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National Physical Laboratory

Quantum Sensing & Metrology: The next frontier

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President Consultative Committee on Ionising Radiation (CCRI)

United Kingdom

INTERNATIONAL YEAR OF
Quantum Science
and Technology

100 years of quantum is just the beginning...

Measurement is ubiquitous in our everyday lives, it makes everything function, but often goes unnoticed








Criticality at the Fukushima Daiichi Nuclear Power Plant & Monitoring for Nuclear Weapons with the CTBTO.

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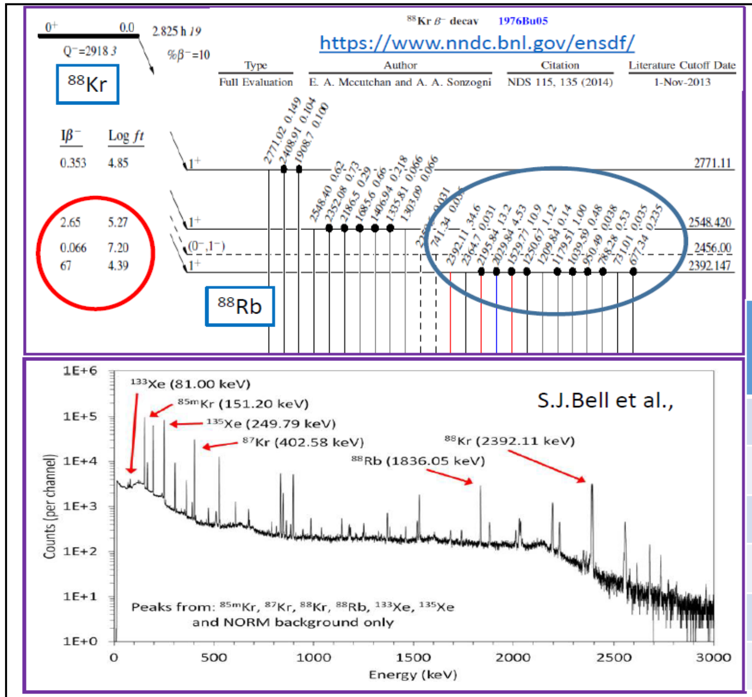
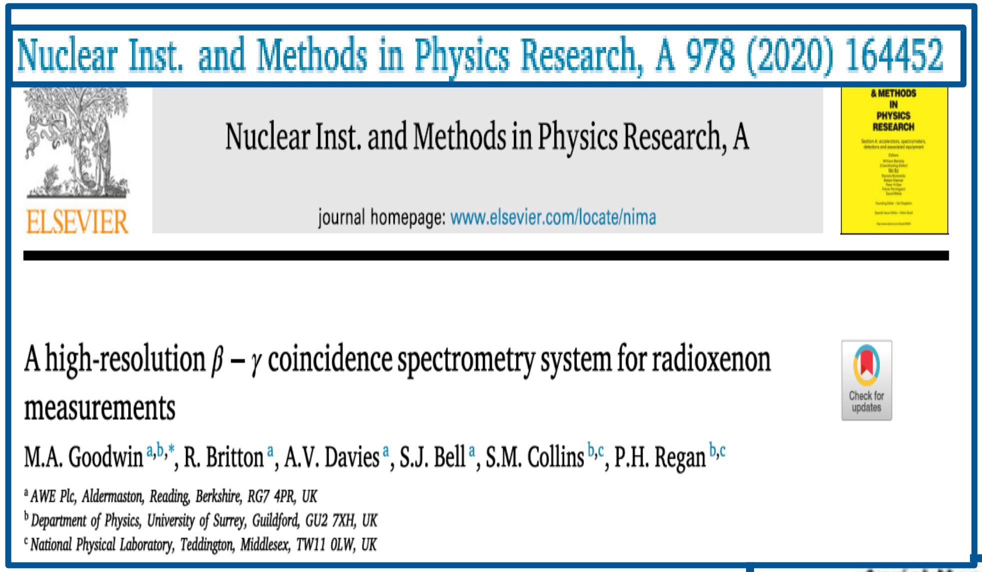


^{88}Kr → ^{88}Rb decay
$T_{1/2}$ = 2.825 hours.

Number of γ rays can give number of ^{88}Kr atoms using

$A = \lambda N$

γ-ray energy (keV)	Emission / 100 decays of ^{88}Kr
196.30	27.3
362.27	2.3
834.83	13.0
1529.77	10.9
2195.84	13.2
2392.11	34.6



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Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A high-resolution $\beta-\gamma$ coincidence spectrometry system for radioxenon measurements

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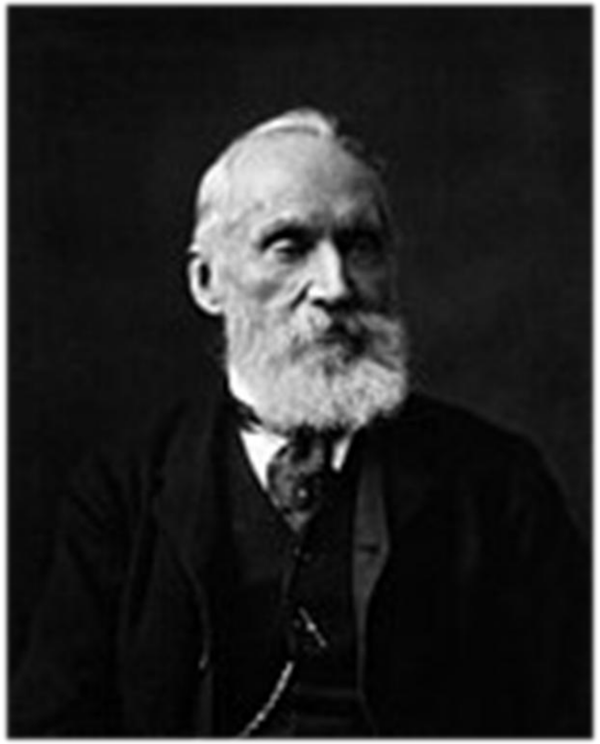
- NPL Nuclear Metrology Group standardisations of radio-Kr fission isotopes.
- ‘Real time’ signatures for reactor criticality, vital in Fukushima clean up.
- New methods with AWE & CTBTO for radioxenon sigs from weapons tests.



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

International agreement: The Metre Convention

- On 20 May 1875, 17 governments signed **The Metre Convention**, to “assure the international unification and improvement of the metric system”
- Diplomatic treaty that established an organizational structure for Member States to act together on units of measurement
- Established the International Bureau of Weights and Measures (BIPM), one of the oldest international organizations still in existence

Salon de l'horloge inside the French Ministry of Foreign Affairs

Seal of the BIPM

Evolution of the SI

The SI constantly evolves unit definitions & realizations to meet user needs for accuracy

1948: Recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention

1960

The name adopted by the 11th CGPM in 1960 for the system with 6 base units.

- kilogram
- second
- metre,
- ampere
- kelvin
- candela

1967

The **second was redefined** – the atomic second

1971

the **mole was introduced** – to provide a unit for chemistry

1979

the **candela** – redefined as monochromatic radiation.

1983

the **meter was redefined** – the first fundamental constant.

1990

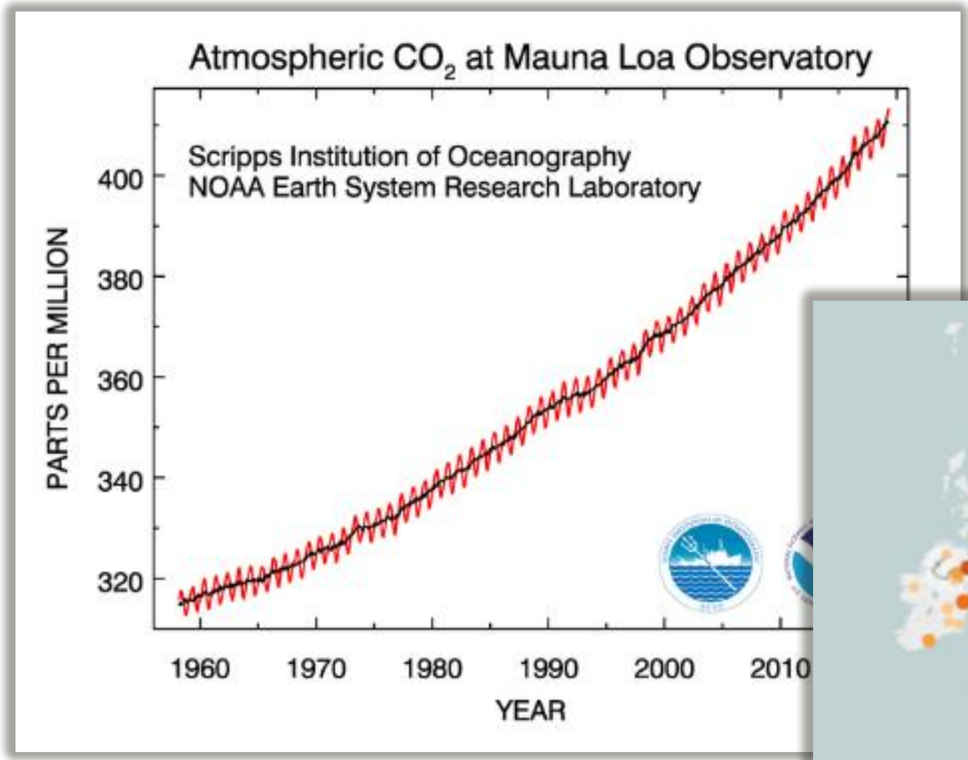
conventions for the **volt** and the **ohm** adopted

