Optics challenges in atom-based QT Sensors

Prof. Kai Bongs, University of Birmingham

Zeiss Symposium “Optics in the Quantum World”

18 April 2018

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

UK National Quantum Technologies Programme

- A **five-year £270M (now £380M) programme** announced by the UK government in 2013.
- Programme started October 2014.
- To exploit the potential of quantum science and develop a **portfolio of emerging technologies** with the potential to benefit the UK.
- Industry, government and academia working together to create opportunities for **UK wealth creation.**

Department for Business Innovation & Skills
EPSRC Pioneering research and skills
Innovate UK Technology Strategy Board
Knowledge Transfer Network
[dstl]
NPL National Physical Laboratory
CESG

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Slide: Courtesy of D. Delpy

The UK Quantum Technology Hubs

- £120M Investment by EPSRC
- 132 partner companies

UK National Quantum Technology Hub in Sensors and Metrology

PI: Kai Bongs
University of Birmingham

QUANTIC

PI: Miles Padgett
University of Glasgow

QUANTUM COMMUNICATIONS HUB

PI: Tim Spiller
University of York

NQIT Networked Quantum Information Technologies

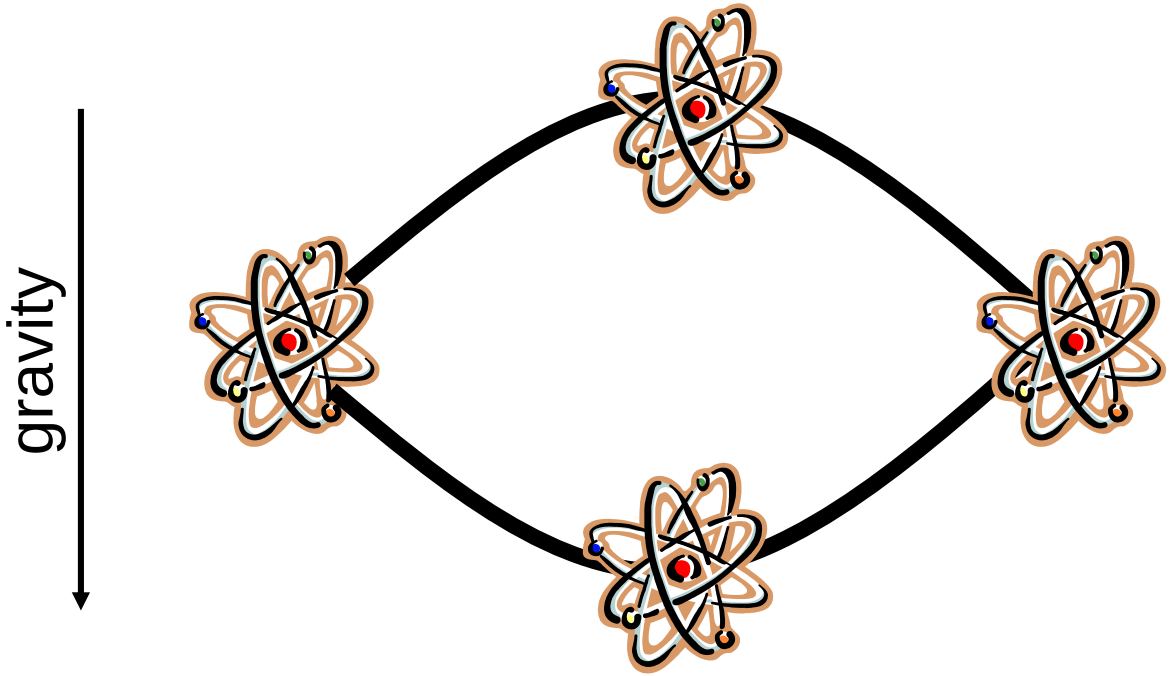
PI: Ian Walmsley
University of Oxford

David Delpy
Chair of UK QT Strategic Advisory Board

UK National
Quantum Technology Hub
Sensors and Metrology

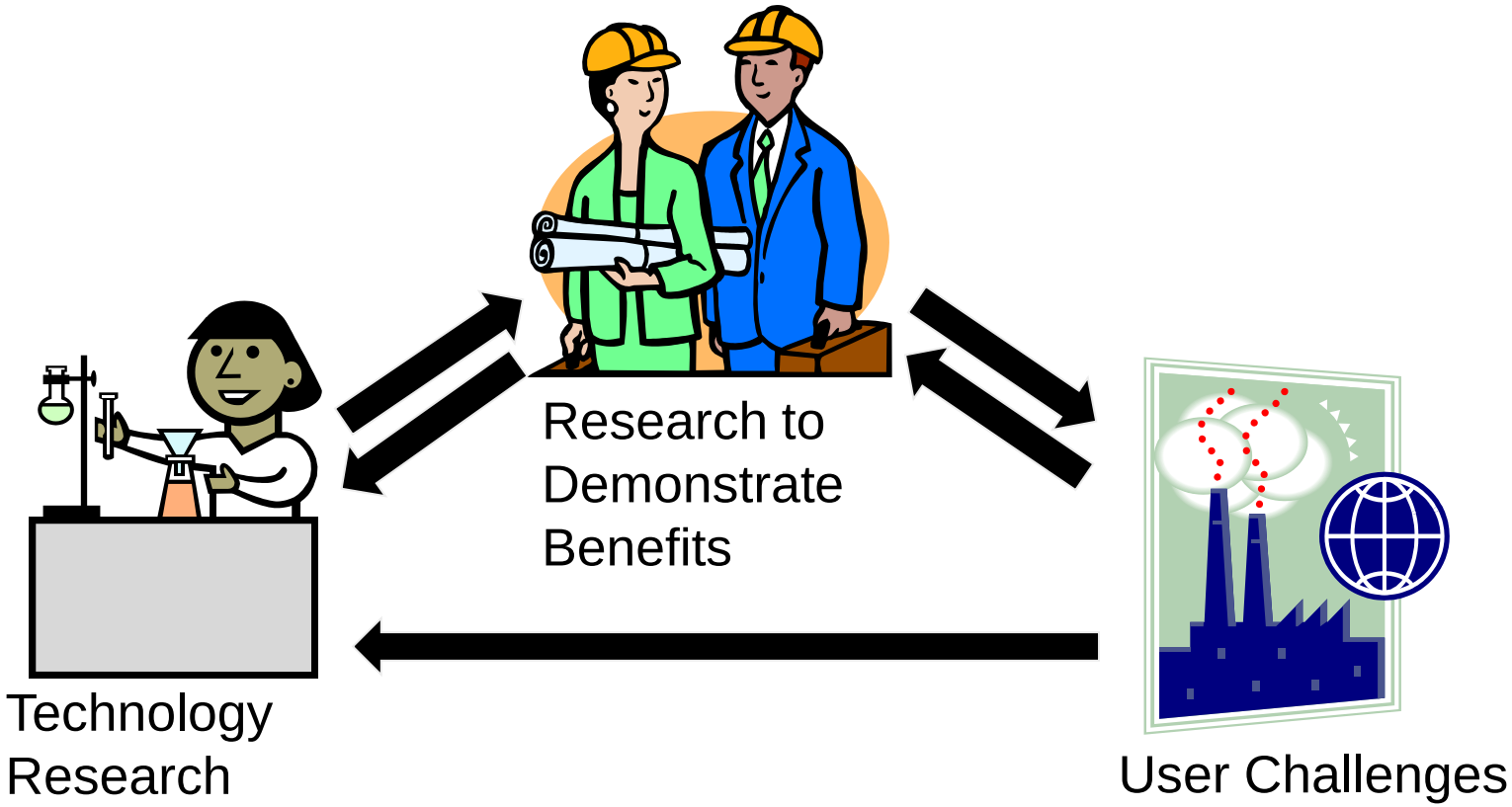
UNIVERSITY OF BIRMINGHAM
University of Glasgow
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA
UNIVERSITY OF Southampton
University of Strathclyde Glasgow
US University of Sussex

What we do: Atoms manipulated by laser light



Also possible: rotation, time, magnetic fields,…

Hub Strategy
"Disruptive Innovation Triangle"

