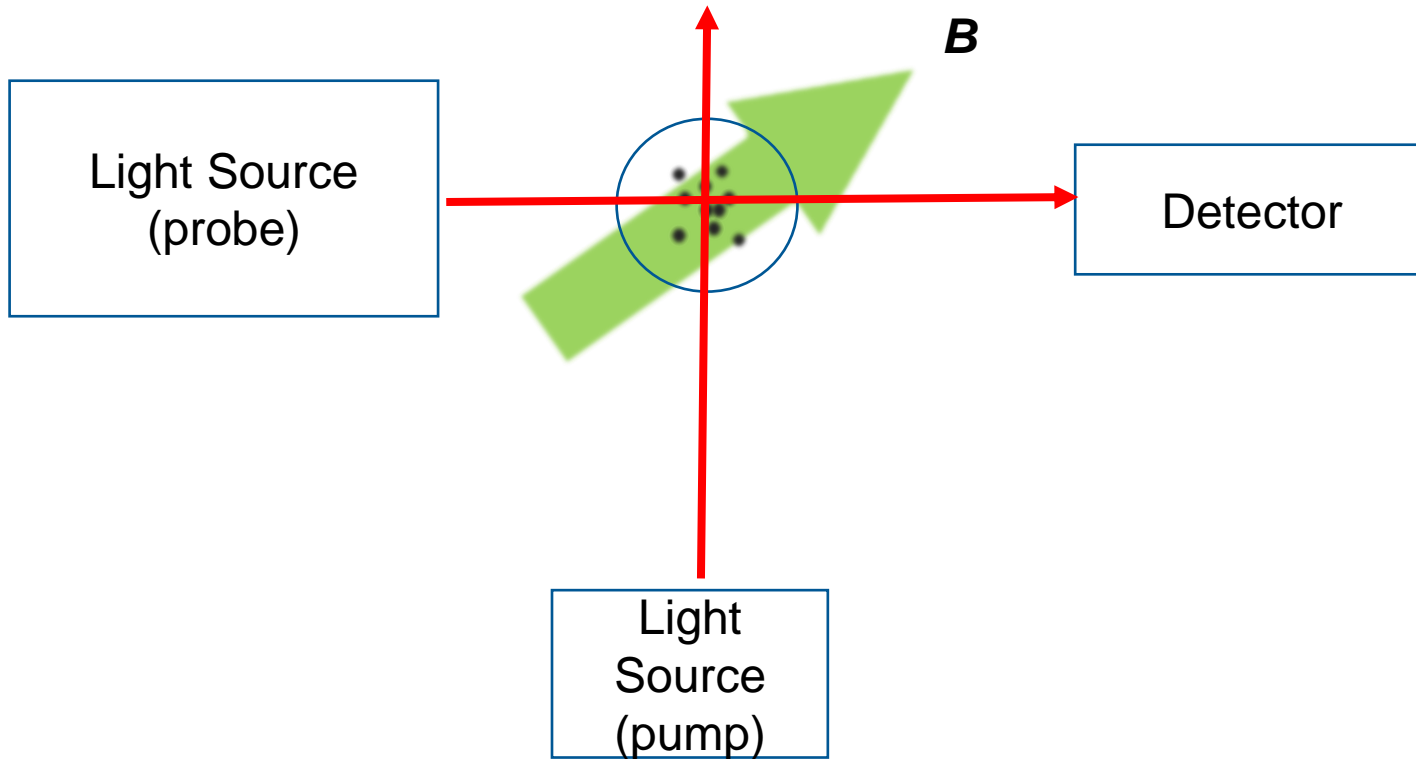
Dark Matter search



Nasa Image

Gravity Probe B mission
(testing Einstein's theories)