the **International Temperature Scale (ITS90)** was adopted

…and many smaller changes as well, except to the kg, until recently…

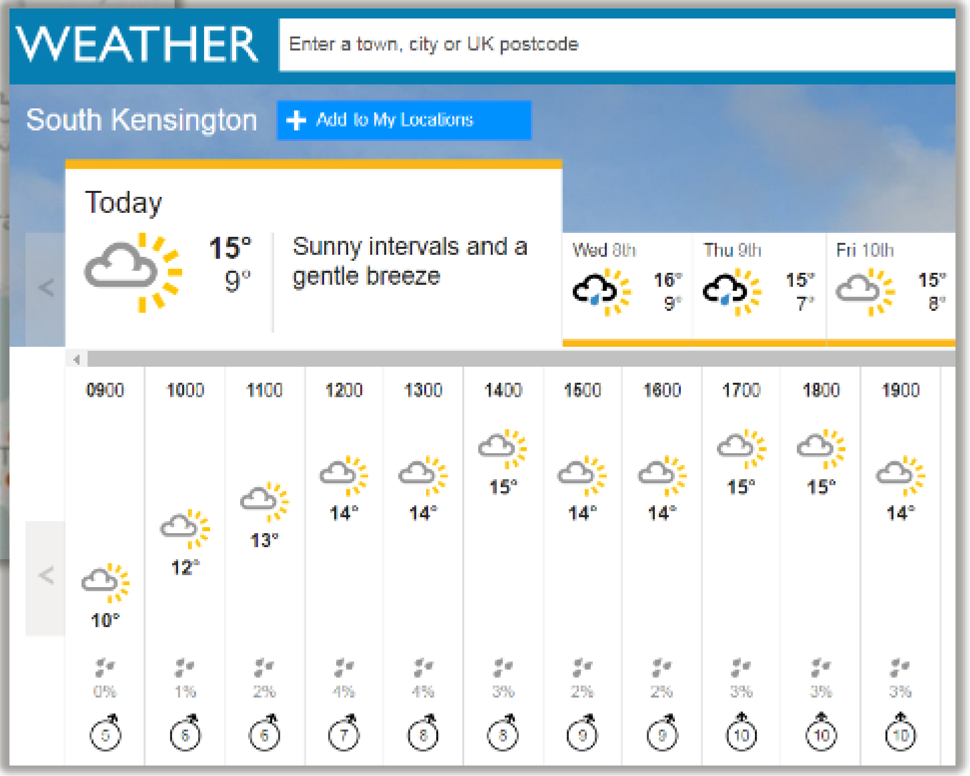
Image courtesy of Martin Milton, BIPM

stable



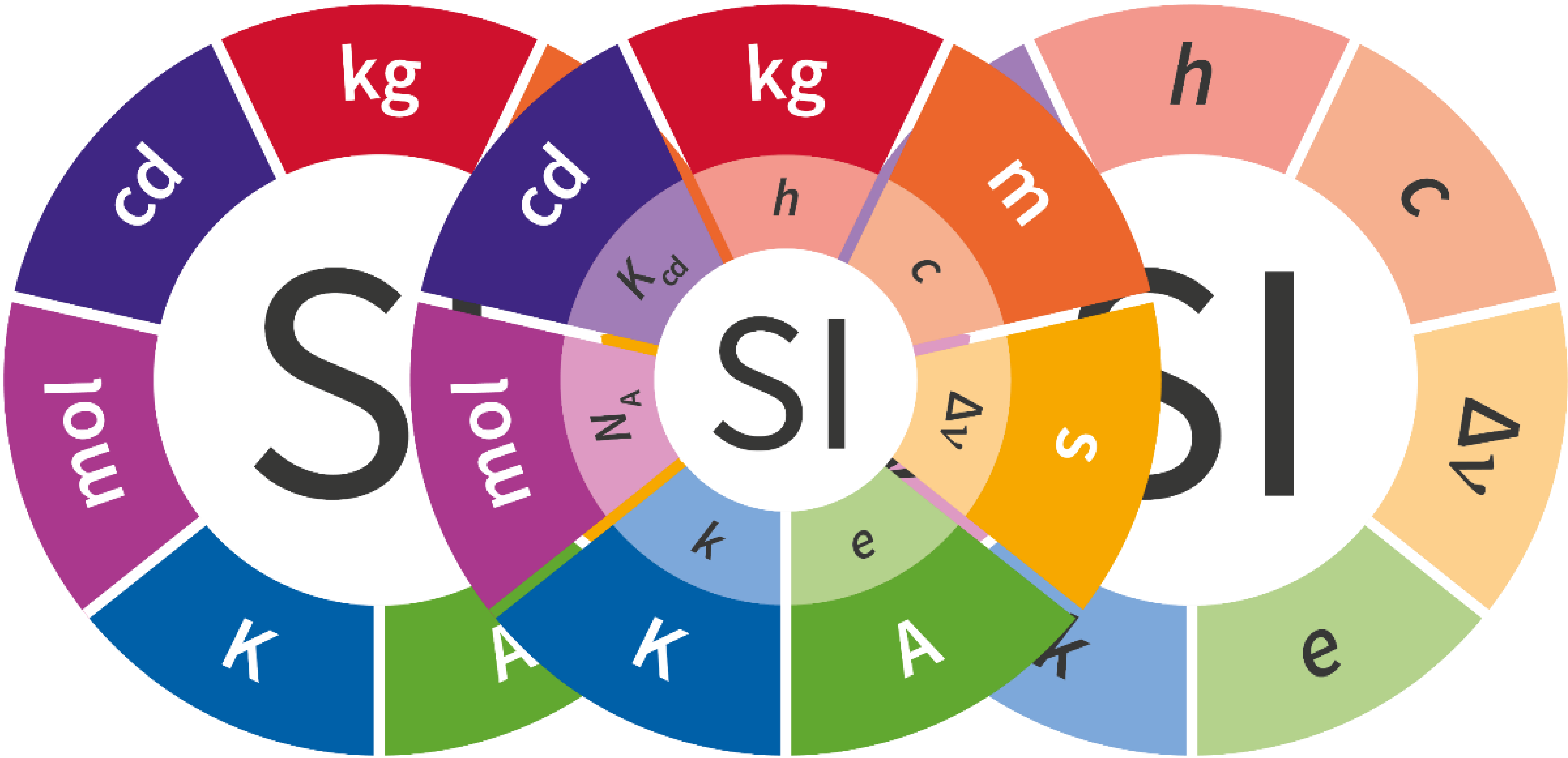
comparable

universal



improving certainty in measurement

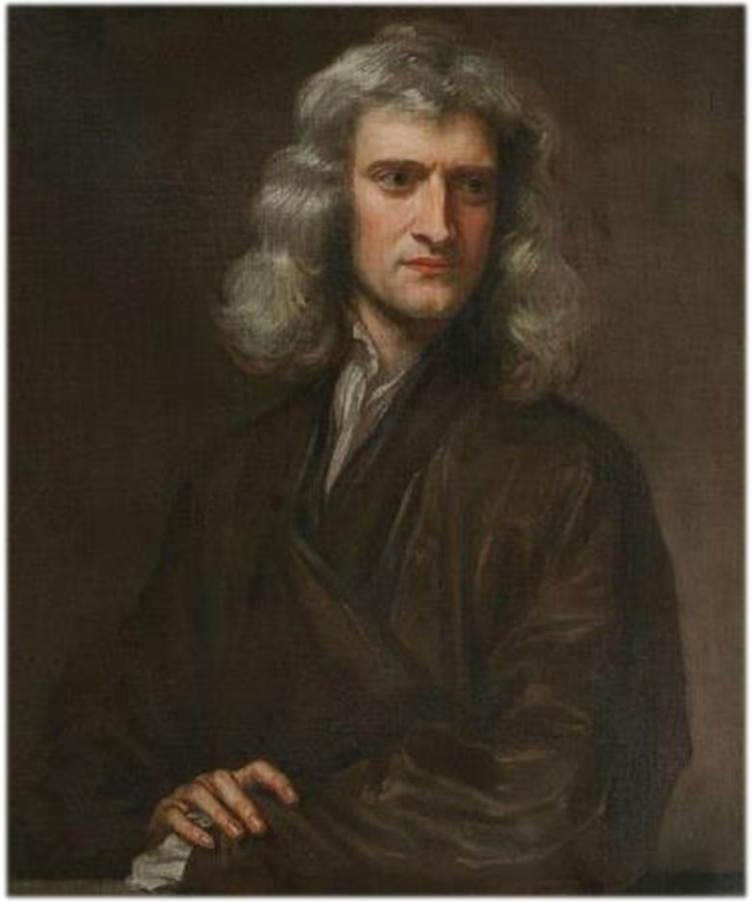
The New International System of Units (2019)



20 May 2025: World Metrology Day

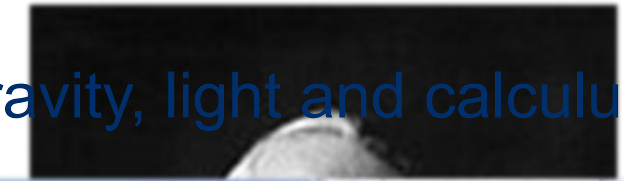
CELEBRATING
BIPM 150
1 8 7 5 – 2 0 2 5

Classical mechanics



Isaac Newton
1642-1726

Gravity, light and calculus



All that remains is more and more precise measurement."

~~Lord Kelvin~~ (1900)

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

$$F = gm$$

Quantum mechanics founders

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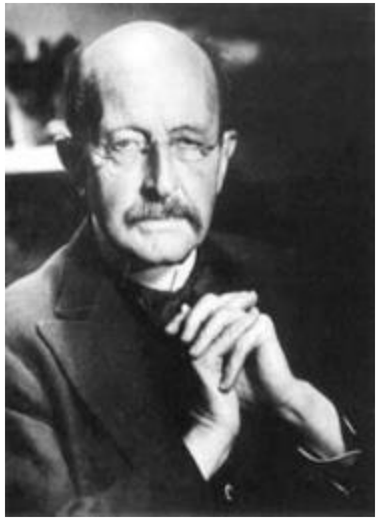
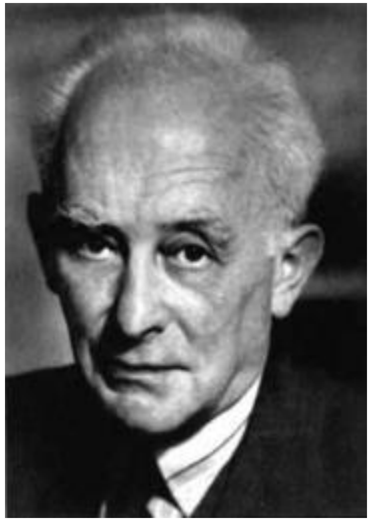


Planck

Einstein

Bohr

Heisenberg



Born

Dirac

Schrodinger

INTERNATIONAL YEAR OF
Quantum Science
and Technology

100 years of quantum is just the beginning...

The strange world of quantum is highly counter-intuitive!

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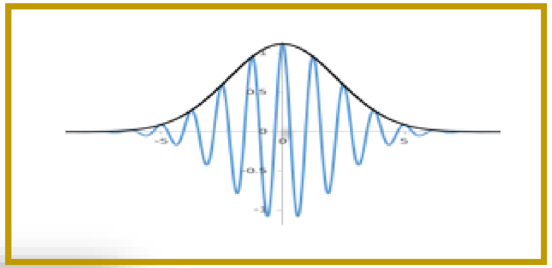
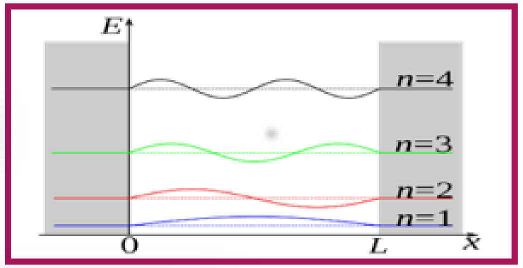
Wave Nature of Matter

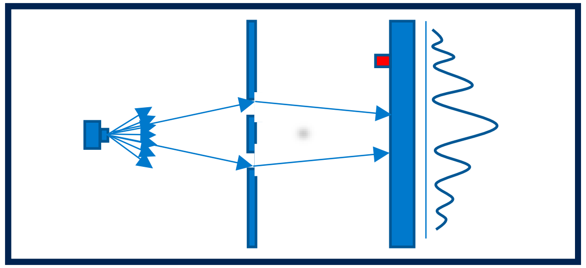


$$\lambda = \frac{h}{p} \text{ and } h \approx 6.6 \ x \ 10^{-34} \ Js$$

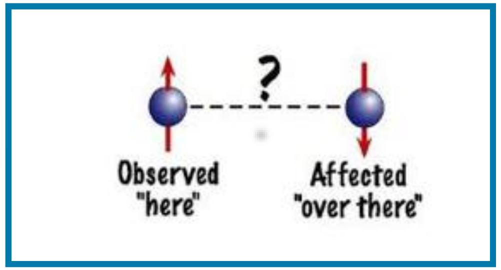
Quantization



Superposition



Entanglement



Quantum Summary

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- 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 unpresented precision

Quantum Applications today

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Loads of modern technology is underpinned by quantum technology

NMR

Lasers

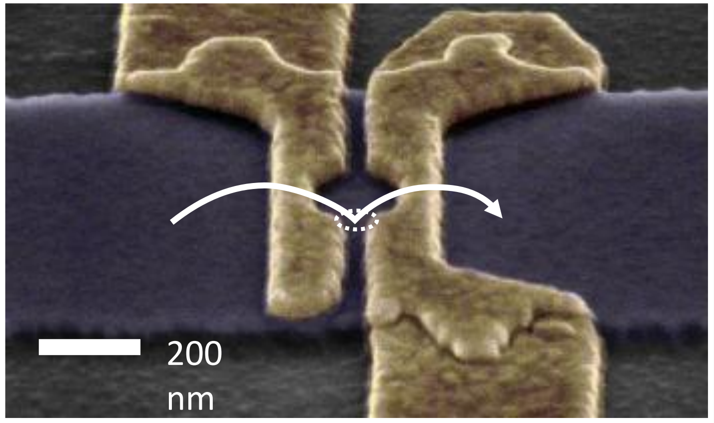
Atomic clocks

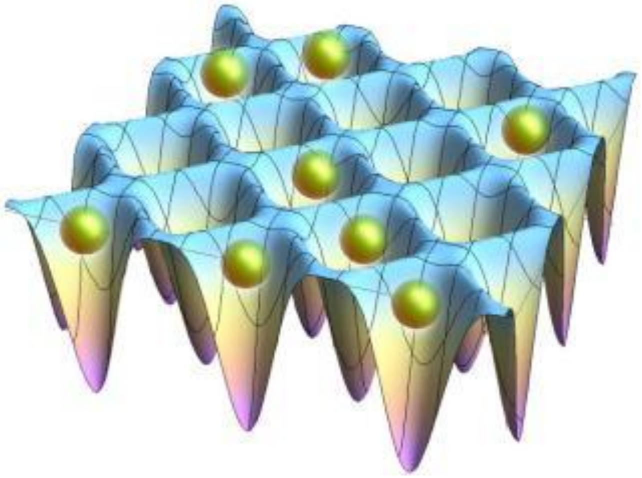
Semiconductors

Nuclear power

How to reach the quantum regime ?