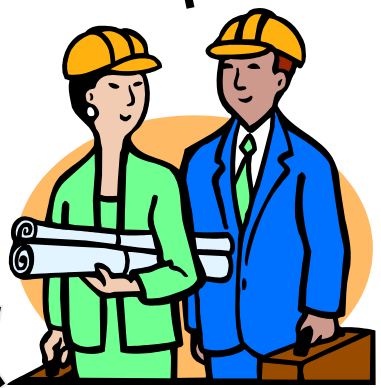


Hub Strategy

Engage the whole Industrial VALUE CHAIN

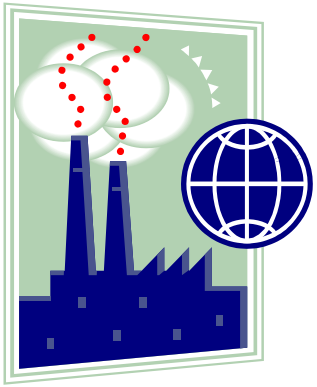
Applications

Supply chain
Components & subsystems

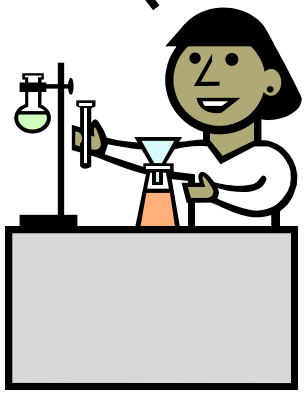


Research to Demonstrate Benefits