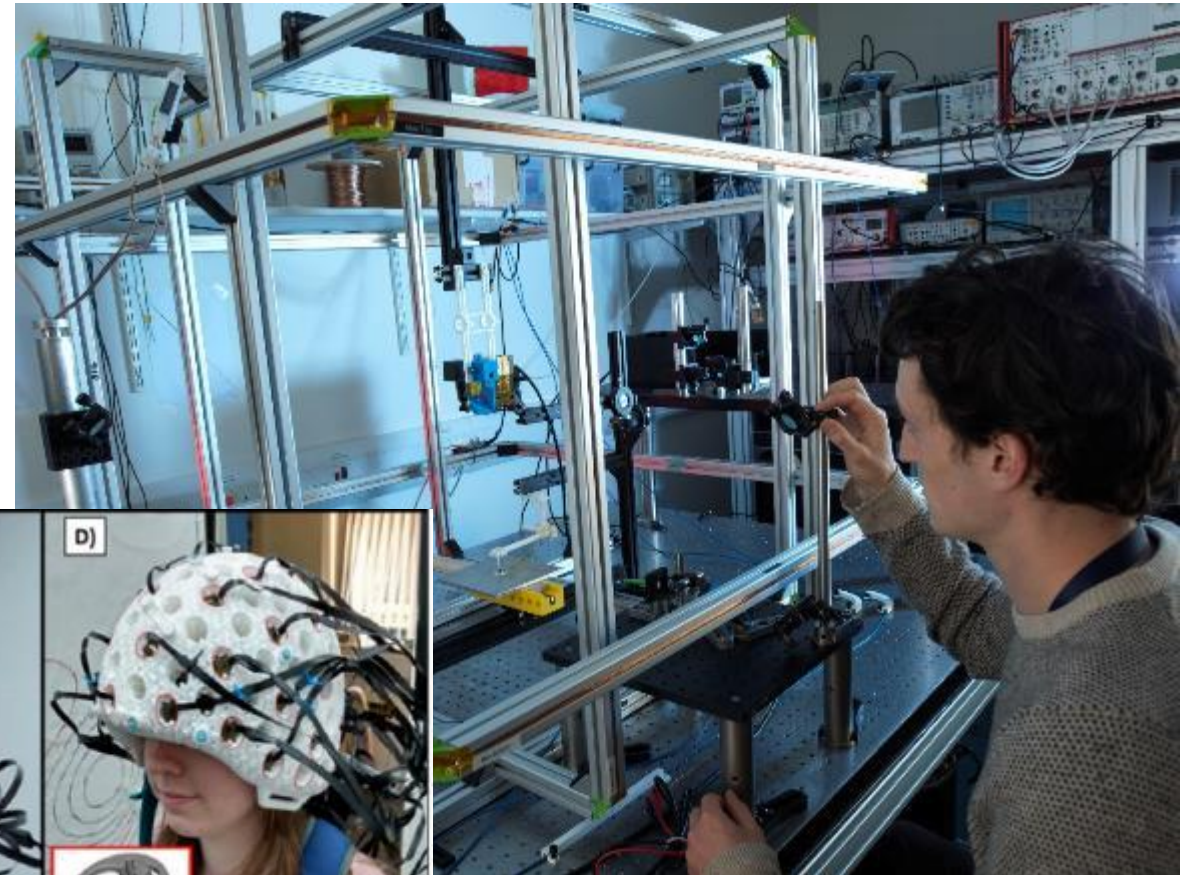
Atomic magnetometry



Atomic magnetometry applications

- Non-Destructive Testing (NDT)
- Inertial sensing for Positioning, Navigation and Timing
- New forms of computing
- OPM-MEG

Optically Pumped Magnetometer
Magnetoencephalography

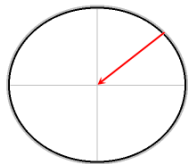


Gravimetry

- Measuring gravity – very important!
- Key to geology, hydrology, climate science, satellite flight etc.



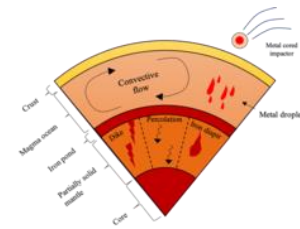
Sphericity



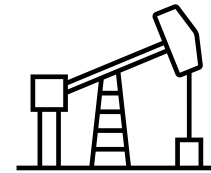
Equatorial 'bulge'



