£1bn commitment 2014-2024

How did we start?

2013 workshop at Chicheley Hall

The National Quantum Technologies Programme established in 2014 with 4 quantum hubs involving 30 university groups; refreshed in 2019. Partnership across government, research and industry
Phase 1 focused on converting research excellence into technology prototypes and plugging the skills deficit

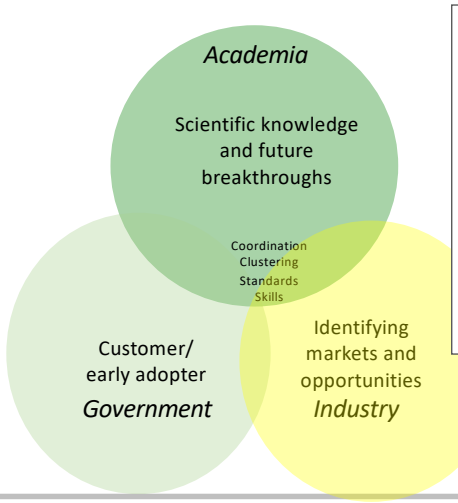
Phase 2 drives commercialisation and economic impact, using network of academic research, government engagement, industry and venture investment, supply chain growth and international collaboration

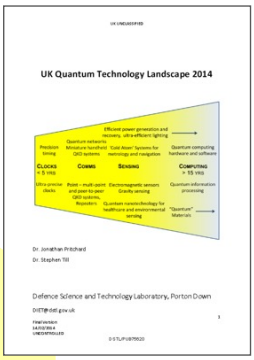
2019-NQCC established

**Peter Knight**

*Blackett Laboratory, Imperial College, London SW7 2AZ, UK*

*Chair of the UK National Quantum Technology Strategic Advisory Board for UKRI*




Department for Business, Energy & Industrial Strategy | UKRI Science and Technology Facilities Council | EPSRC Pioneering research and skills | Knowledge Transfer Network | dstl | NPL National Physical Laboratory | National Cyber Security Centre a part of GCHQ | Innovate UK

1

# The Quantum Age

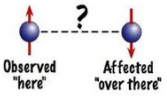
- First quantum age gave us lasers, semiconductors…
- Now exploit quantum coherence?
- Impacts multiple sectors: beware of naive ”sector think”
- Enhanced capabilities in timing, sensing, imaging, computing, communications, and more
- Needs to fit with existing infrastructure
- Technology can be faster, cheaper, and higher-performing

**Superposition**

| Classical Bit | Quantum Bit (qubit) |
|---|---|
| 0 or 1 | 0 and 1 |

quantum matter can be in two different states at the same time: measurement causes a collapse to one state.

**Entanglement**




“connection” between separated particles where a measurement of one immediately affects the wavefunction of the other

2

Government Office for Science

## UK Quantum Programme

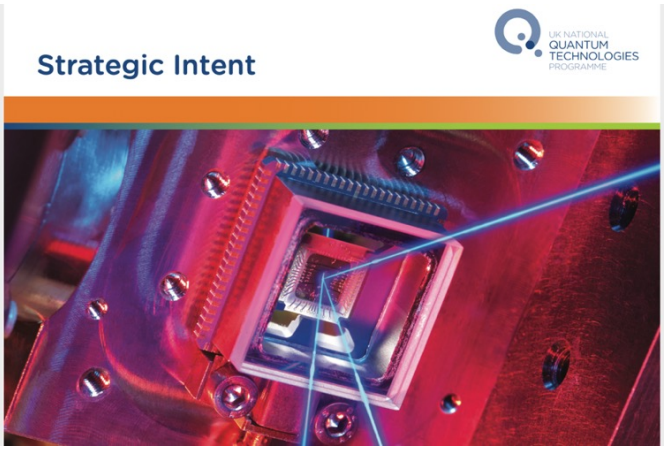
- **Compact atomic clocks**: for time stamping, flywheels for gps resilience;
- **Quantum metrology and sensors**: where quantum effects such as entanglement or superposition are exploited for highly sensitive measurements;
- **Quantum secure communications:** offer new communication channels, e.g. quantum key distribution (QKD), as well as transmission systems and components that are specific to quantum communications;
- **Quantum simulators**: which enable the accurate modelling of real molecules and materials;
- **Quantum computation**: information processing by using quantum superposition & entanglement



3

## UK Quantum Strategic Intent

https://uknqt.ukri.org/files/strategicintent2020/




### A new strategic vision for the next 10 years

**An evolved vision to create a 'quantum enabled economy', in which quantum technologies:**

- are an integral part of the UK's digital backbone and advanced manufacturing base;
- unlock innovation across sectors to drive growth and help build a thriving and resilient economy and society and;
- contribute significant value to the UK's prosperity and security.

**To achieve this, we aim to make the UK:**

- a global centre of excellence in quantum science and technology development;
- the 'go-to' place for quantum companies or for global companies to locate their quantum activities, and;
- a preferred location for investors and global talent.