End-User **Systems**

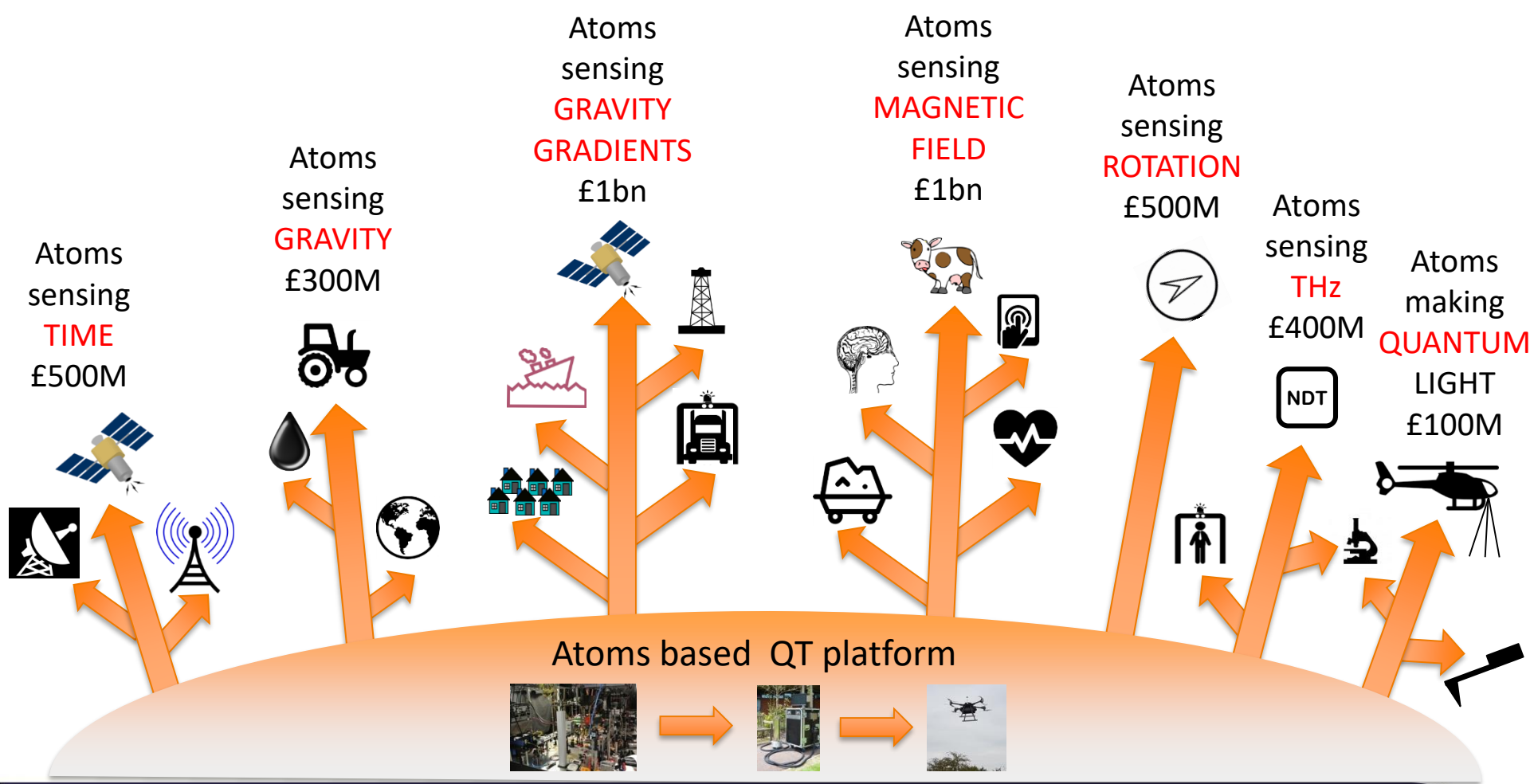


User Challenges



Technology Research

Roadmaps towards £3bn market opportunity



Hub-Related UK QT Ecosystem

77 collaborative projects with industry

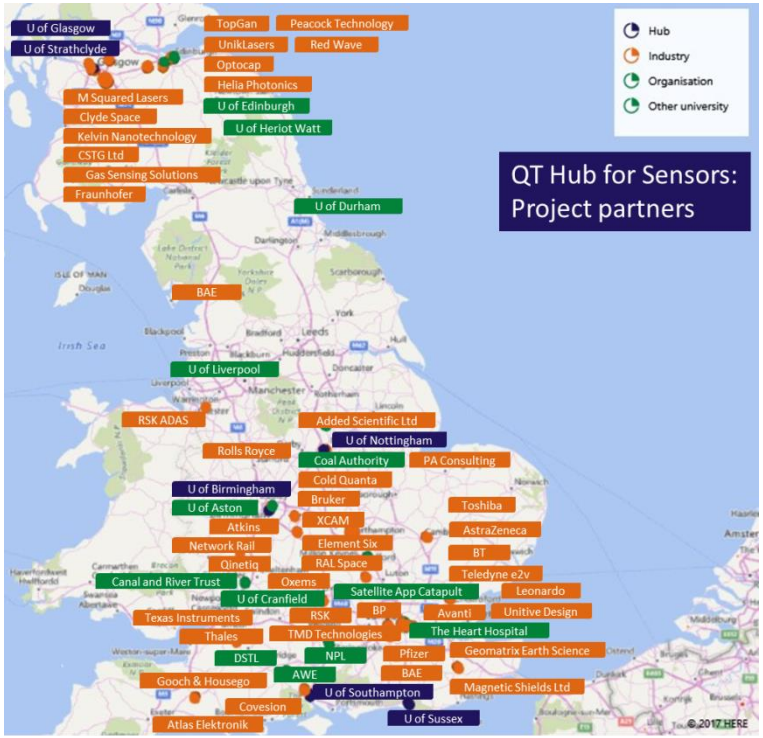