Mountain ranges



Mantle & core mass distribution



Large reservoirs



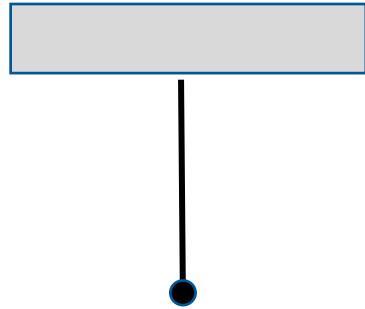
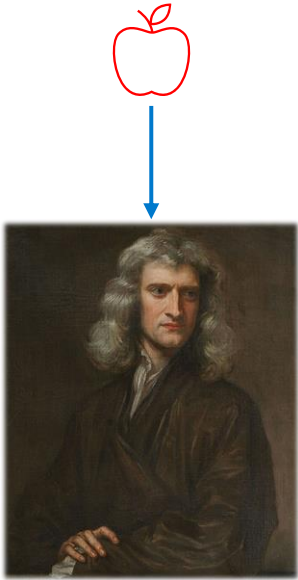
Tides



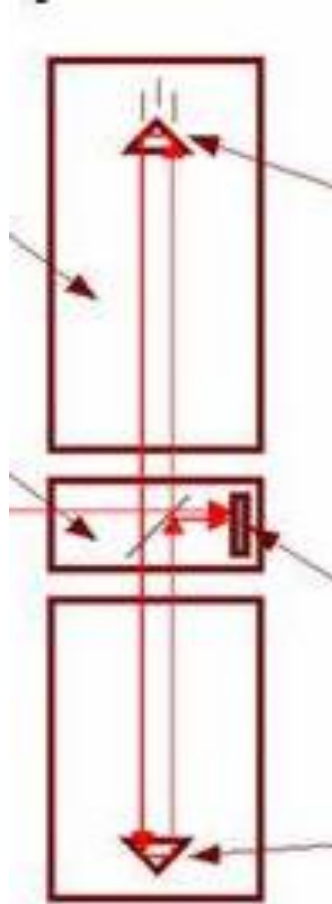
Large buildings

$$1 \text{ 'g'} = 9.8072467 \dots \text{ ms}^{-2}$$