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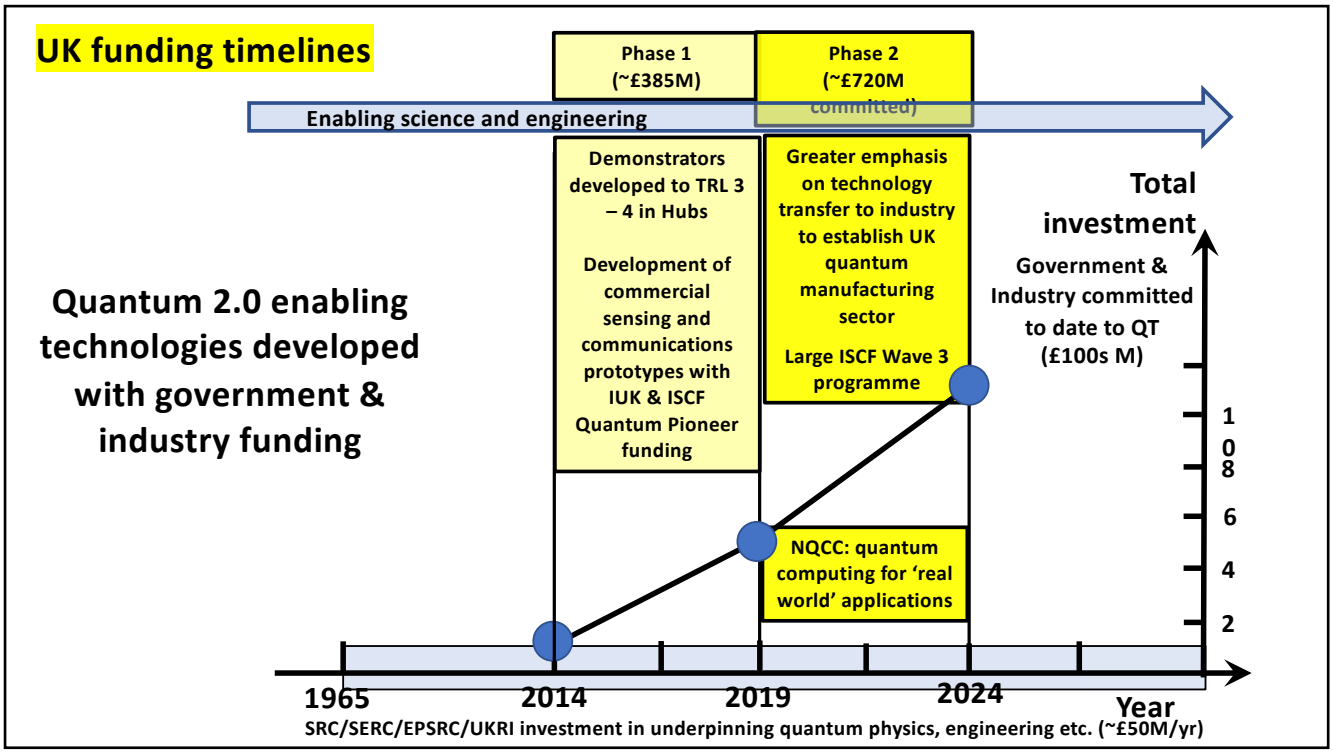
## UK funding timelines




5

## UK government commitment £270M in 2013 has grown…….

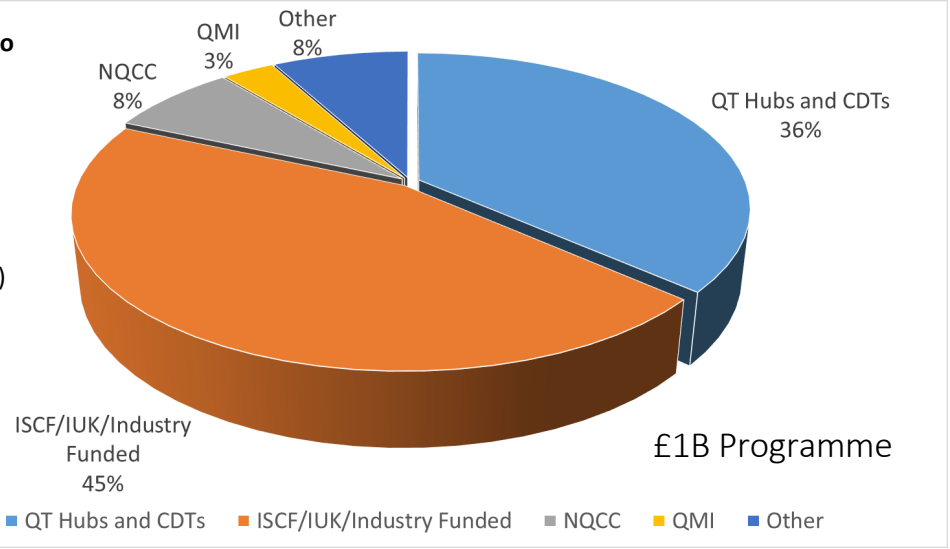
INDUSTRIAL STRATEGY

UK Research and Innovation

**Phase 1 started 2014 with £270M in 2013 budget, grew to £400M+ by end in 2019; research hubs, skills and industry support**

**Phase 2 built on this: started 2019-**

Hubs renewed (£80M + £15M)
ISCF Waves 2 and 3 (£20M + £153M + £205M Industry)
Skills Package (£67M)
NQCC (£75M+)
International (Singapore with STFC, Canada, Australia)