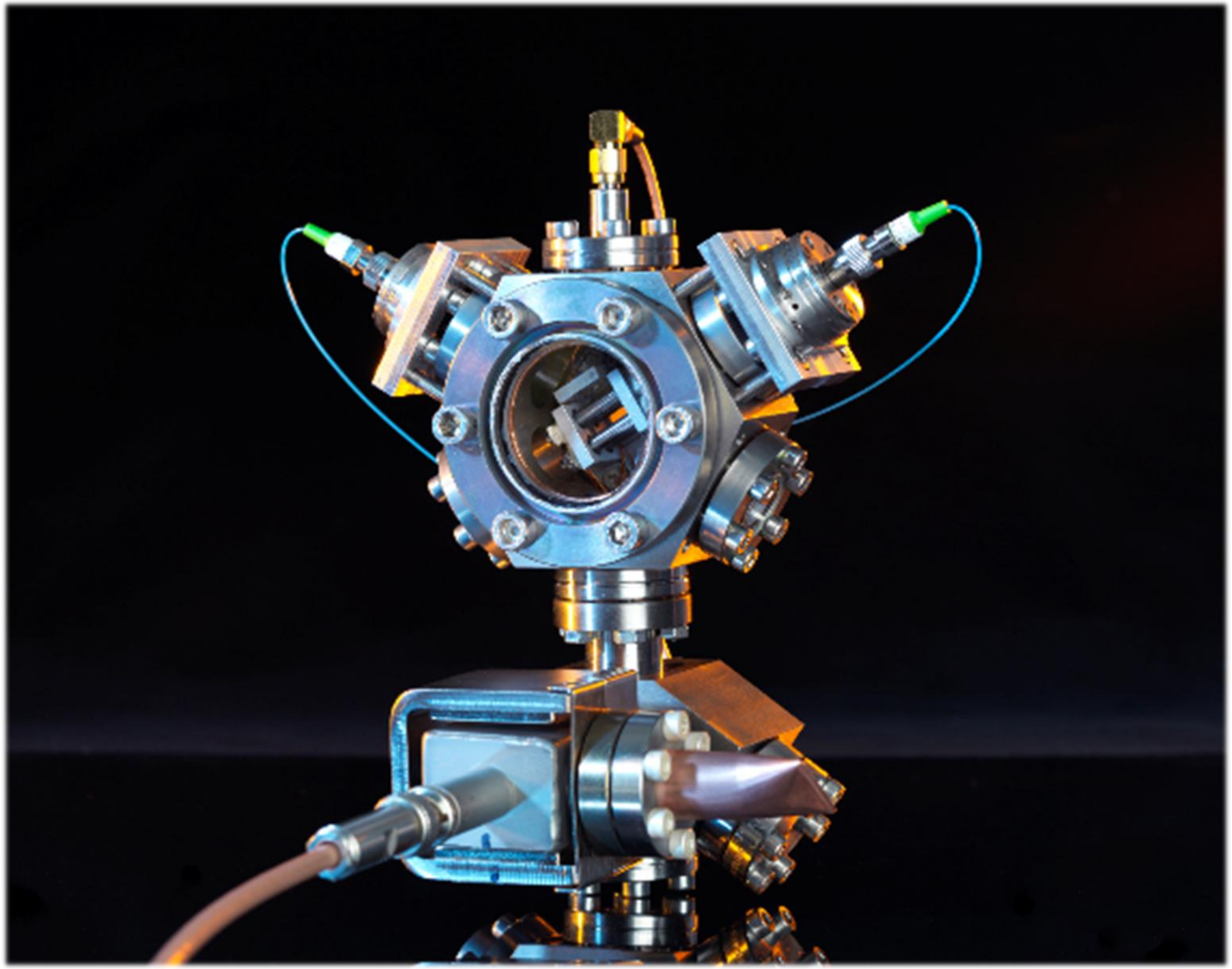
- Make things very small





- Make things very cold

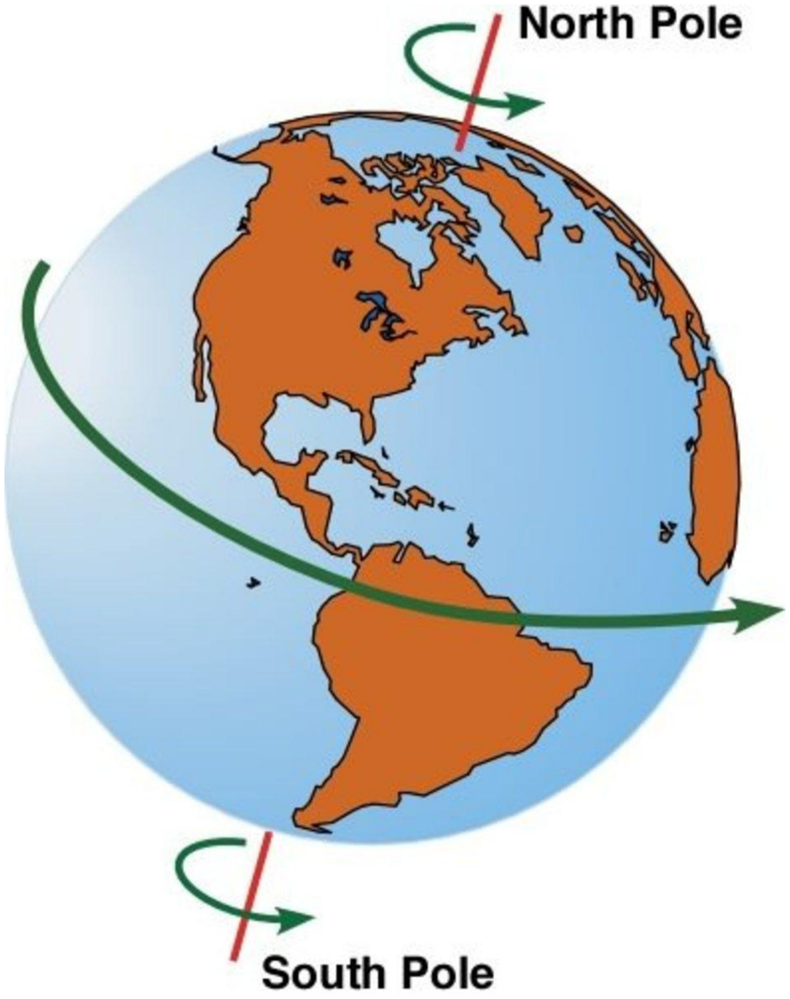
Laser Cooling



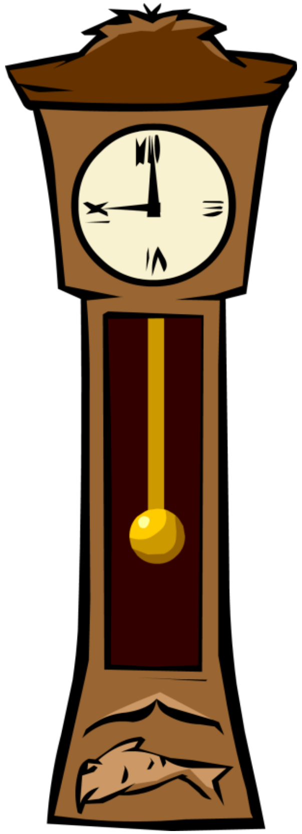
Plane = Atom

Balls = Photons

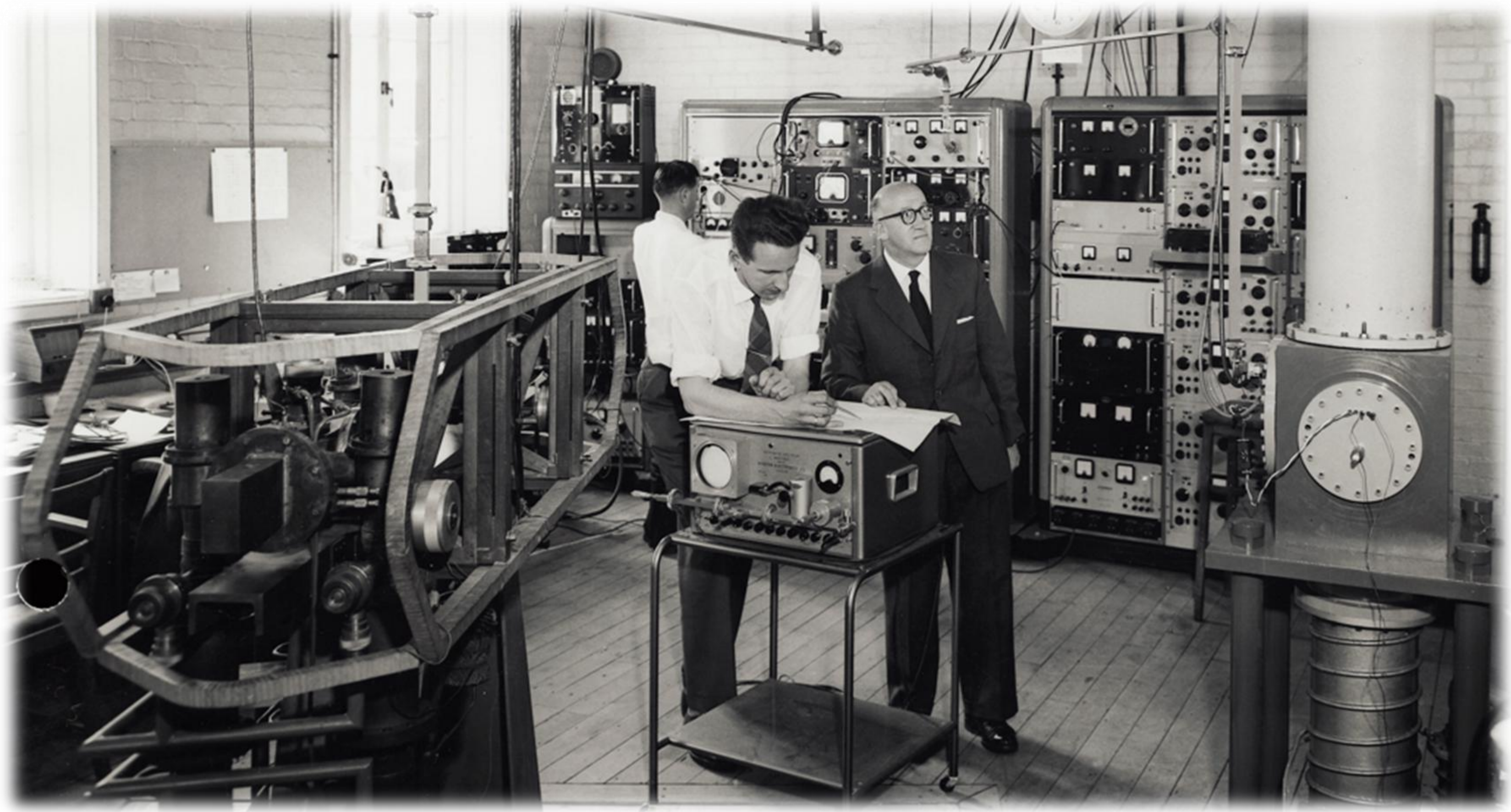
Before atomic time



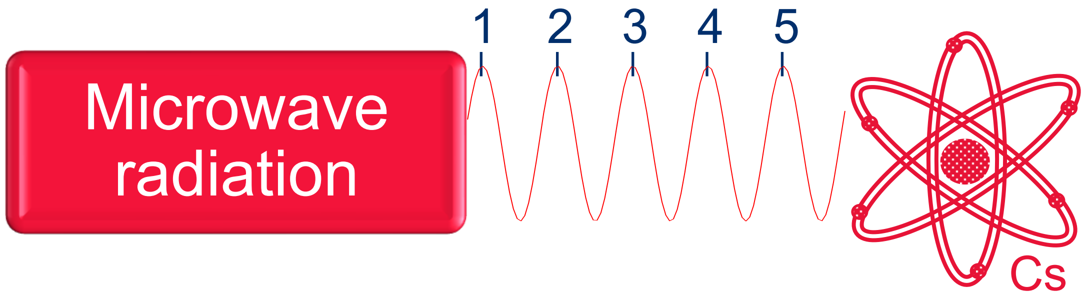
Ephemeris time

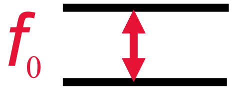


NPL 1955: birth of atomic time



How do atomic clocks work?



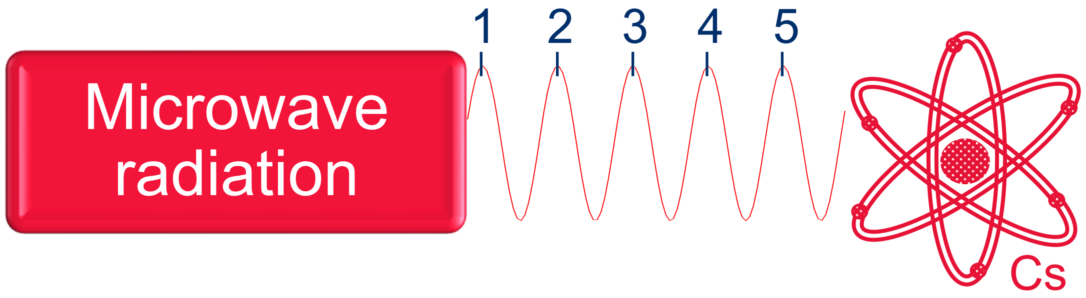


9 192 631 770 Hz

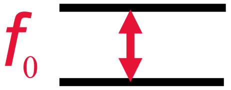
microwave frequency

Second defined with Cs transition frequency

How do atomic clocks work?