Traditional ways of measuring gravity

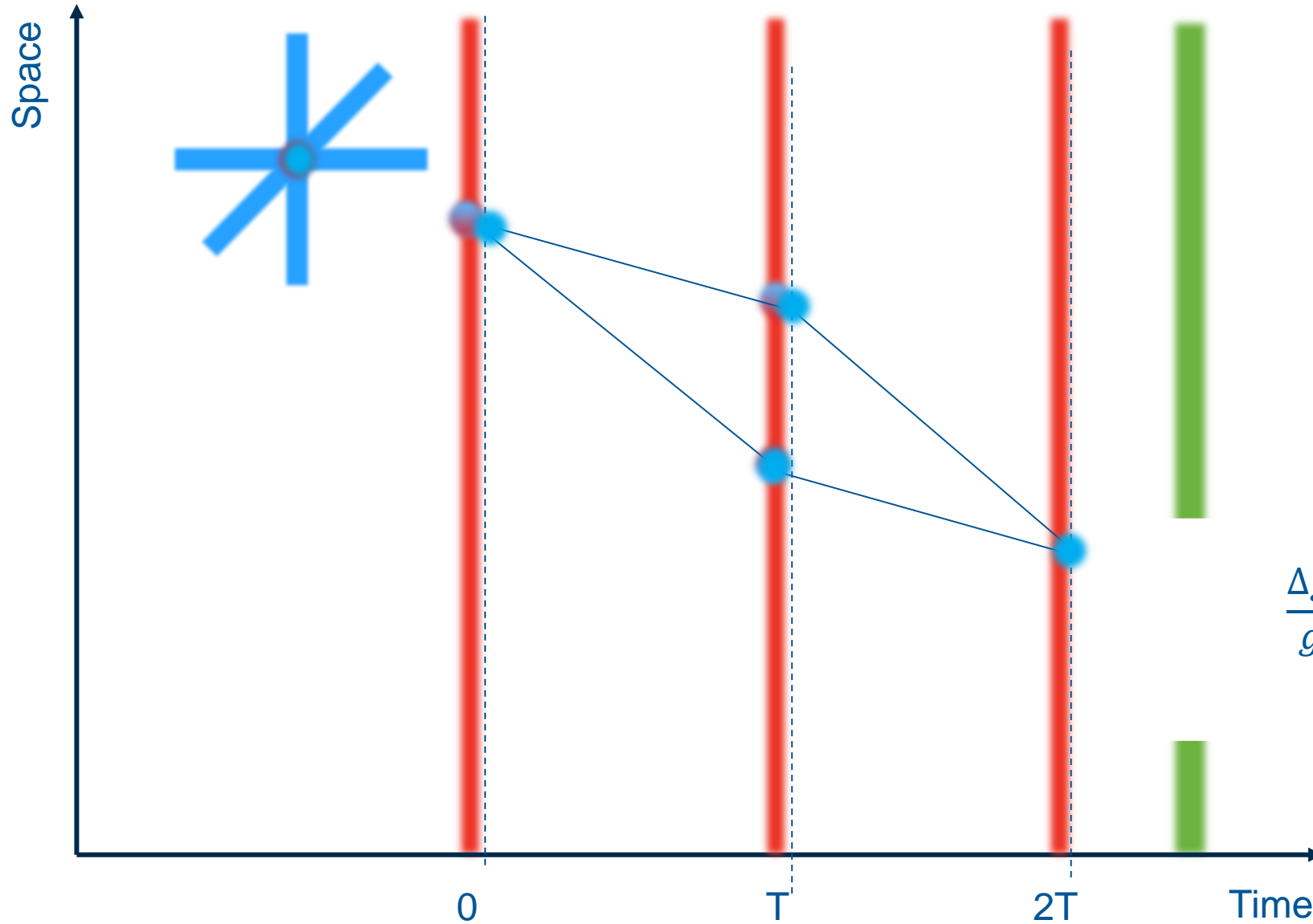


$$T = 2\pi \sqrt{\frac{l}{g}}$$

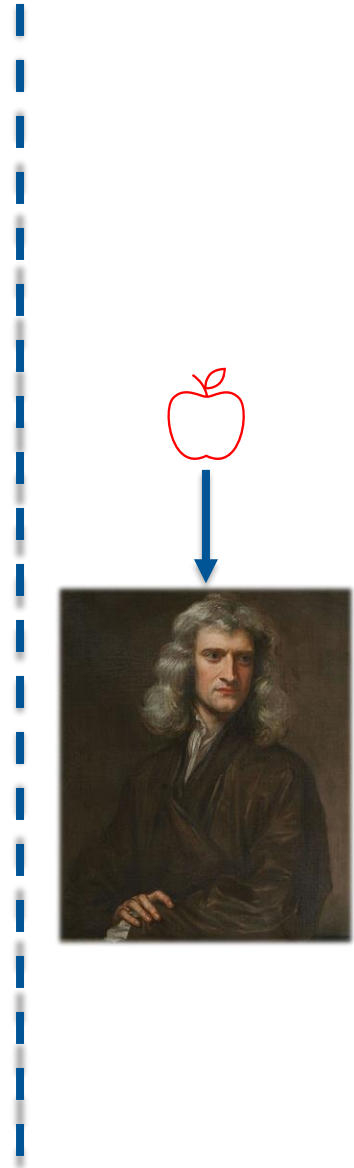


Courtesy Microg LaCoste

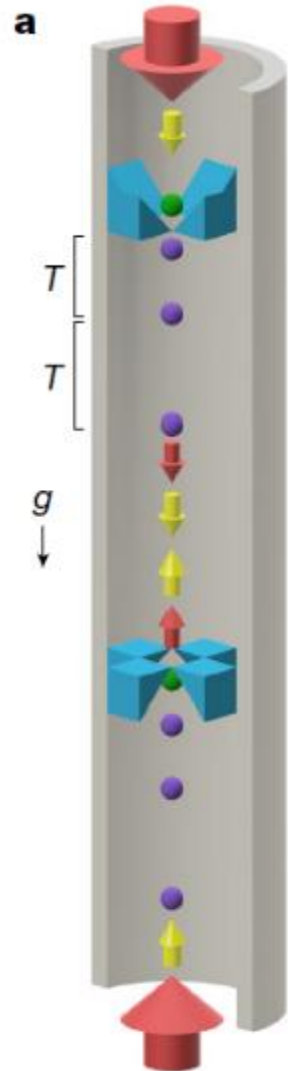
Atomic Gravimeters (from apples to atoms)