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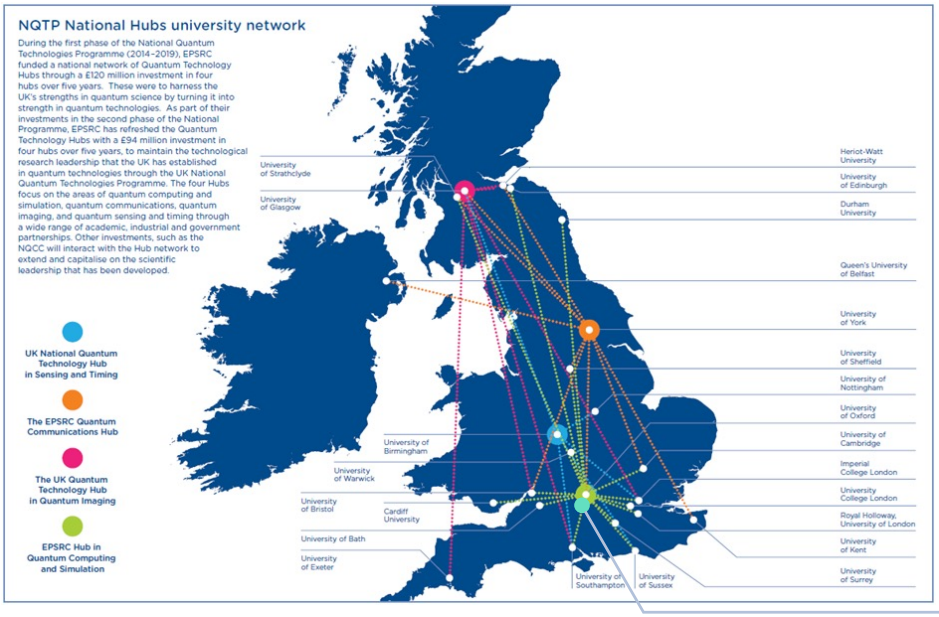
*Beyond the 'Eight great' technologies …*
#9: National Quantum Technologies Programme




NQTP Strategic Intent: Nov 2020
Anchored In UK QT start-up Scene 2020

| | |
|---|---|
| **125** MSc candidates | **175** PhD candidates |
| **300** Hub partners | **85** QT Apprenticeships |
| **41** UK start-ups **370** employed | **> £135m** UK V/C funds raised |
| **40** UK Quantum Suppliers | **£1bn** UK public/private investment |


7

## The International Landscape

| | Quantum spend (2021) | Quantum publications | Quantum patent applications | 2021 ranking |
|---|---|---|---|---|
| China | 1 | 4 | 1 | 1 |
| USA | 2 | 1 | 3 | 1 |
| Germany | 3 | 2 | 4 | 3 |
| **UK** | **5** | **2** | **9** | **4** |
| Japan | 8 | 6 | 2 | 4 |
| France | 4 | 6 | 10 | 6 |
| Canada | 10 | 5 | 8 | 7 |
| Australia | 9 | 11 | 7 | 8 |
| Italy | 12 | 8 | 12 | 9 |
| Korea | 15 | 13 | 5 | 10 |

| | Corporate Engagement | Number of Start-ups | Start-up Capital Raised | Supply Chain Maturity* | 2021 ranking |
|---|---|---|---|---|---|
| USA | 1 | 1 | 1 | 1 | 1 |
| **UK** | **3** | **2** | **3** | **3** | **2** |
| Canada | - | 3 | 2 | 4 | 3 |
| Japan | 4 | 6 | 7 | 6 | 4 |
| France | 5 | 5 | 8 | 5 | 4 |
| China | 2 | 8 | 9 | 7 | 6 |
| Germany | 5 | 4 | 16 | 2 | 7 |
| Australia | - | 8 | 4 | 9 | 8 |
| Italy | - | 14 | 20 | 9 | 10 |
| Korea | - | 23 | 20 | - | 10 |

** excluding nanofabrication infrastructure*

### 2020-21 Government Announced Investment

- **$10.4bn** of new quantum tech funding has been announced since Jan 2020
  - 55% in Europe & ME, 31% in North America, 14% in Asia

### 2020-21 Government Awarded Investment

- **$1.4bn** of new quantum tech awards announced since Jan 2020, 45% in the US

### Industrials

- **$4.9bn** of investment raised by the start-up & SME community made public since Jan 2020 including SPAC raises of $2bn by IonQ, $1.6bn by Rigetti and $115m by Arqit plus Honeywell/CQC merger - $300m
- Estimated **$1.6bn** spent by the IT Majors in quantum computing development to date
- 15+ investment deals with undisclosed valuations including growing Corporate Venturing



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# UK NQTP SWOT

| Opportunities and Strengths | Threats |
| --- | --- |
| • Coherence of NQTP<br>• Integration of research and commercialisation<br>• Importance of the Challenge Fund<br>• Active VC community<br>• Buy-in from senior government figures | • Lack of continuity: stop/start support<br>• Lack of progress so far in long term plan post-Phase 2<br>• Hype<br>• Skills shortage<br>• Very rapid expansion in competition internationally |

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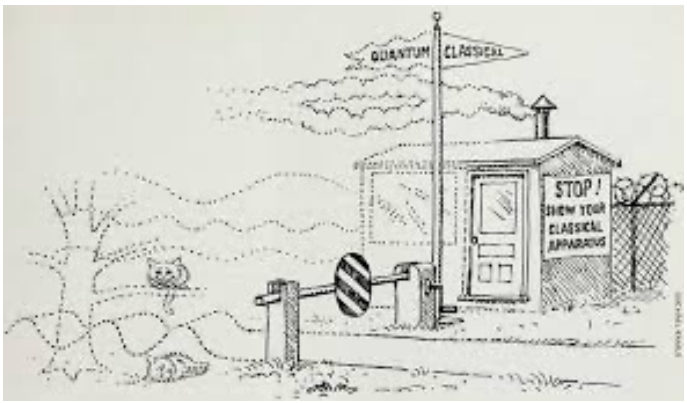
## The Exquisite Sensitivity of Quantum Coherence

$$\exp(-nGt)$$

- Quantum coherence is fragile and becomes exponentially more fragile as the system size (n) grows.
- Our enemy in building a quantum computer with error correction
- Our ally in building quantum sensors and the awareness of the environment
- This is why we don't see Schroedinger cats in the everyday world and why its hard to build a quantum machine at scale