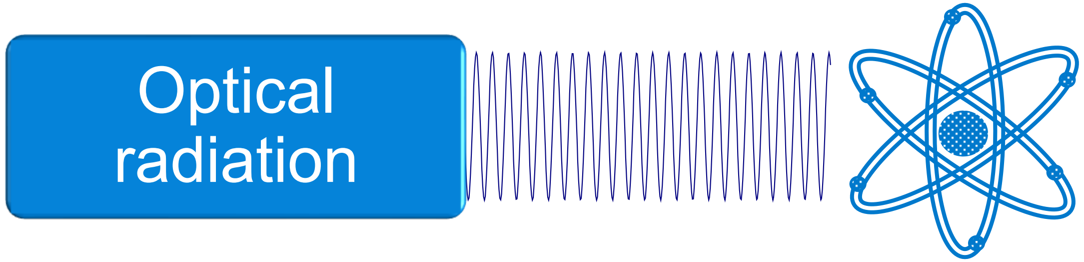
$E = hf$



9 192 631 770 Hz

few GHz ~ 10^9 Hz

microwave frequency



optical frequency

few hundred THz ~ 10^{14} Hz

Progress in atomic clock measurements

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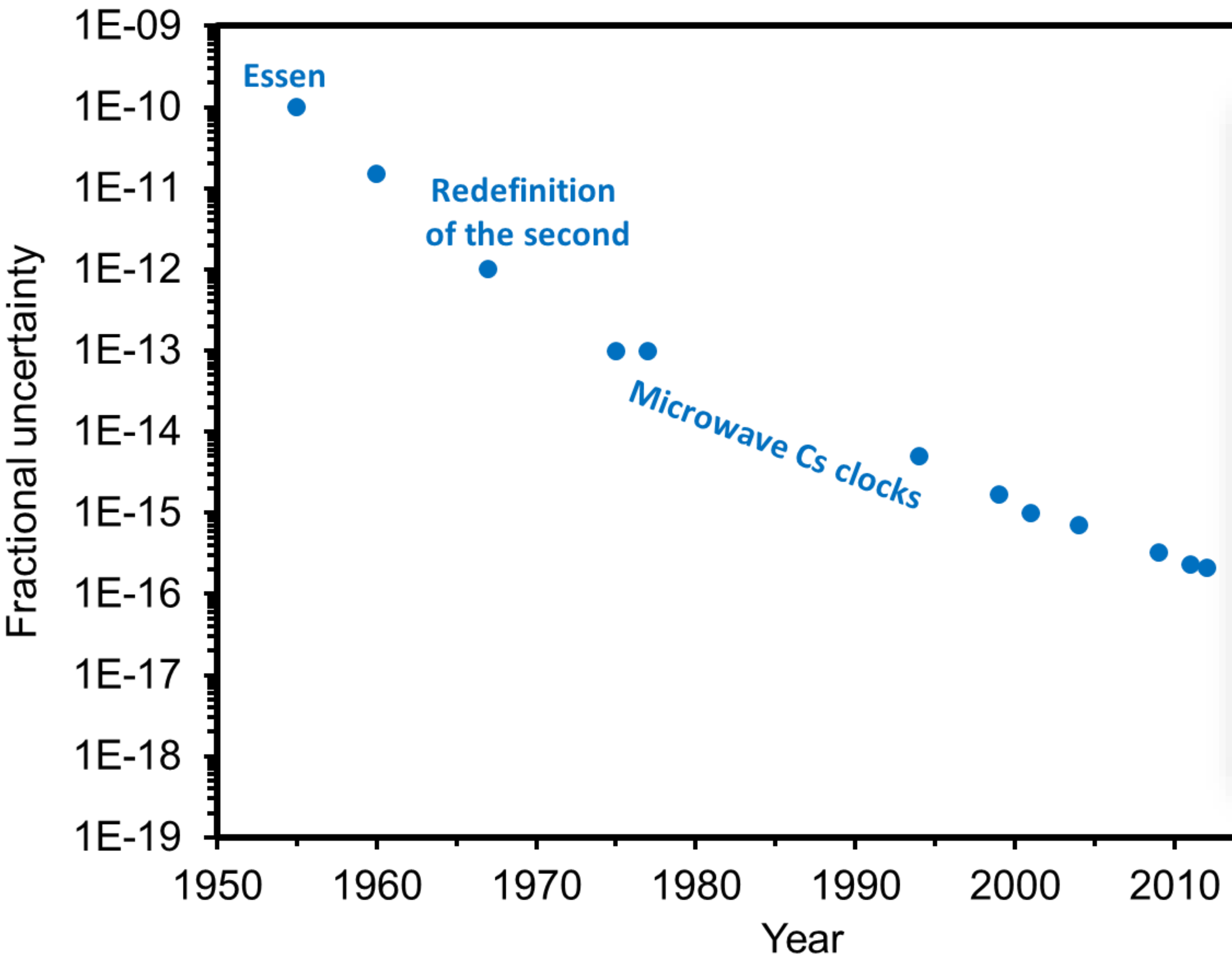
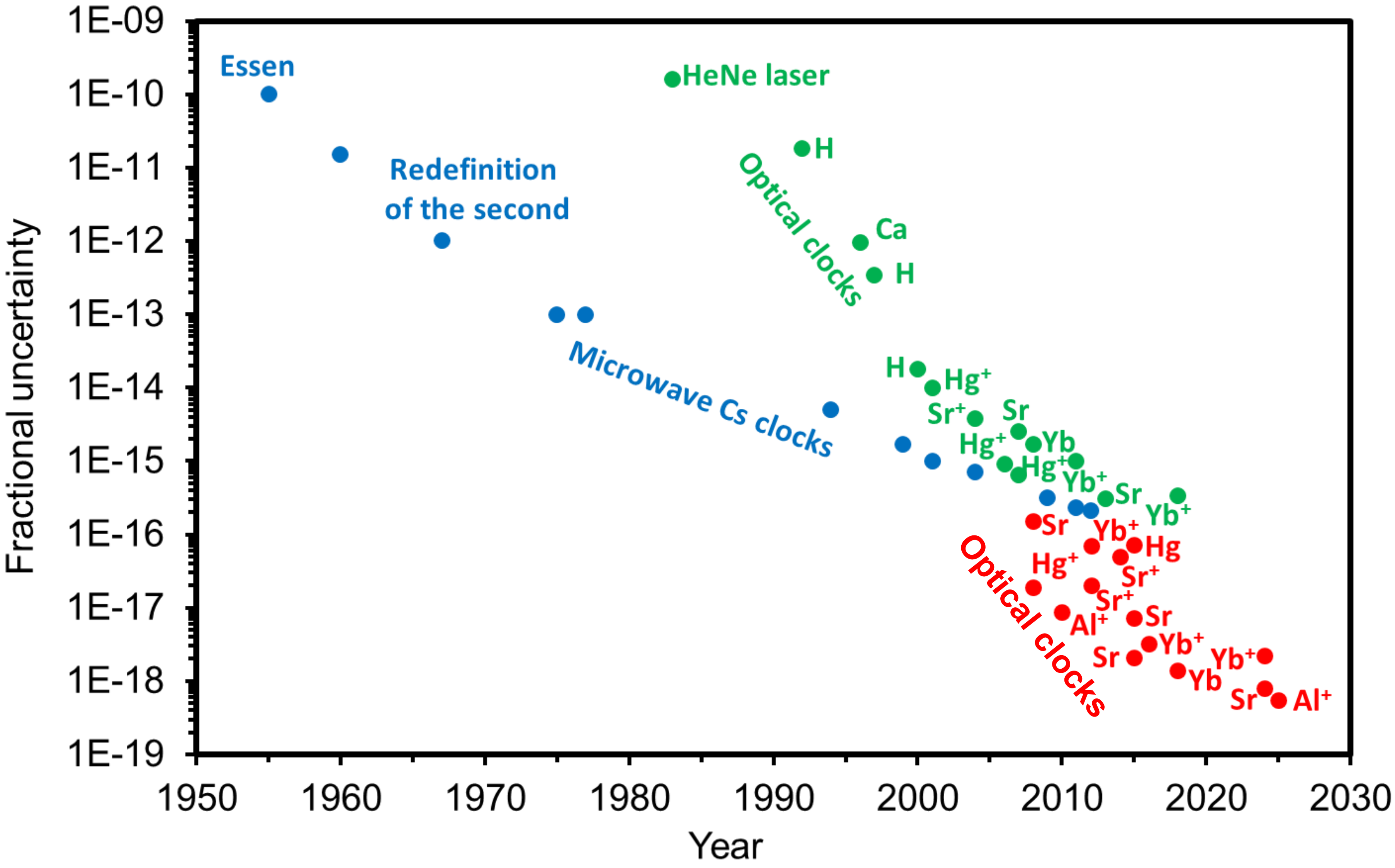