$$\frac{\Delta g}{g} = (k_{eff} T^2 \sqrt{N})^{-1}$$

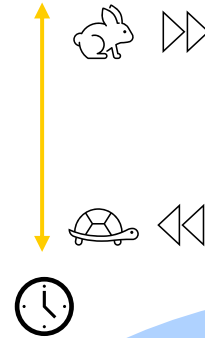
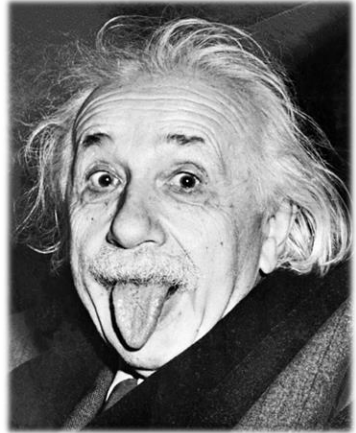
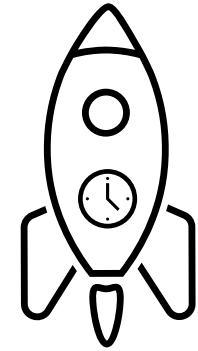


Birmingham Mobile Atom Gravimeter



Atomic ~~clocks~~ gravimeters?

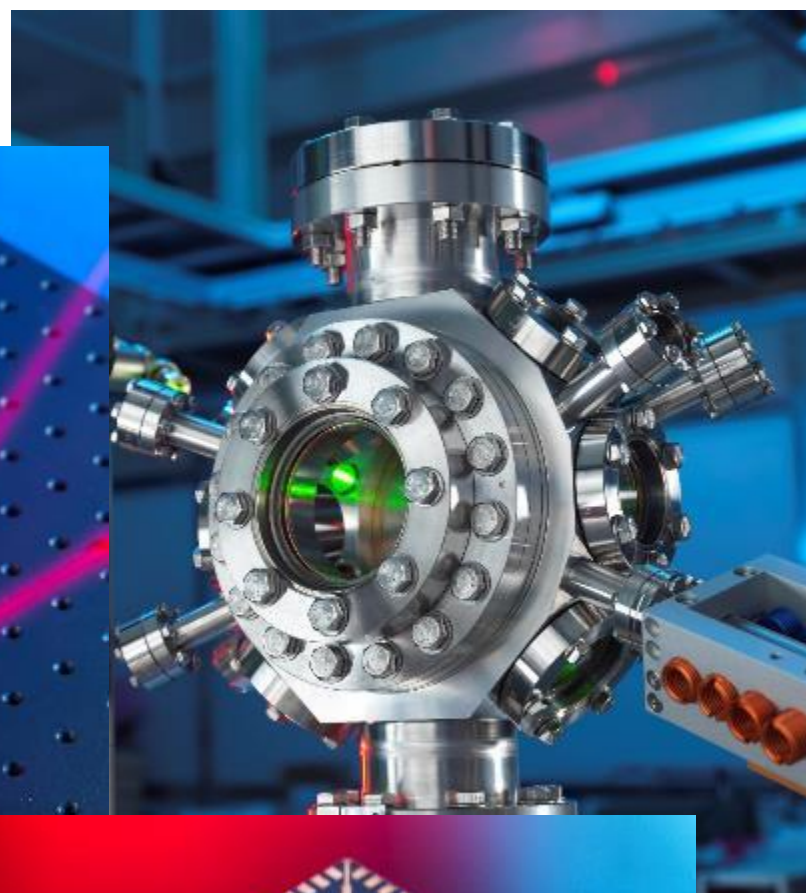
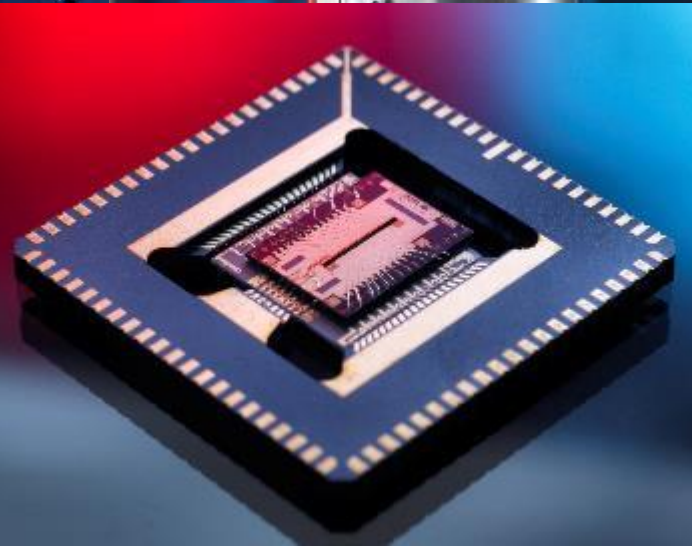
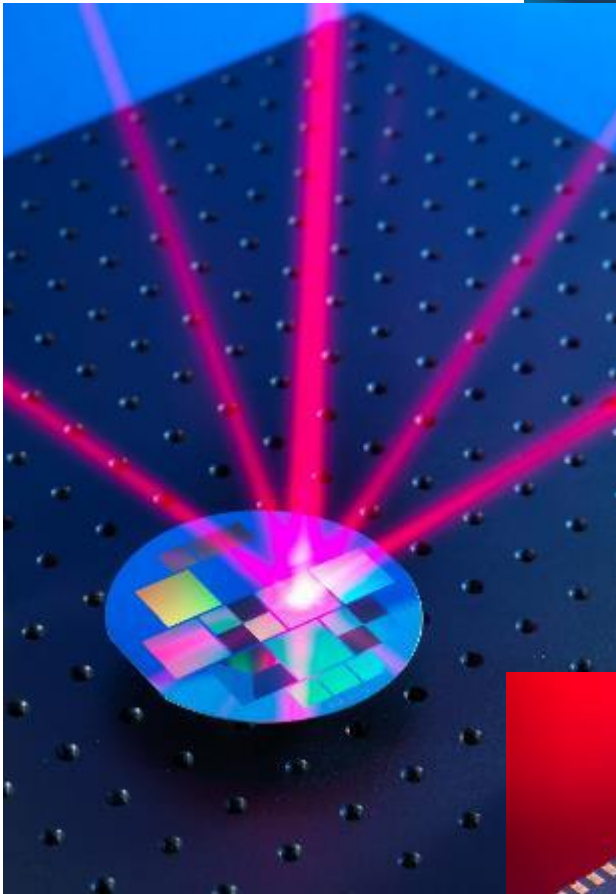
- General Relativity → gravitational time dilation
 - Time flows slower in higher gravitational potentials
- Earth's core 2.5 yrs *younger* than crust!
- Atomic clocks incredibly sensitive
 - Time 'speedup' detected across 1 mm cloud of atoms!
- Use clocks as sensors for missing 'dark' matter?