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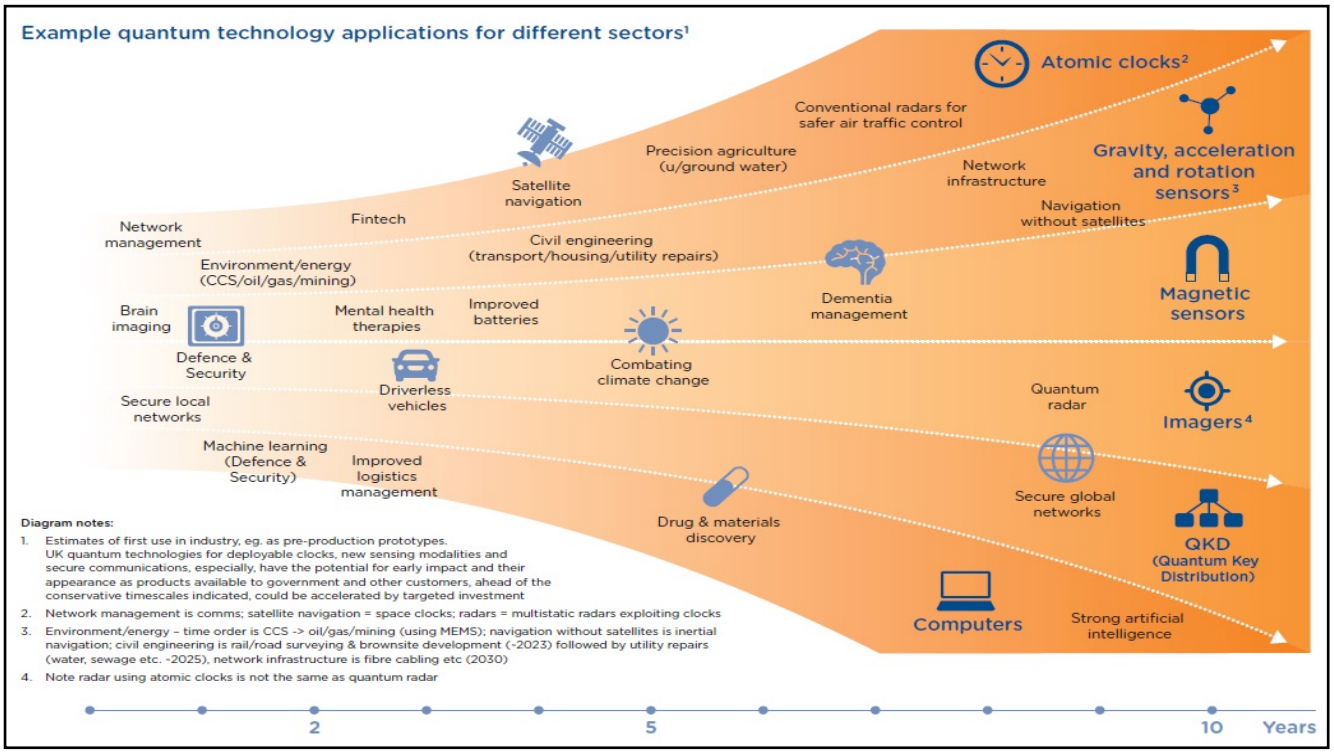


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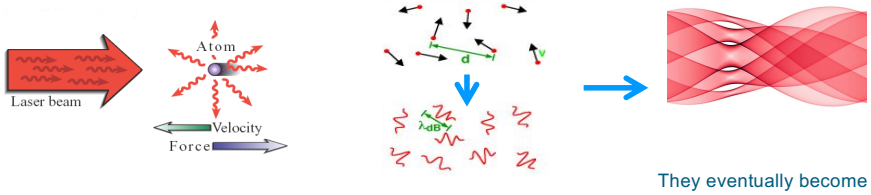
## Cold atoms – enabling science

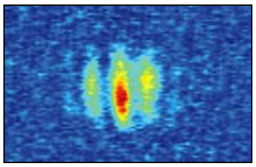



Laser cooling can be used to cool atoms to < 0.000,001 degrees above absolute zero

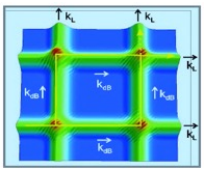
As they continue to cool their wave - like properties dominate

They eventually become indistinguishable and condense into a "Bose condensate"

This is now a "matter wave", akin to a coherent laser beam



Matter waves interfere, just like two light beams



Suitably configured, they can measure rotation, gravity and acceleration

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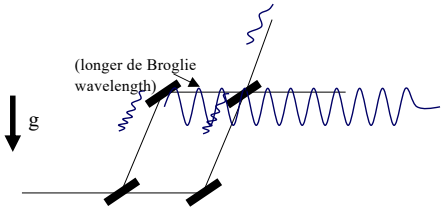
From Mark Kasevich

# de Broglie wave sensors

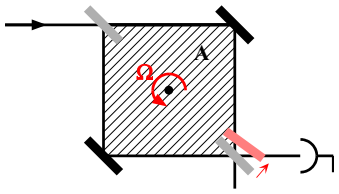
**Gravity/Accelerations**

As atom climbs gravitational potential, velocity decreases and wavelength increases