The best Cs fountain clocks are reaching uncertainties of 10^{-16}

Progress in atomic clock measurements



The best Cs fountain clocks are reaching uncertainties of 10^{-16}

The best optical clocks are reaching uncertainties below 10^{-18}

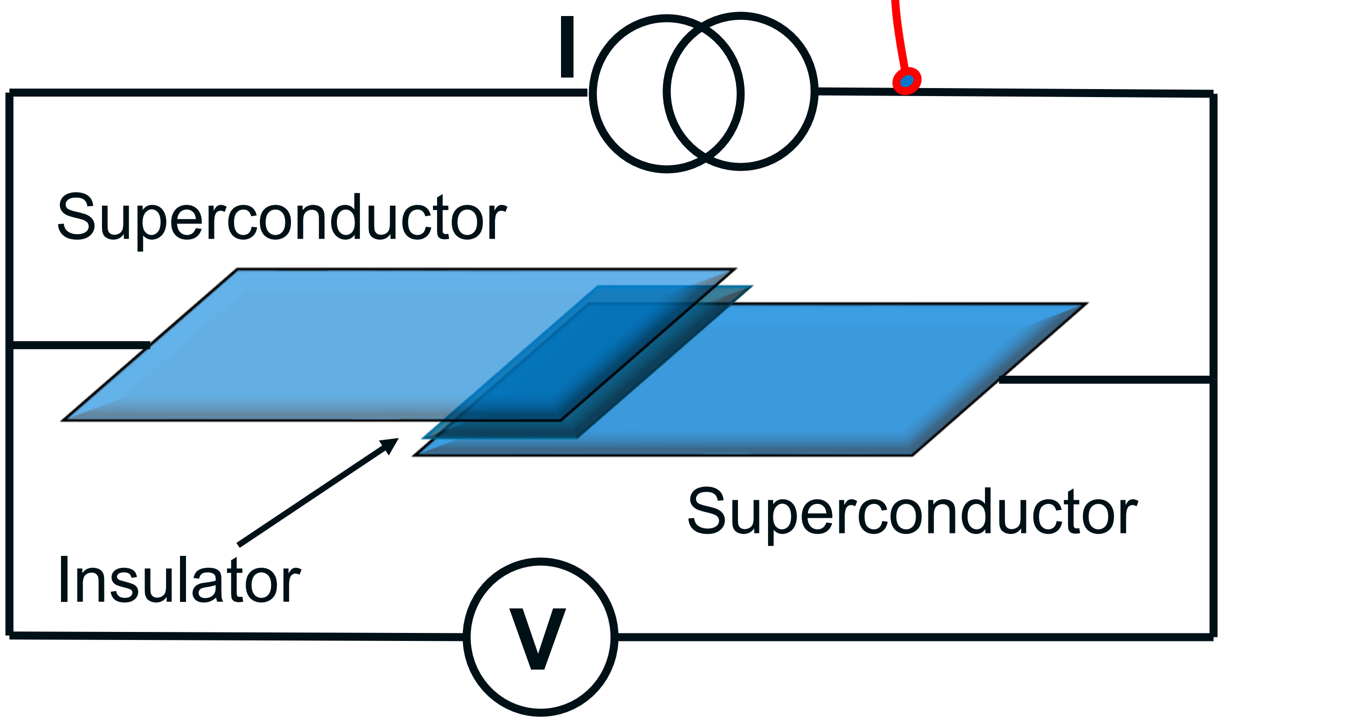
Quantum Electrical Metrology and the SI

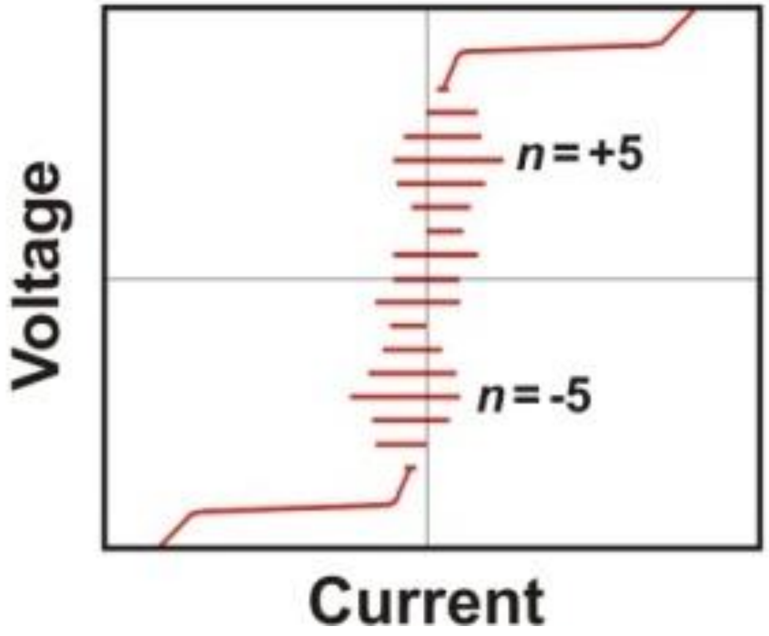
Josephson effect

Predicted in 1962 by Brian Josephson

Nobel Prize in physics in 1973

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

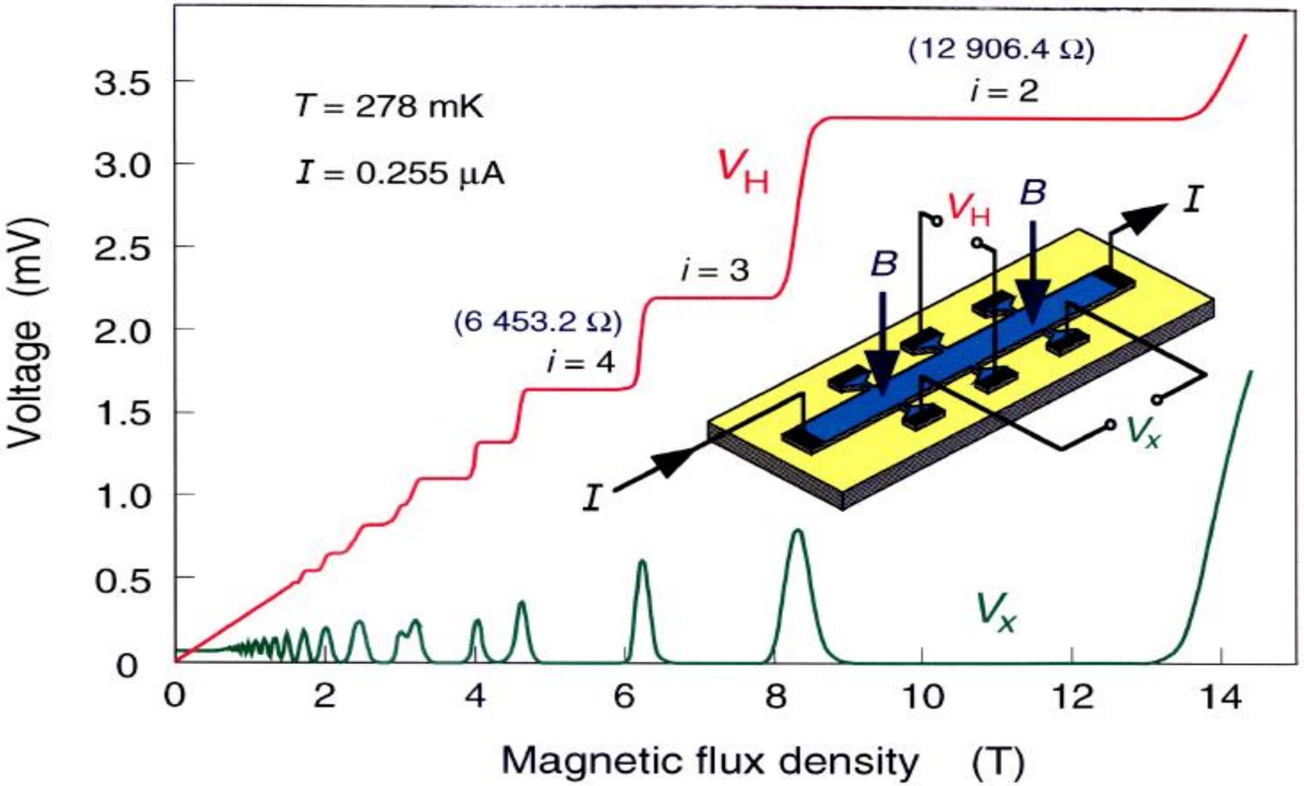




The quantum Hall effect

Discovered in 1980 by Klaus von Klitzing

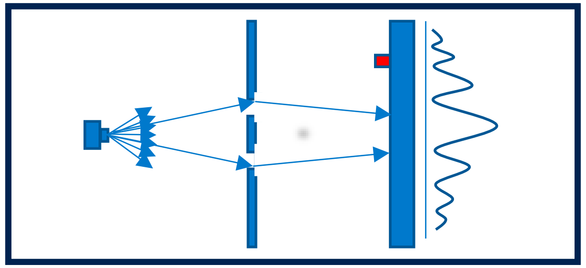
Nobel Prize in Physics in 1985



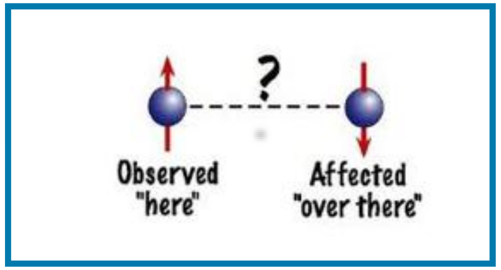
$$R_H = \frac{h}{e^2} \cdot \frac{1}{i}$$

Quantum Revolution #2

Superposition

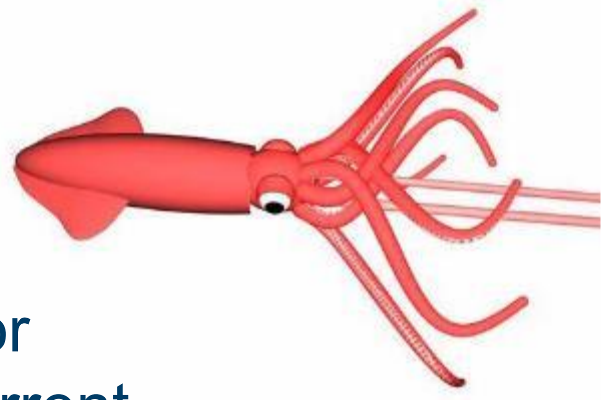


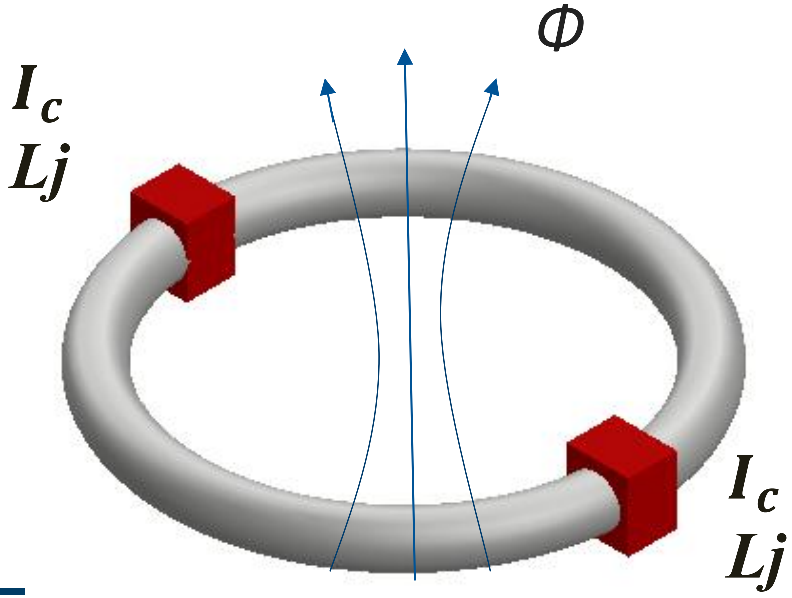
Entanglement



The SQUID

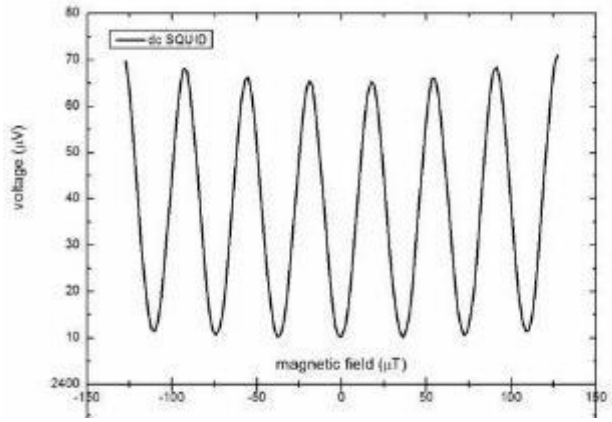
Superconducting QUantum Interference Device





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

An interferometer for superconducting current



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

Field produced by the brain	Earth Magnet field	Fridge magnet	Loudspeaker magnet	Neutron Star
~1 pT	30 microT	5 mT	1 T	~MT
0.000000000001	0.000030	0.005	1.0	1,000,000