100ns
In
43 days

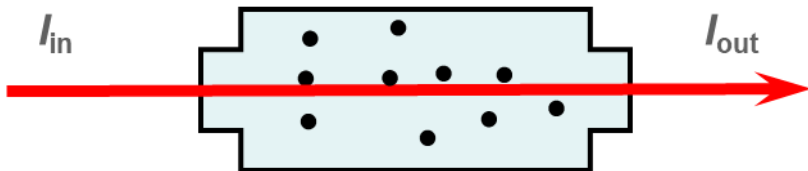
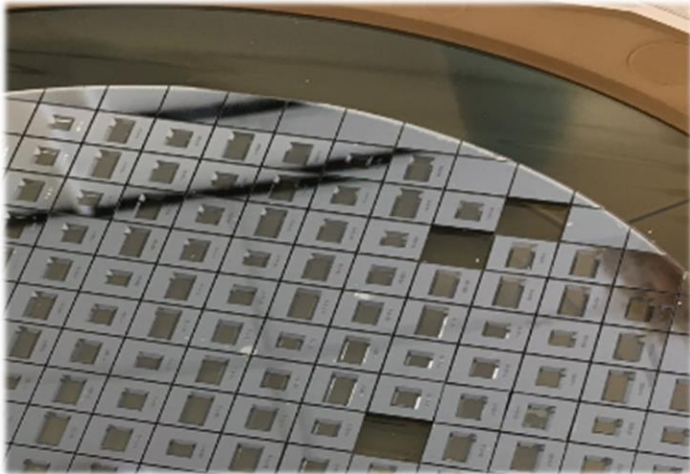