**Rotations**

Sagnac effect for de Broglie waves

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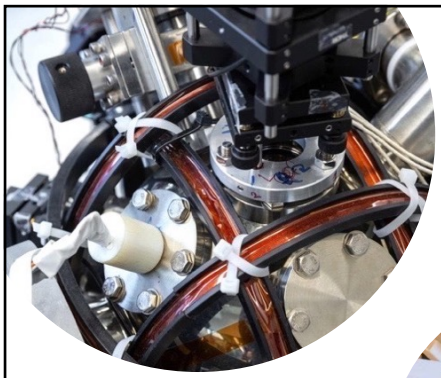
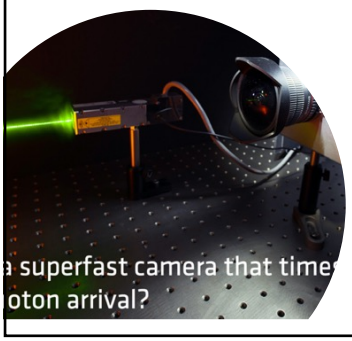


# Quantum sensors, timing and imaging




- New time standards and chip scale atomic clocks to address GPS resilience
- The quantum navigator
- Quantum chips for accelerometry, gyroscopes, gravimetry, magnetometry
- Imaging through walls and around corners
- Gravity sensors for oil, gas, minerals and defence
- Electromagnetic field sensors
- Implanted sensors improving health
- Improved magnetic sensing – heart, brain imaging
- Novel cameras with single photon detection for ranging and imaging: “making the invisible visible”
- Seeing without being seen

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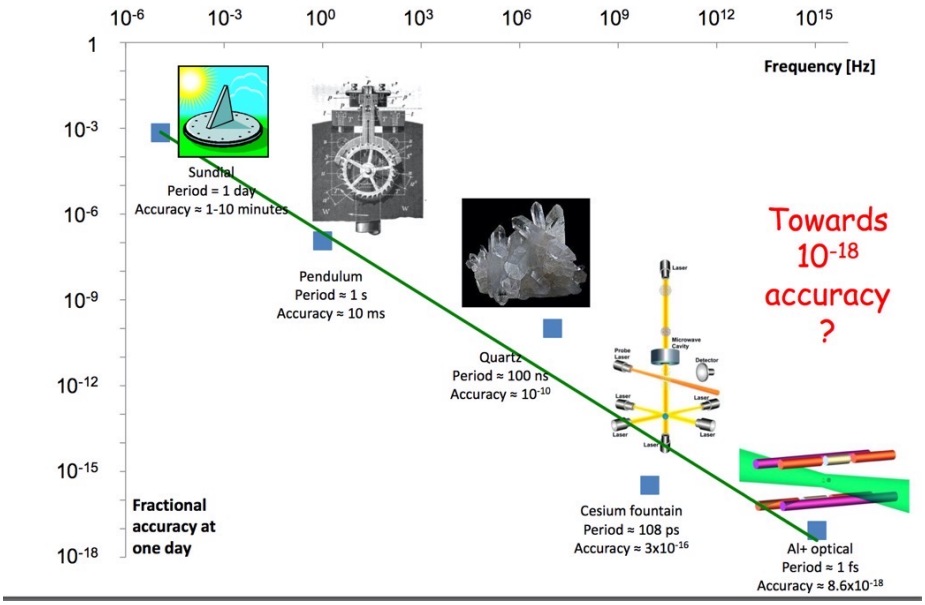
Clocks

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# Atomic clocks

| | | | |
|---|---|---|---|
| Location finding | Precision navigation and navigation in outer space | Variability of Earth's rotation rate and other periodic phenomena | Earth's crustal dynamics |
| Secure telecommunications | Very Long Baseline Interferometry | Spectroscopy | Expression of other physical quantities in terms of time |
| | Tests of constancy of fundamental constants | Tests of the special and general theories of relativity | |

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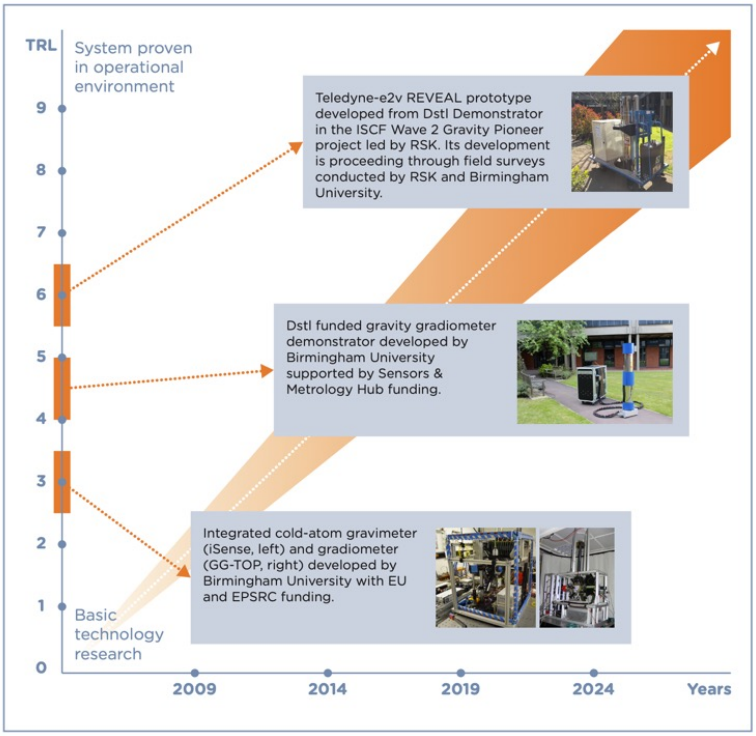
## Gravimeters




Development of 'gravity sensors' could facilitate the detection of previously unknown fossil fuel deposits, or enable more accurate mapping of buried civil infrastructure such as pipes and cables.