Quantum Magneto Encephalography

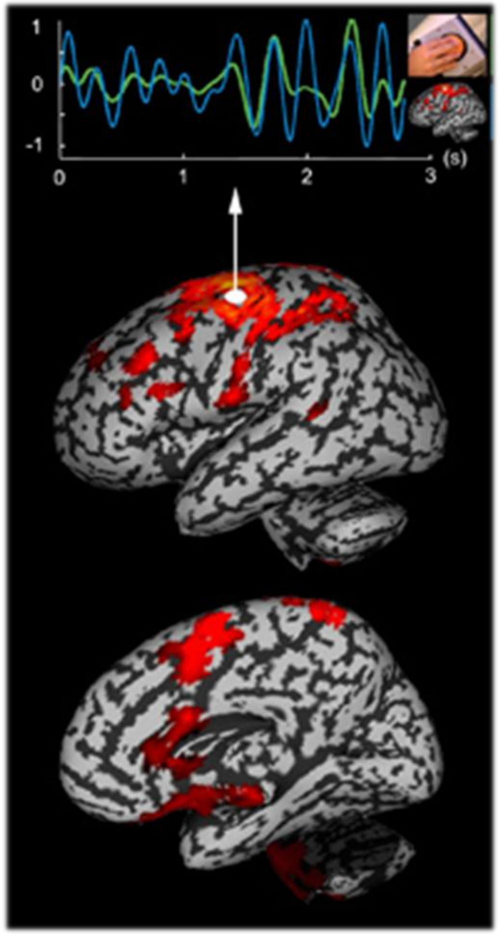
Courtesy CTF MEG systems

Epilepsy: 60M people world-wide

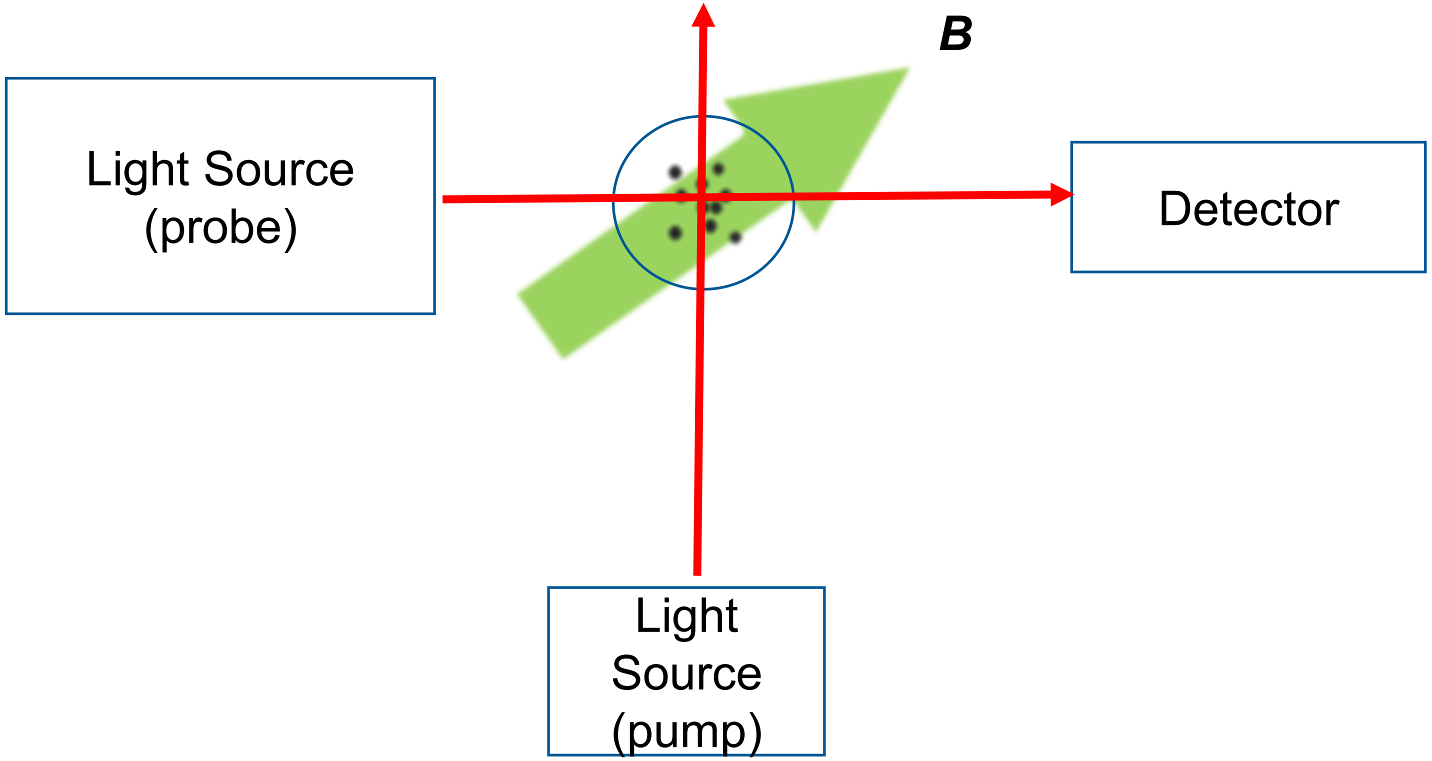
Dementia: 1% GDP

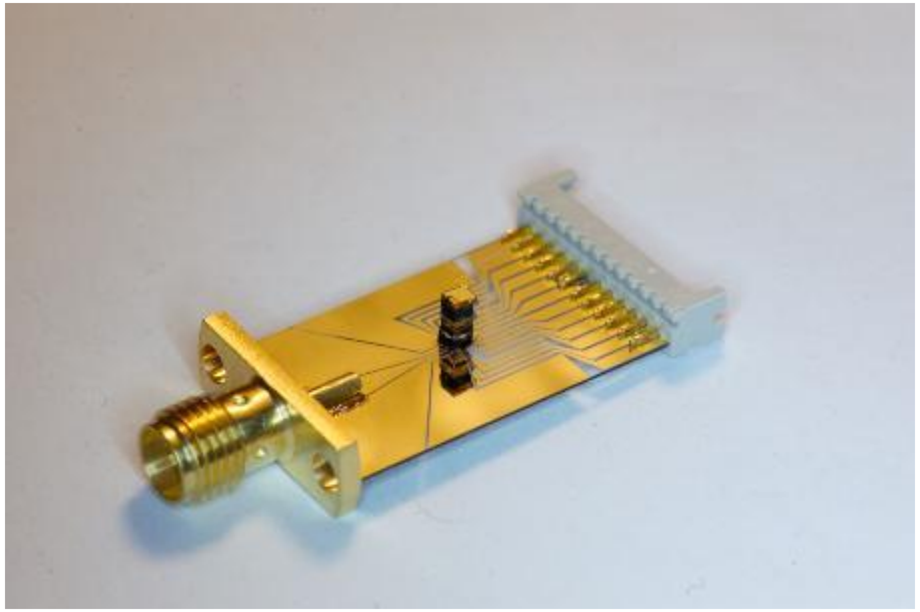
Schizophrenia: 1% of population

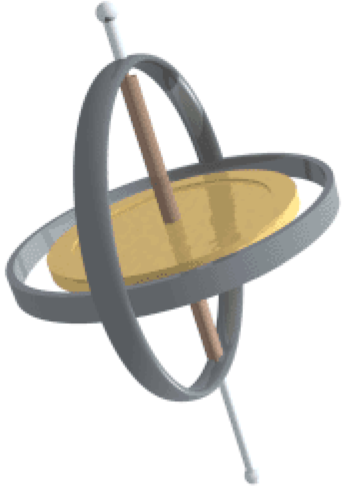
Trauma: 100,000 / year in the UK



Atomic magnetometry



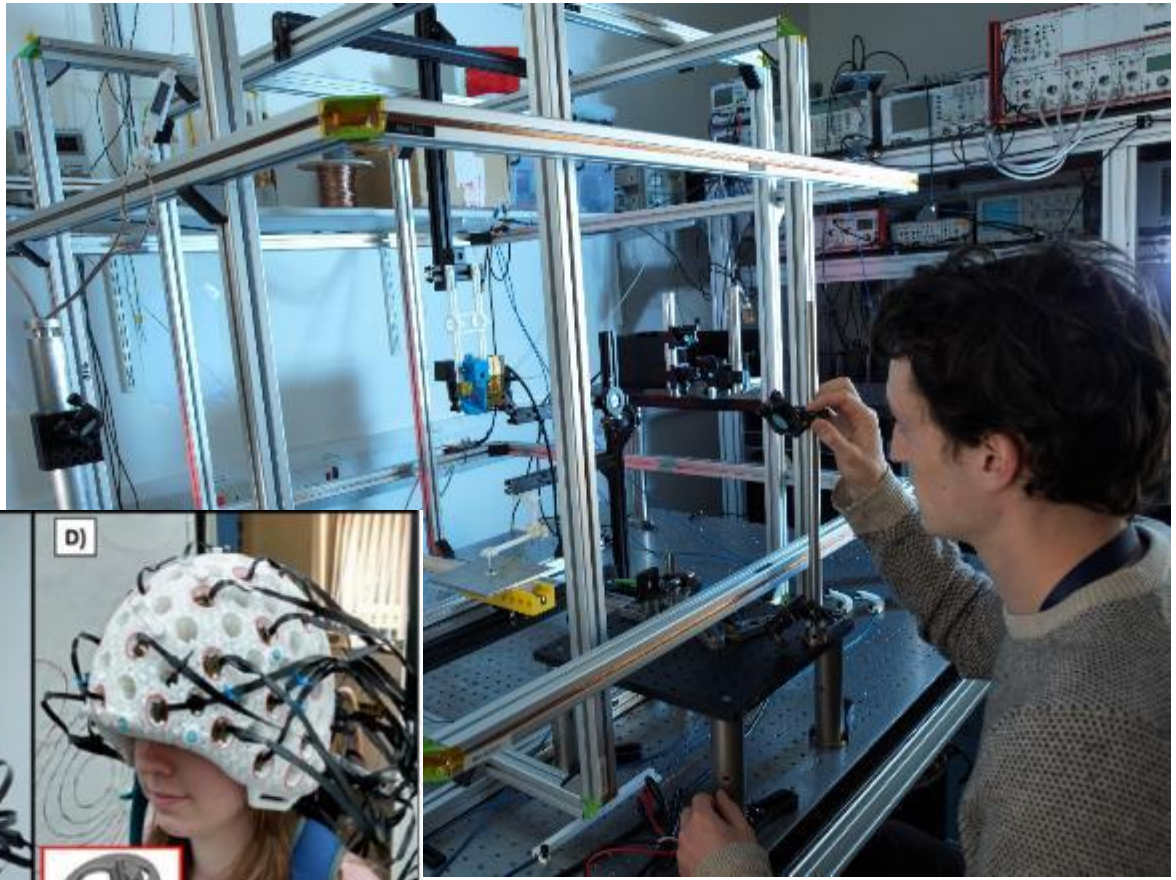


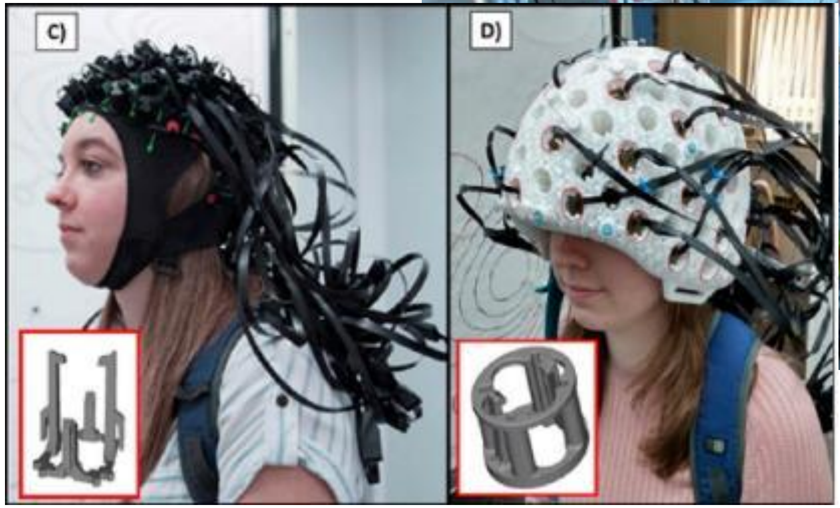


Atomic magnetometry applications

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

Optically Pumped Magnetometer
Magnetoencephalography





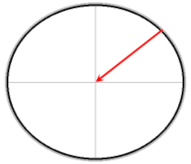
NeuroImage **2020**, 219, 116995

Courtesy: Niall Holmes, University of Nottingham; Lisa Gilligan-Lee, University of Nottingham)

Gravimetry

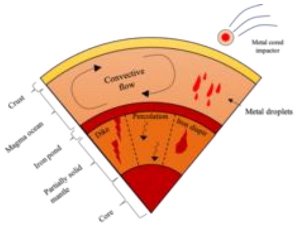
- Measuring gravity – very important!
- Key to geology, hydrology, climate science, satellite flight etc.

Sphericity

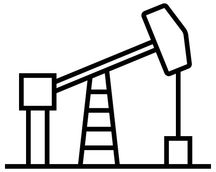


Equatorial ‘bulge’

Mountain ranges



Mantle & core mass distribution



Large reservoirs

Tides

Large buildings

$$1\ \text{‘g’} = 9.8072467\ldots\ \text{ms}^{-2}$$

Birmingham Mobile Atom Gravimeter

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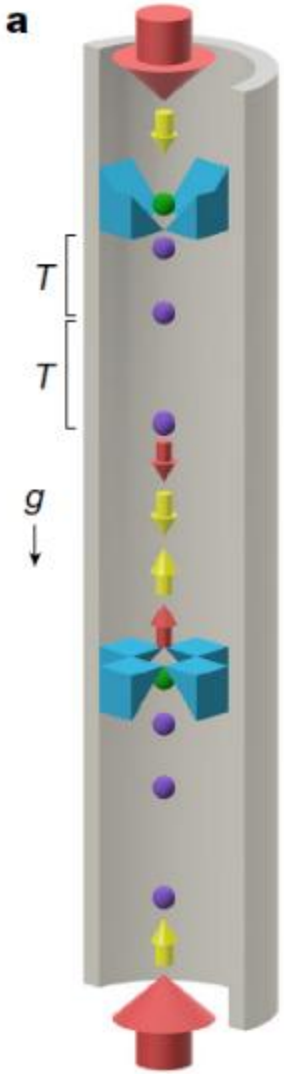
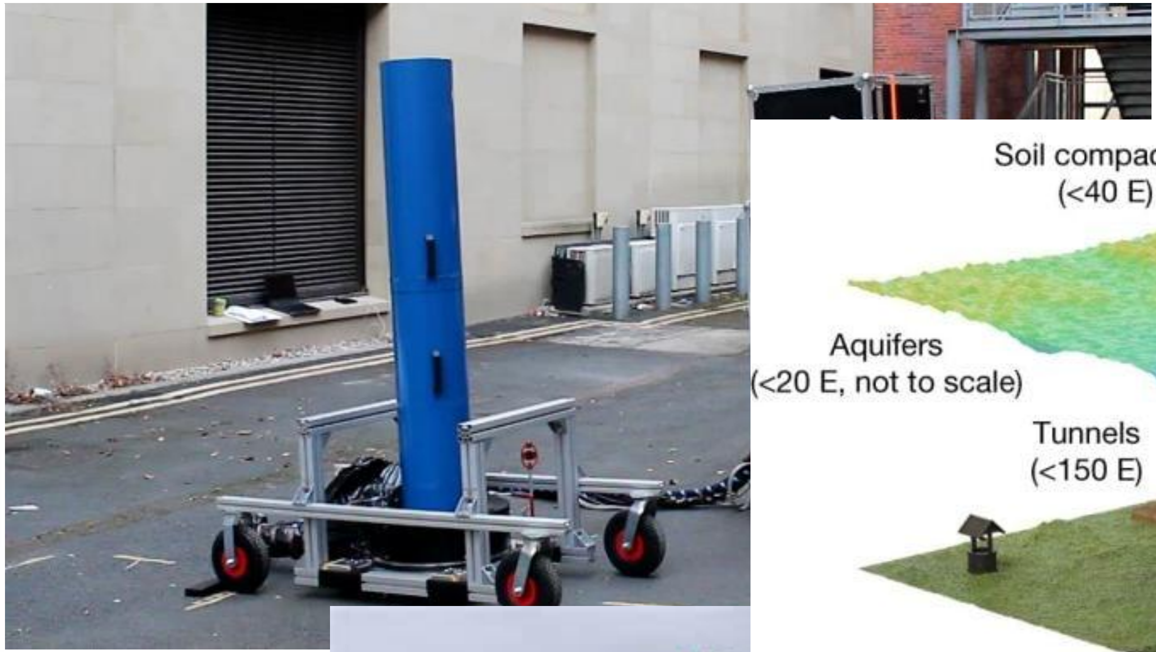
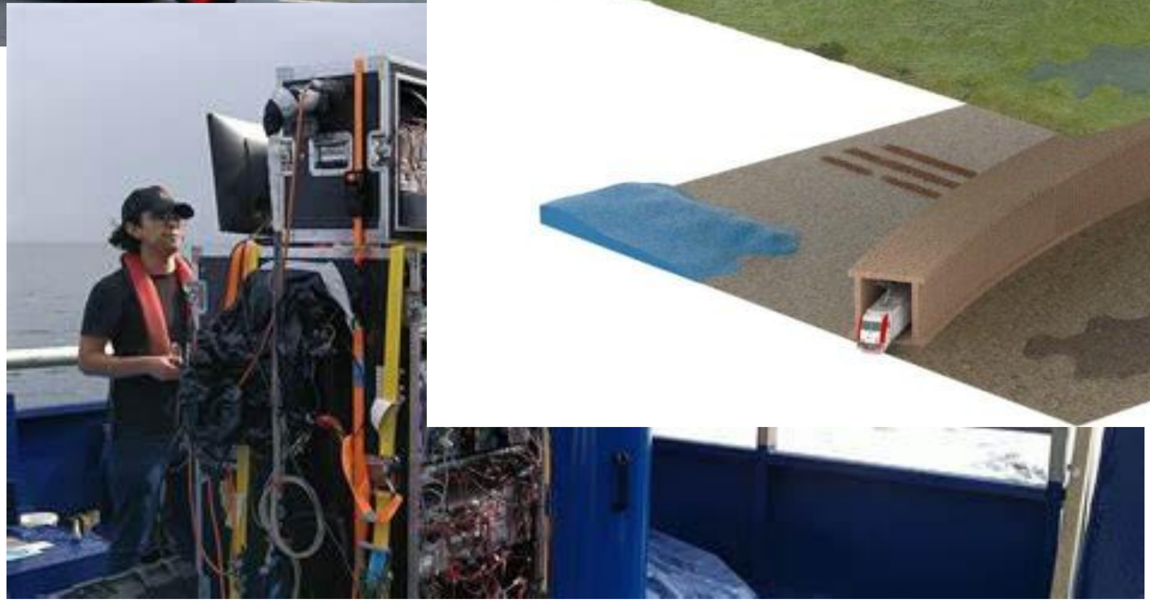
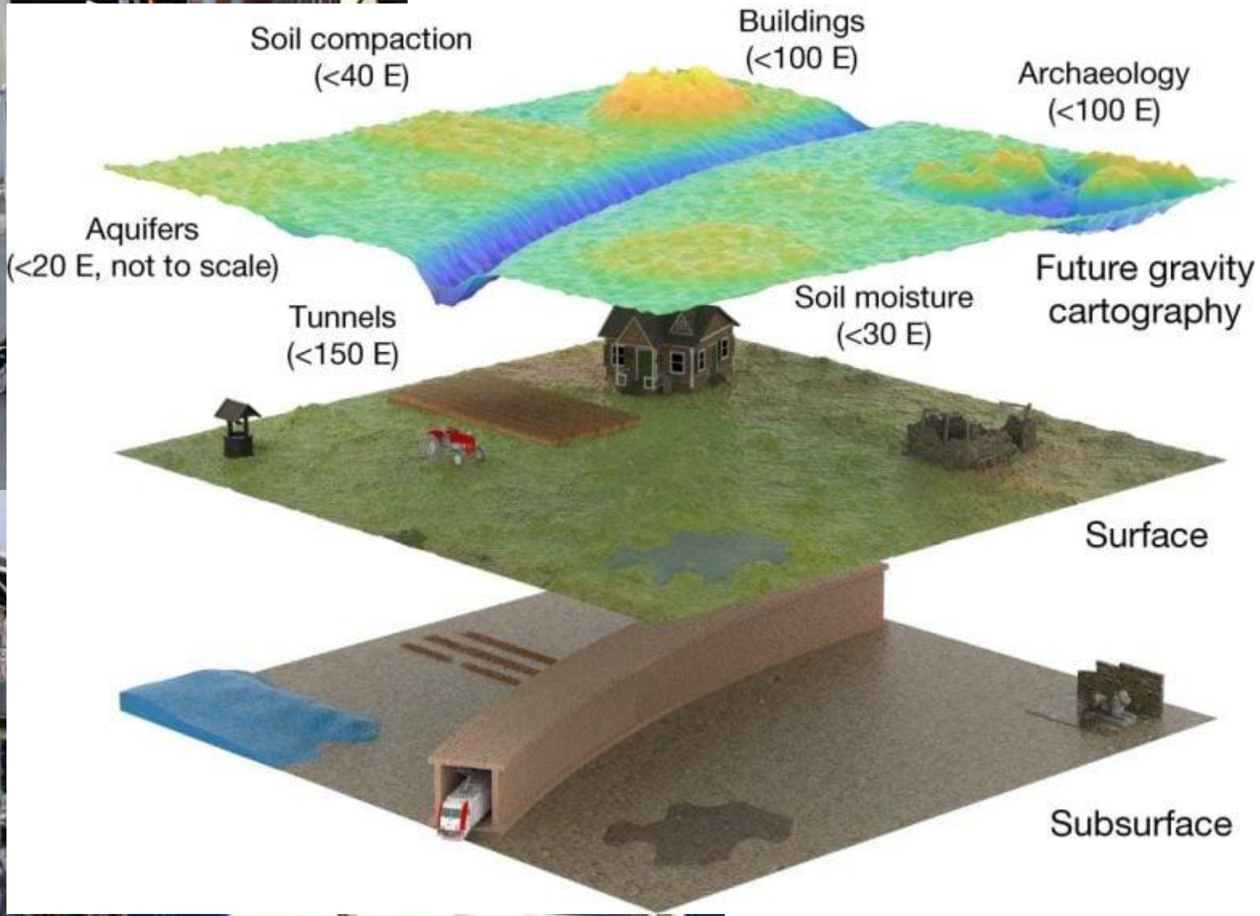