22 Bishopsgate London

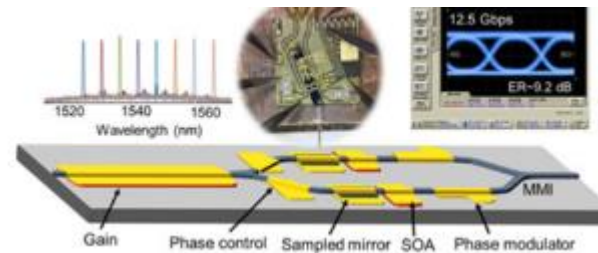
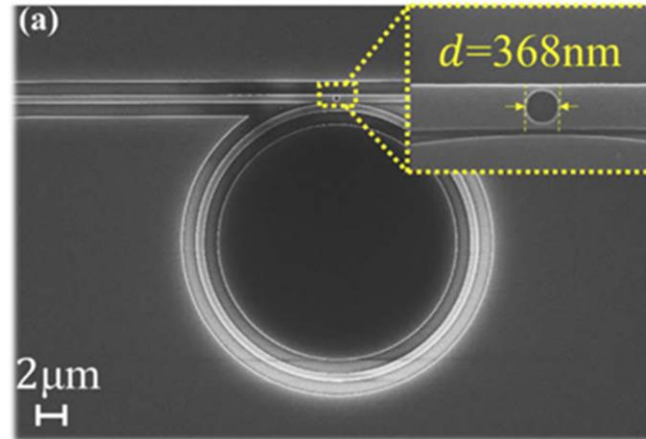


Self-Calibrating standards

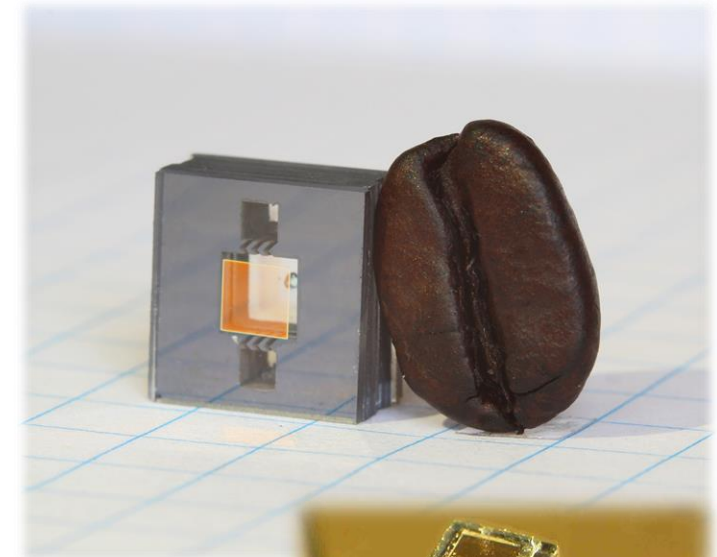
Doppler Broadening Thermometry



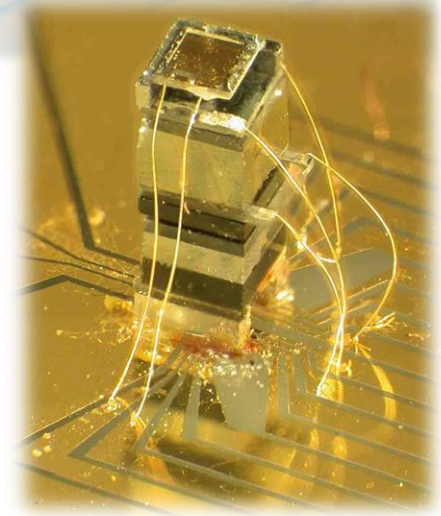
Active Ring Resonator Thermometry



NIST Chip-scale clock



NIST Chip-scale Magnetometer



Summary

- Quantum sensing better than classical, but a bit “weird”!
- Next quantum revolution is here
- Quantum technology will continue to shape our lives!





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