43 industry partners

£50M project value

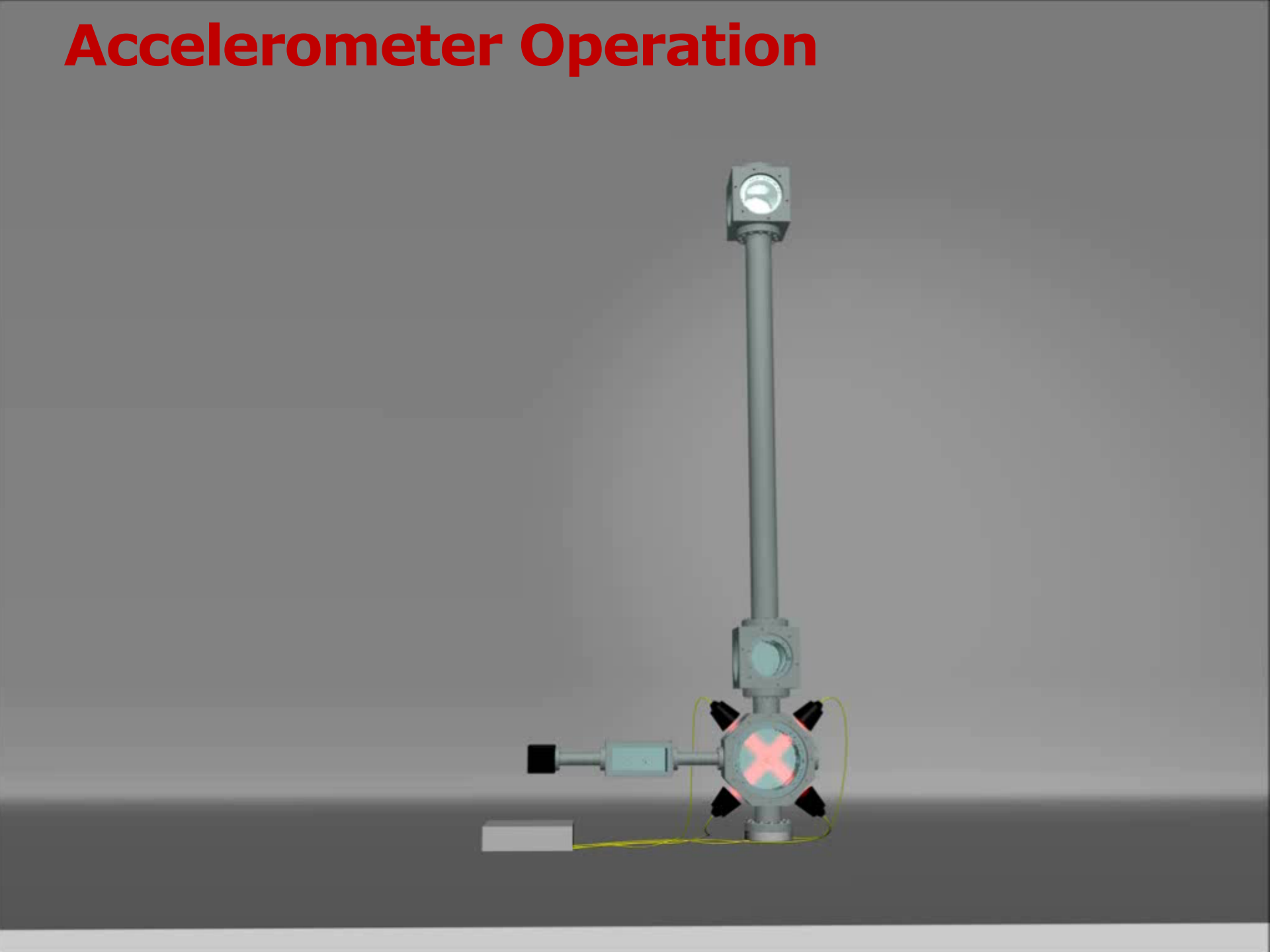
50 jobs in industry

9 patent applications

132 Records of invention

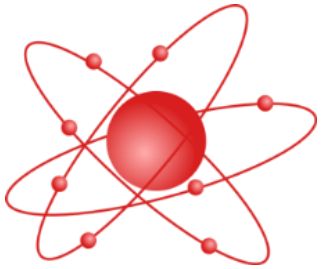


Accelerometer Operation