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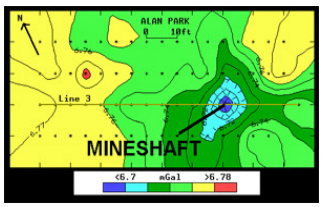
## Development project:
Gravity imager

- Matter wave gravity gradiometer array
- "Pictures" local mass distribution
- Markets include military, oil and gas, civil engineering
- Identification of tunnels, IEDs…

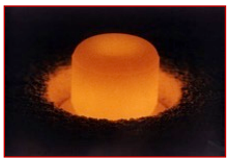



Existing example using crude, ground based measurements

VOID
Density ~ 0

WATER
Density =1

ROCK
Density ~ 2.5 - 3



PLUTONIUM
Density = 19.8

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# Gravity sensing – The opportunities

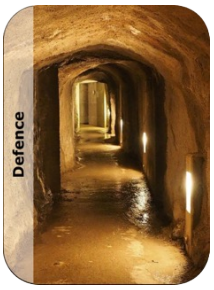
**Improving Infrastructure Productivity** | **Seeing the Invisible** | **Situational Awareness**


- 1.37m streetworks p.a.
- 2.4m road openings
- Projected costs p.a.: £3.19bn


- Surveys reduce risks
- ROI on utility surveying $3.41-£20
- 5% of project budget for surveying ➔ reduce overspend to 25%


- 16% of utilities damaged by contractor in UK
- Sinkhole occurrence increased fivefold in 2014


- 30% of exploratory bore holes drilled are successful
- Exploration market ~£7bn




- Increasing black market for tunneling machinery in hostile & security critical environments

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UK Quantum Technology Hub Sensors and Timing

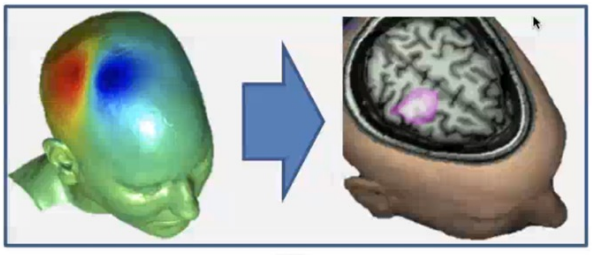
# Magnetoencephalography (MEG)

University of Nottingham UK | CHINA | MALAYSIA

**Optically pumped magnetometers (OPMs) measure magnetic fields generated by brain activity – a process called MEG**

**Conventional MEG uses superconducting technology (SQUIDs). OPMs are smaller, lighter & operate at body temperature.**

- Offer higher sensitivity
- Better spatial precision
- Adapt to fit any head size – including infants
- Enable free movement during scanning



Already being used in hospitals for MEG-guided epilepsy surgery

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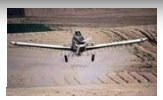
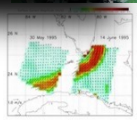
## World-wide dependency on GNSS – *PNT Taken for Granted – the "Stealth" Utility*

- Civil
  - Transportation
    - Aviation
  - Other
- Military



The ***Majority*** of these Applications were not part of the original "formal definition" of GPS

They resulted from:

- Civil Creativity
- Plummeting cost of GPS receivers
- Virtually 100% Reliability and Availability

Three Wishes - Dr, Parkinson 2017

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## Newark Airport and the GPS Jammer

- Truck driver with $100 GPS jammer, accidentally jams Newark airport: in engineering firm worker in New Jersey has a GPS jammer to block installed tracker so his bosses don't know where he is all the time. However, his route takes him close to Newark airport, and his jammer affects its satellite systems. Planes couldn't land
- In July 2010 two men were jailed in the UK for a total of 16 years after they admitted being members of a gang that stole 40 lorries and their loads with a total value of £6m ($9.6m). They had used GPS jammers to prevent the vehicles being tracked after the thefts.


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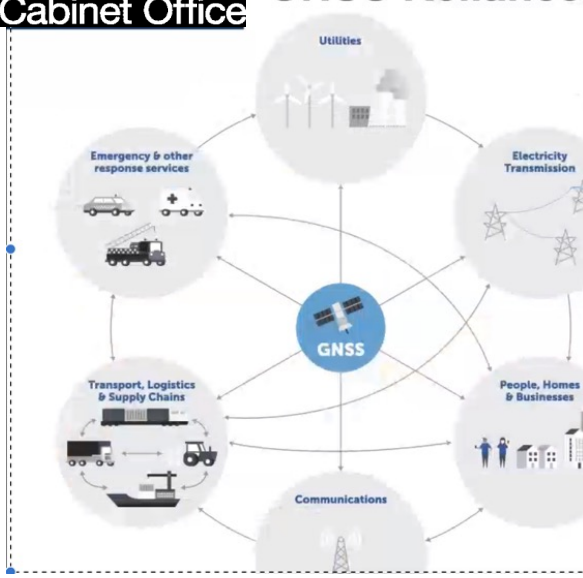
Cabinet Office

## GNSS Reliance & Vulnerability





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## Cabinet Office PNT Study – our Key Findings