Atomic ~~clocks~~ gravimeters?

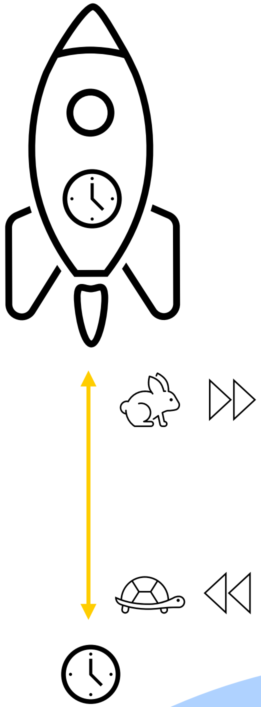
- General Relativity → gravitational time dilation

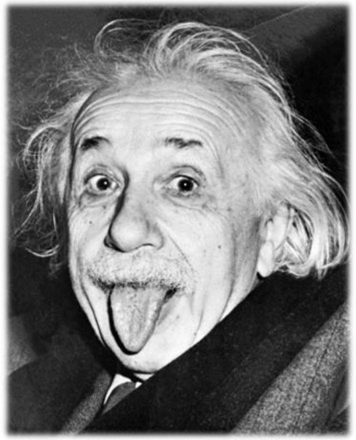
  Time flows slower in higher gravitational potentials

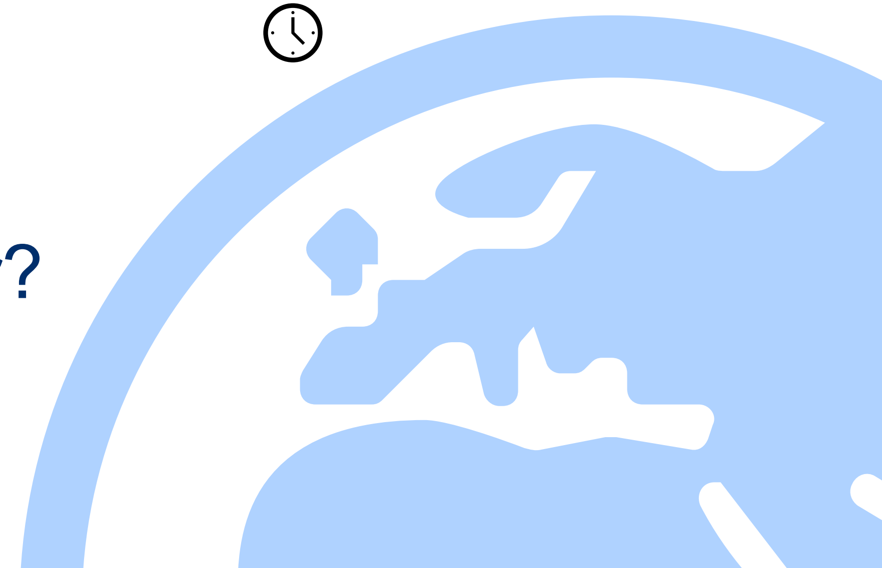
- Earth's core 2.5 yrs *younger* than crust!
- Atomic clocks incredibly sensitive

  Time 'speedup' detected across 1 mm cloud of atoms!

- Use clocks as sensors for missing 'dark' matter?

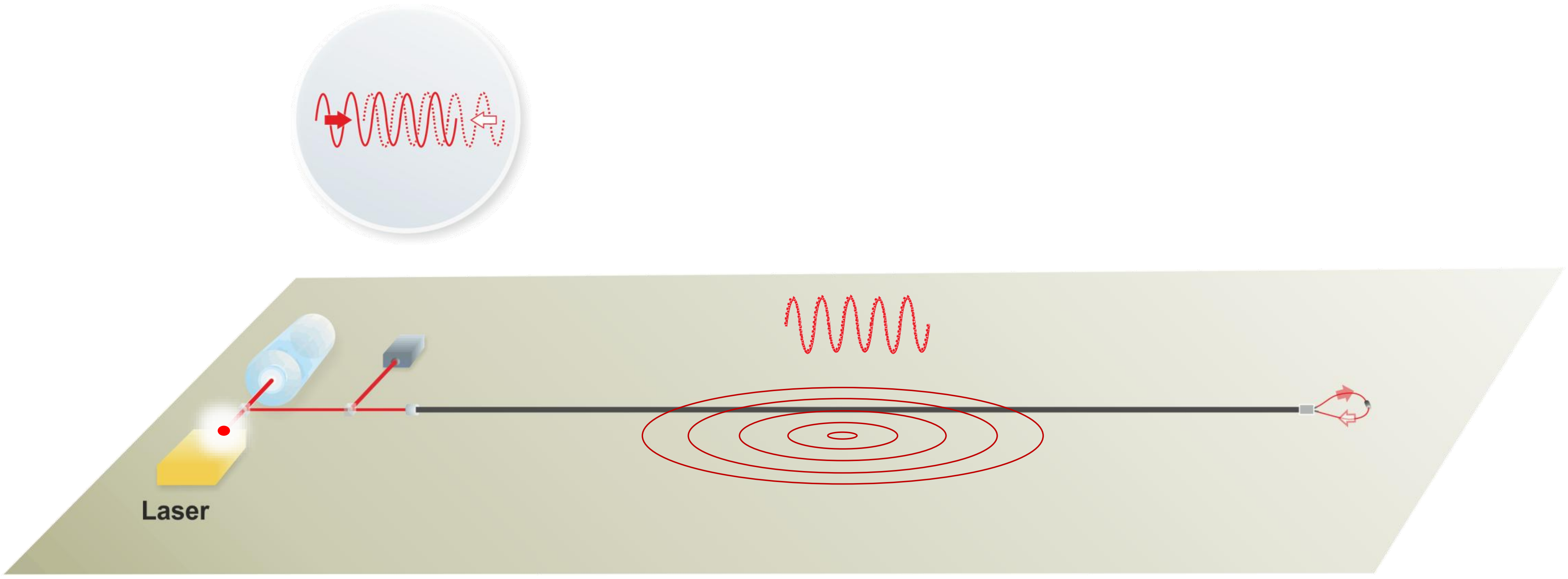




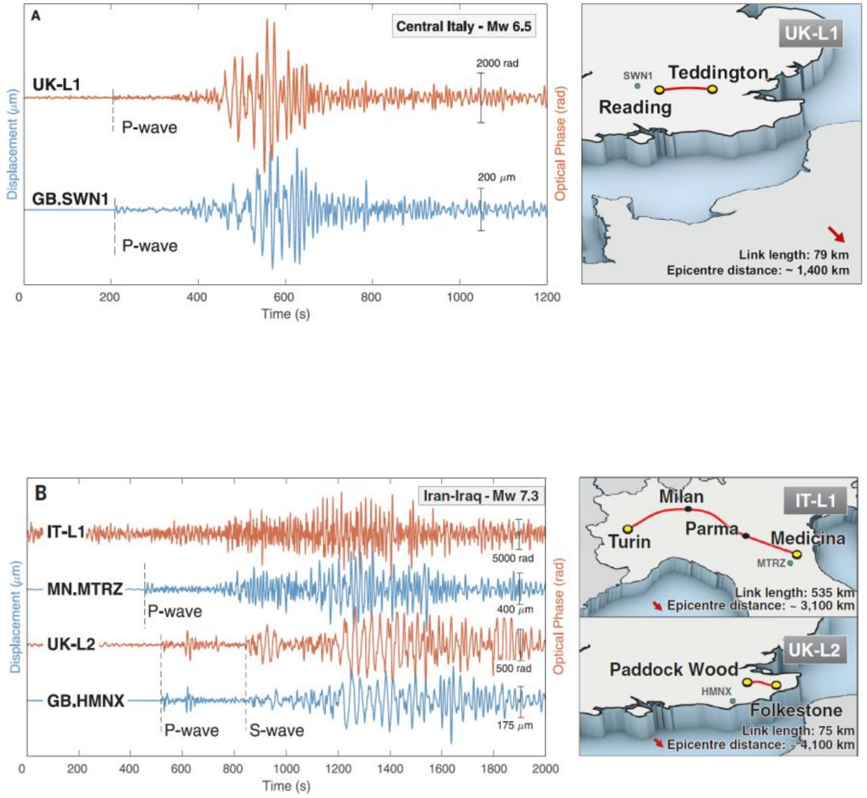


Optical clock comparison in Europe

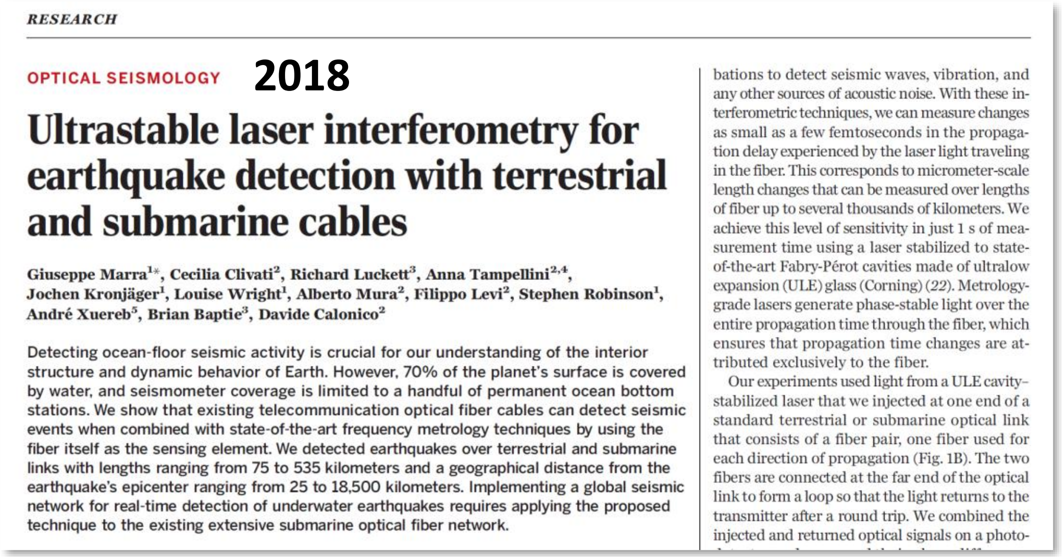
Detection principle



Detection of earthquakes with ultra-stable optical links



"Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables", Marra G, Clivati C, Luckett R, Tampellini A, Kronjäger J, Wright L, Mura A, Levi F, Robinson S, Xuereb A, Baptie B and Calonico D., Science, 361 (2018)



RESEARCH

OPTICAL SEISMOLOGY **2018**

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1*], Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

Detecting ocean-floor seismic activity is crucial for our understanding of the interior structure and dynamic behavior of Earth. However, 70% of the planet's surface is covered by water, and seismometer coverage is limited to a handful of permanent ocean bottom stations. We show that existing telecommunication optical fiber cables can detect seismic events when combined with state-of-the-art frequency metrology techniques by using the fiber itself as the sensing element. We detected earthquakes over terrestrial and submarine links with lengths ranging from 75 to 535 kilometers and a geographical distance from the earthquake's epicenter ranging from 25 to 18,500 kilometers. Implementing a global seismic network for real-time detection of underwater earthquakes requires applying the proposed technique to the existing extensive submarine optical fiber network.

bations to detect seismic waves, vibration, and any other sources of acoustic noise. With these interferometric techniques, we can measure changes as small as a few femtoseconds in the propagation delay experienced by the laser light traveling in the fiber. This corresponds to micrometer-scale length changes that can be measured over lengths of fiber up to several thousands of kilometers. We achieve this level of sensitivity in just 1 s of measurement time using a laser stabilized to state-of-the-art Fabry-Pérot cavities made of ultralow expansion (ULE) glass (Corning) (22). Metrology-grade lasers generate phase-stable light over the entire propagation time through the fiber, which ensures that propagation time changes are attributed exclusively to the fiber.