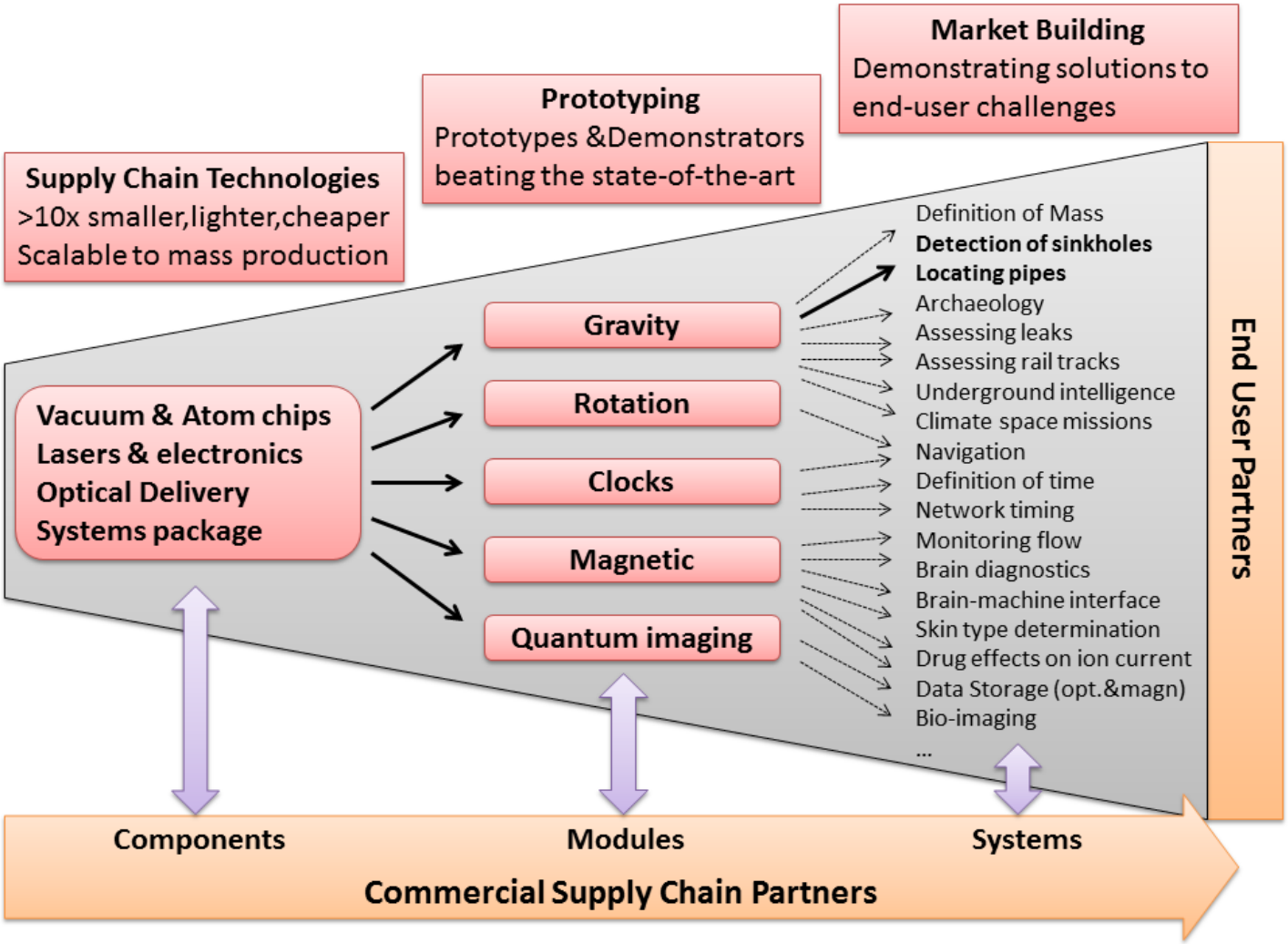


Why Cold Atom Quantum Technology?

- Already outperform classical counterparts
- Huge scaling potential (1000 x better)
- Free of mechanical wear
- Absolute – i.e. long term stability
- Excellent common mode rejection as gradiometer