- The UK is **critically dependent on PNT:** it's integral to our safety, security and prosperity and wider global interests.
- The UK has requirements for **assured PNT information around the world**. 'Assured' PNT refers to ability to access a trusted source of accurate PNT information (reliability, redundancy and resilience).
- Solutions to the UK's PNT requirements must be **diverse, adopting a 'system of systems' approach** with a holistic mix of technologies (terrestrial and space-based).
- For the 131 use cases we identified, 115 required a space-based solution as their primary source of PNT.
- Threats and Hazards with potential to disrupt the UK's access to PNT **are increasingly diverse, prolific and capable**. Half of use cases were judged not to be resilient.
- There remains **a low level of understanding** about the dependencies on, and risks to, PNT in many UK sectors. There is a risk that users are not aware of the vulnerabilities they have to disruption.
- BEIS now charged with delivering cross-government PNT delivery

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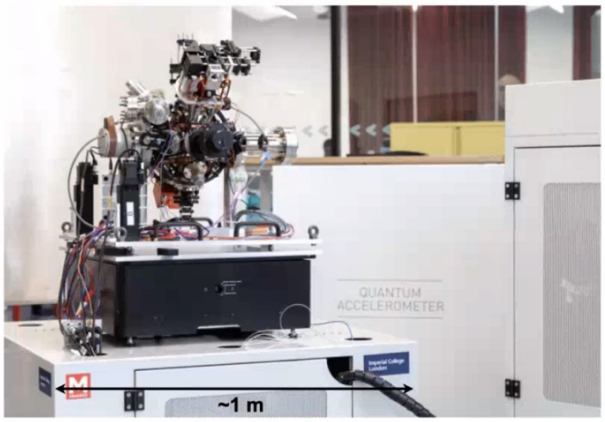
# Quantum navigator

UK Quantum Technology Hub Sensors and Timing

## Quantum Accelerometer / Gyroscope




- Imperial College London & M Squared Lasers engineering 1 axis accelerometer: aim 50 ng resolution
- Quantum gyroscope with angular random walk: aim < 1 µrad/s (17.5 ndeg/s))
- Theoretical bias drift many magnitudes lower than laser ring gyros & present IMUs
- Potential issue is low measurement bandwidth –> hybrid solutions being pursued
- Present system: 2 x 1 m³ boxes to test physics & performance

Imperial, M Squared, DSTL

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## Case study:
## SPLICE: gas plume visualisation technology

- Uses time correlated single photon counting and exploits previous NQTP funded R&D in QuantIC and Bristol University
- £2.46m grant funding from IUK to commercialise world-leading technology for gas imaging
- 11 organisations, led by QLM, evaluated by NPL, and including end users National Grid Plc, Ametek Land and BP
- Addresses a multi-£100m business opportunity to help the global oil & gas industry combat climate change

### Single photon lidar imaging of carbon emissions

- Accurate, repeatable, eyesafe measurements at standoff distances of 150m
- Uses mature telecoms technology for affordable and versatile emissions monitoring systems
- Portable and simple to use and export data
  - Heat maps overlaid on visual scene and, with known wind velocities, gives dynamic leak rate data in near-real time
  - Pre-programmable, autonomous measurements for a range of emissions


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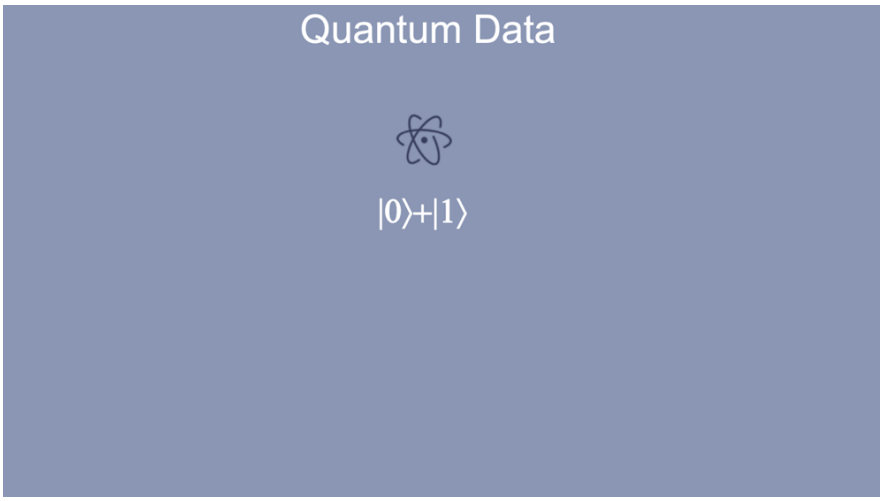
# QUBIT scale (adapted from John Martinis)

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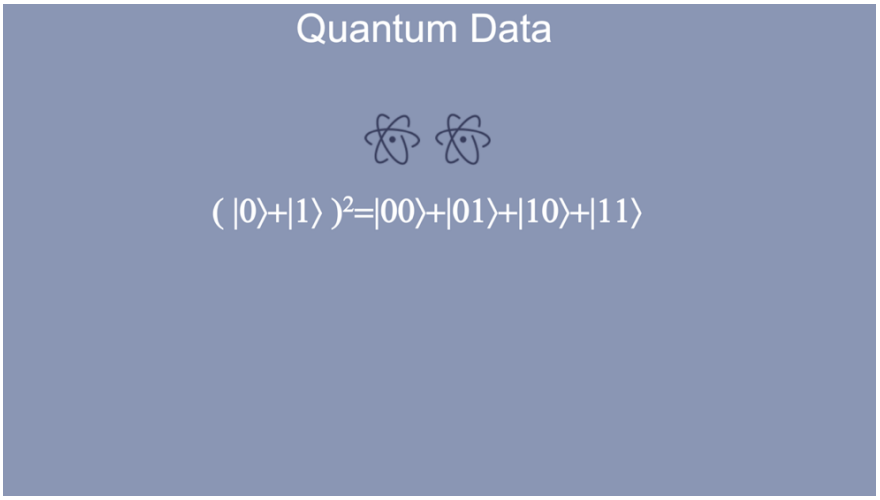