Our experiments used light from a ULE cavity-stabilized laser that we injected at one end of a standard terrestrial or submarine optical link that consists of a fiber pair, one fiber used for each direction of propagation (Fig. 1B). The two fibers are connected at the far end of the optical link to form a loop so that the light returns to the transmitter after a round trip. We combined the injected and returned optical signals on a photo-

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British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

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Almost all seismic stations are on land!

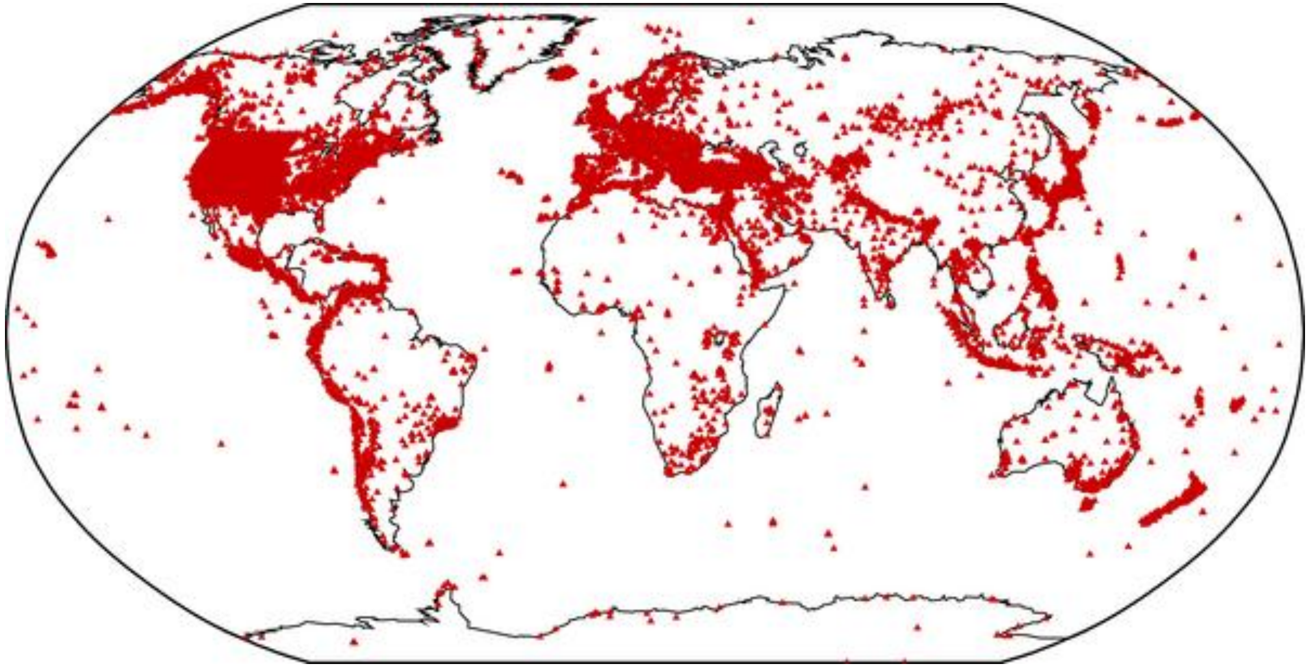
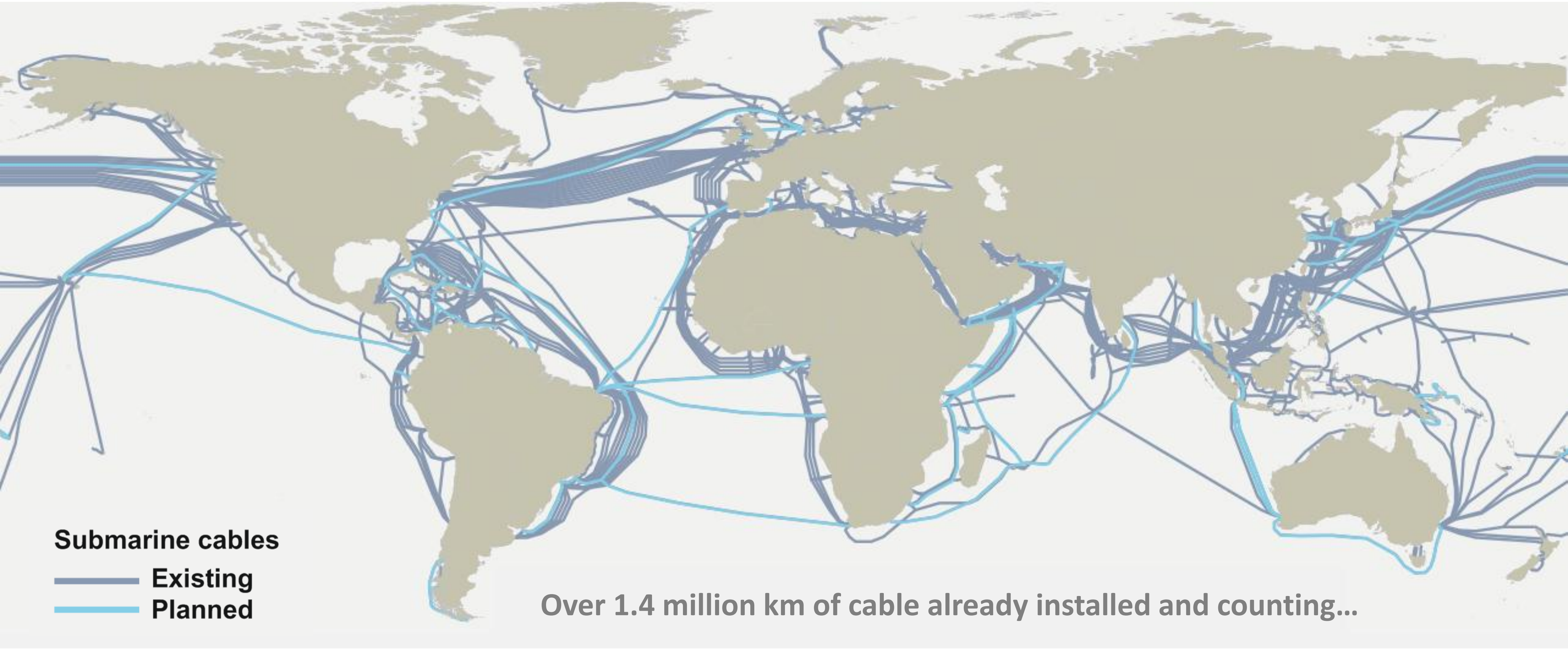


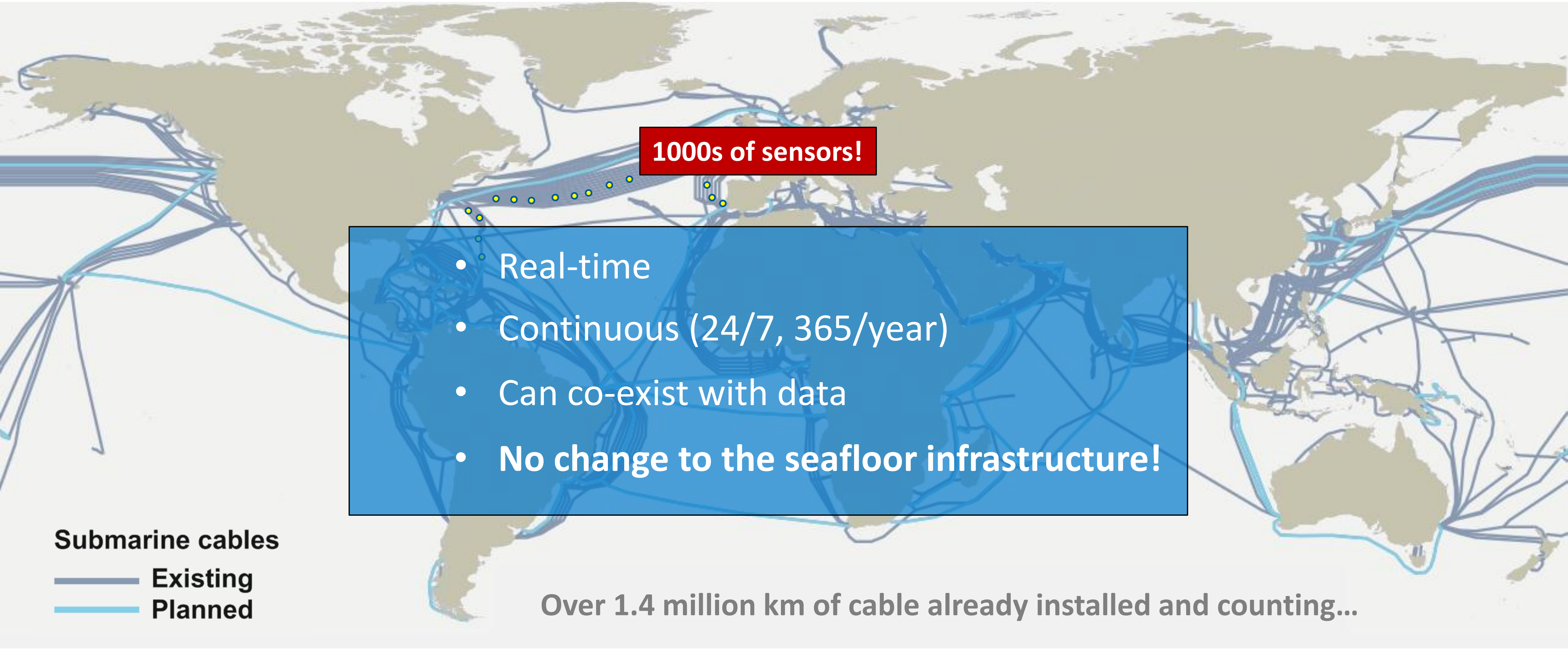
Image from the International Registry of Seismograph Stations (IR) website

A global network of environmental sensors



Over 1.4 million km of cable already installed and counting…

A global network of environmental sensors



- Real-time
- Continuous (24/7, 365/year)
- Can co-exist with data
- **No change to the seafloor infrastructure!**

Over 1.4 million km of cable already installed and counting…

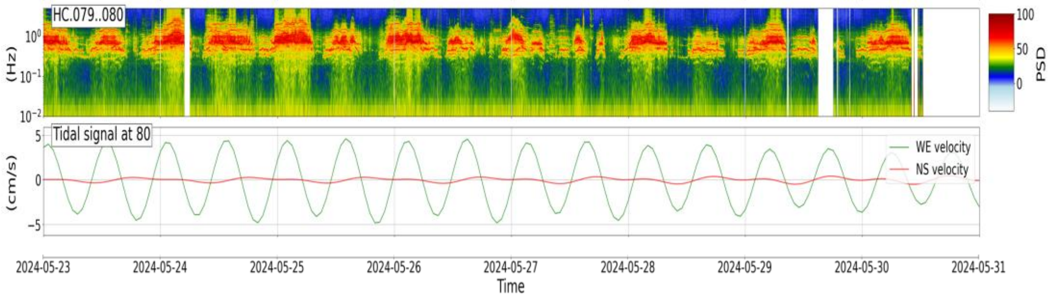
Using seafloor cables for climate change research

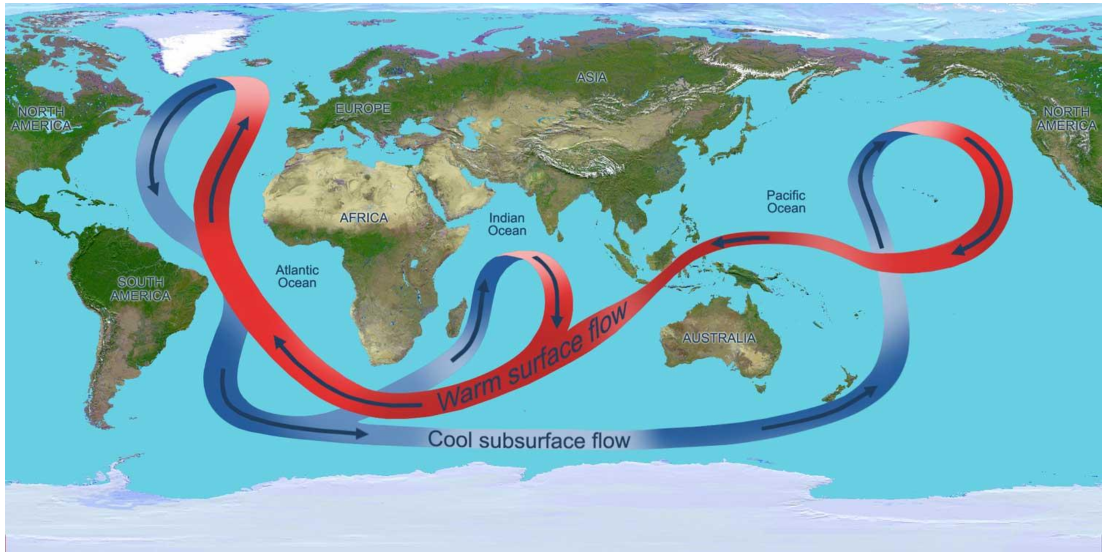
Detecting ocean currents

Advanced Research + Invention Agency ARIA

NPL

National Oceanography Centre





Interferometric-based seismic detection tests on Southern Cross Next cable

Seismic analysis:

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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Thank You!

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