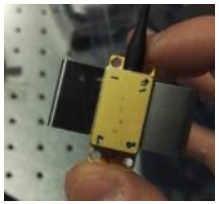


Activities and Links



Miniature Standardised Cold Atom Systems

Laser Systems



University of Glasgow

M SQUARED

KELVIN NANOTECHNOLOGY

Compound Semiconductor Technologies

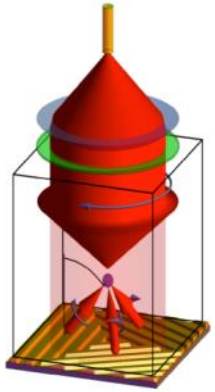
IQE

optocap

Fraunhofer UK

M SQUARED

Grating-MOT

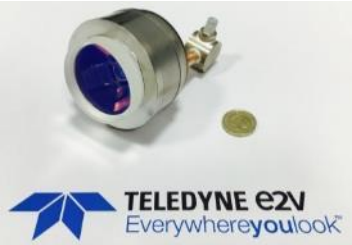


University of Strathclyde Glasgow

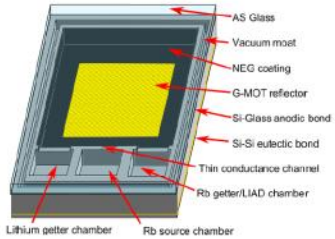
KELVIN NANOTECHNOLOGY

TMD

Miniature Vacuum

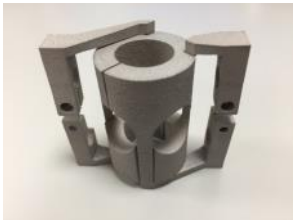


TELEDYNE e2V Everywhereyoulook



UNIVERSITY OF Southampton

3D printed coils



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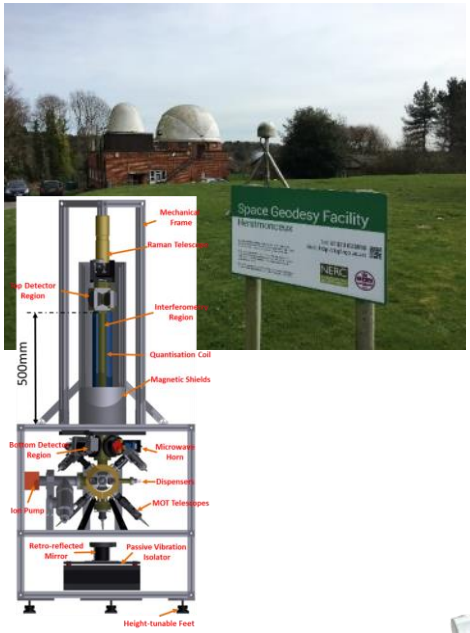
ADDED SCIENTIFIC

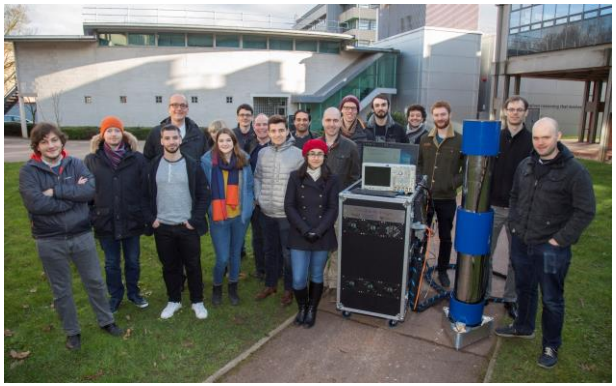
3D printed magnetic shields

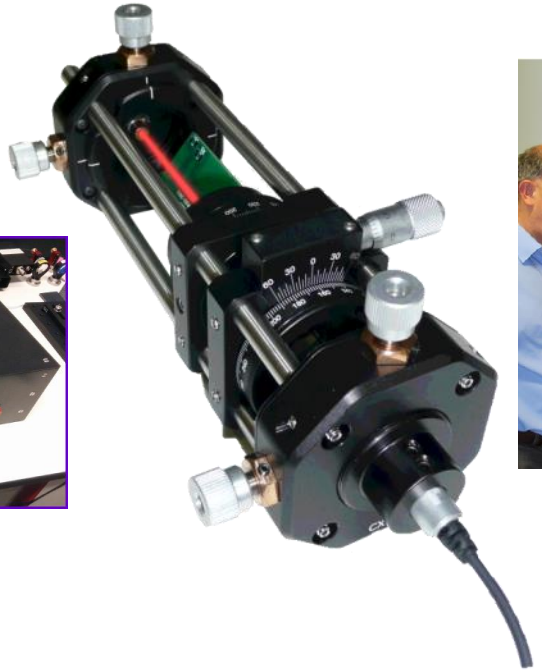
UNIVERSITY OF BIRMINGHAM

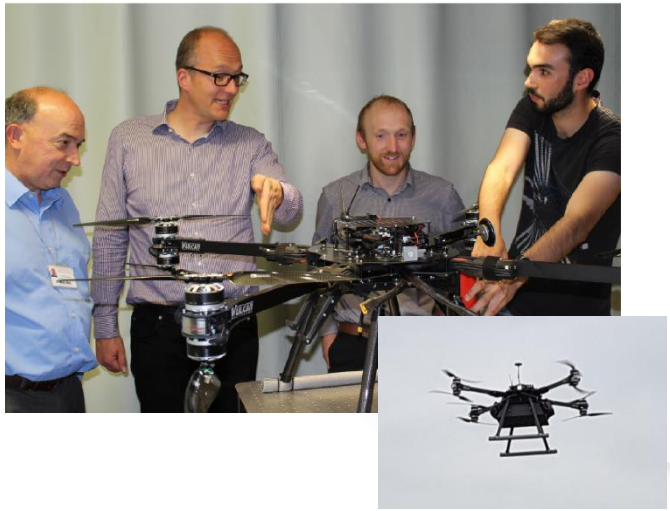
Magnetic Shields Electromagnetic Engineering