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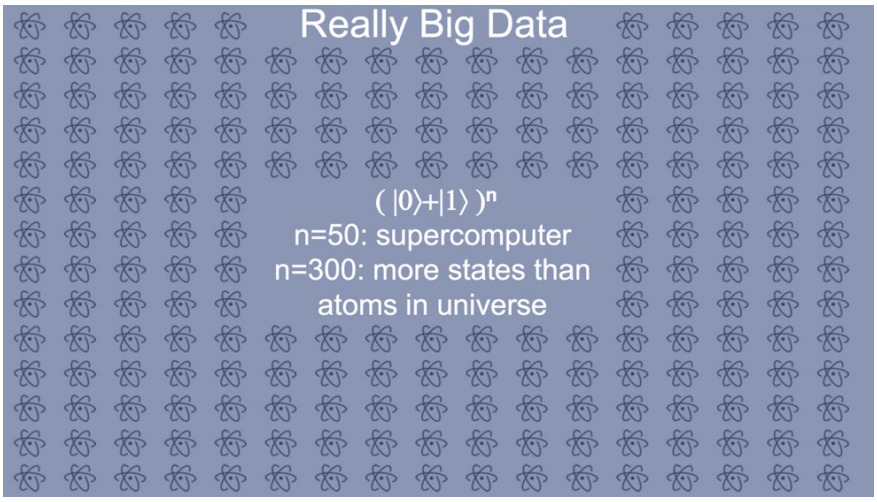
# QUBIT scale (adapted from John Martinis)




Google's 53 qubit processor gives $2^{53} = 10^{16}$

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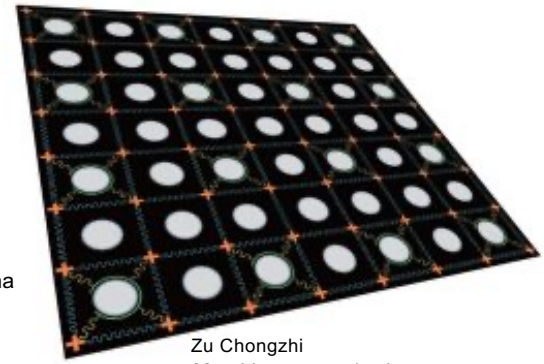
## Next generation quantum computing – NISQ era (5 – 10 years)

**Circuit based quantum computing**

- Many different types:
  - Trapped ions – longest useful qubit lifetimes
  - Superconducting – largest current qubit count
  - Semiconductors
- Current - Noisy Intermediate Scale Quantum (NISQ)
  - 100's of physical qubits with no error correction
- Experimental devices fabricated US UK EU and China
  - US and China lead on superconducting types
  - US, UK and China fabricating trapped ion types
- Quantum computers will be used with High Performance Computers



Zu Chongzhi
62 qubit superconducting quantum processor
Produced by University of Science and Technology China (USTC)

- NISQ facilitates evaluation of quantum chemistry and machine learning (ML) techniques
- Current NISQ prototypes demonstrated 'advantage' over classical computers for specific but not useful problems

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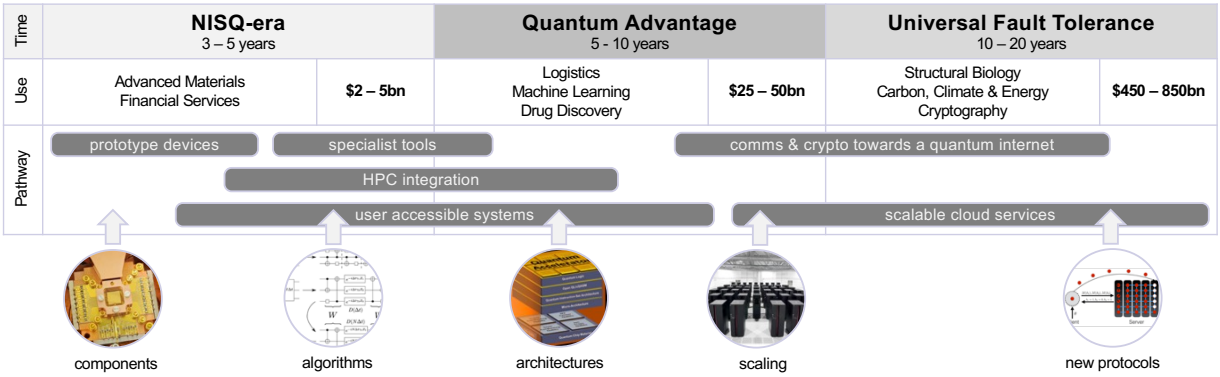
30

## Quantum Computing: The challenge & the opportunity




National Quantum Computing Centre

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## Impact


- Impact on wider UK scene
  - QT for Fundamental Physics
  - QT for Medicine and Healthcare
  - QT and the Environment
  - The international picture of rapidly increasing interest investment emulating the UK
- Impact
  - Balance national prosperity and sovereign capabilities
  - Quantum advantage and threat mitigation
  - Resilience: PNT and CNI; crypt, defence and NS applications


**Chip-scale atomic clock**

National Quantum Computing Centre

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