Demonstrators







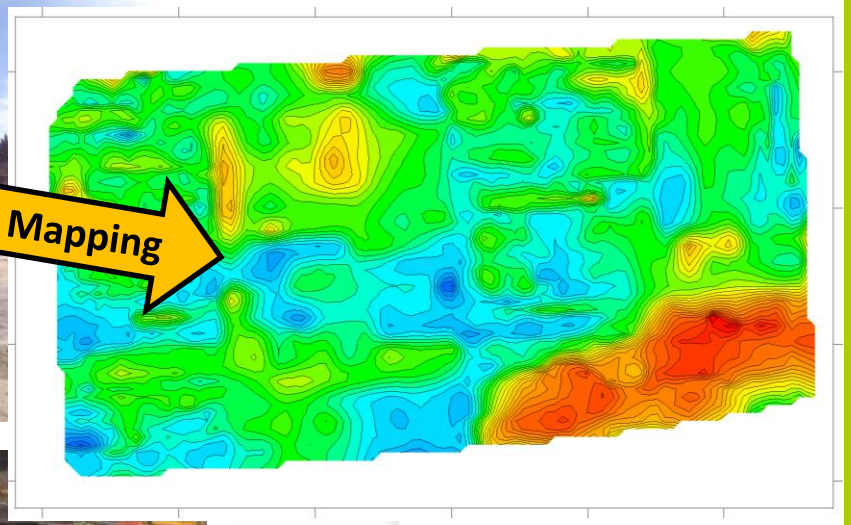


Market Example WP11:
QT Gravity Gradient Sensors for Underground Mapping

UNIVERSITY OF BIRMINGHAM

RSK

Gravity Mapping



UK cost of digging up the roads : £5bn/yr

Functional Brain Imaging

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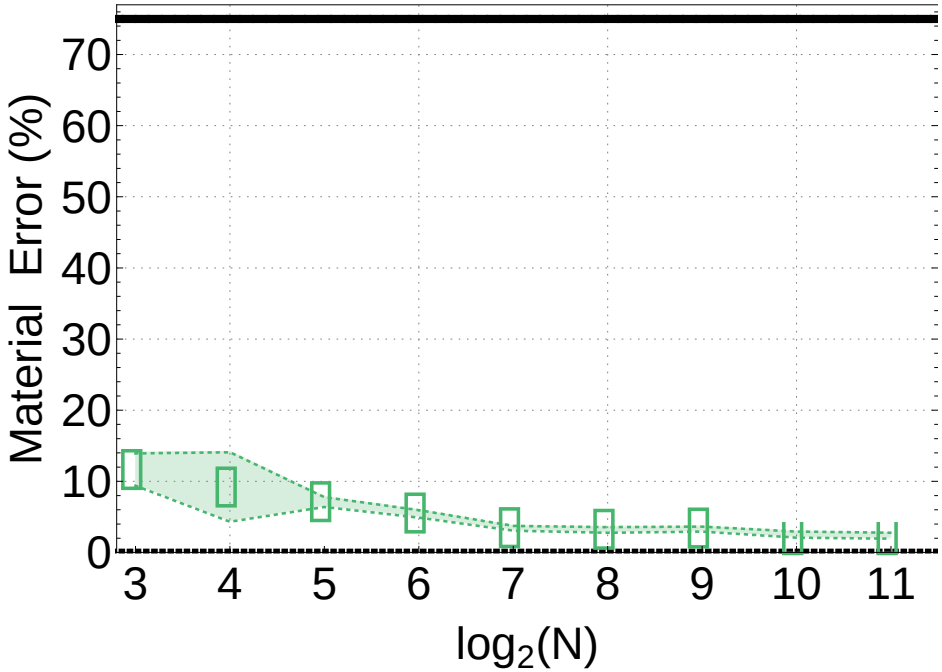
Functional brain imaging currently requires patients to remain still in a highly restricted environment.

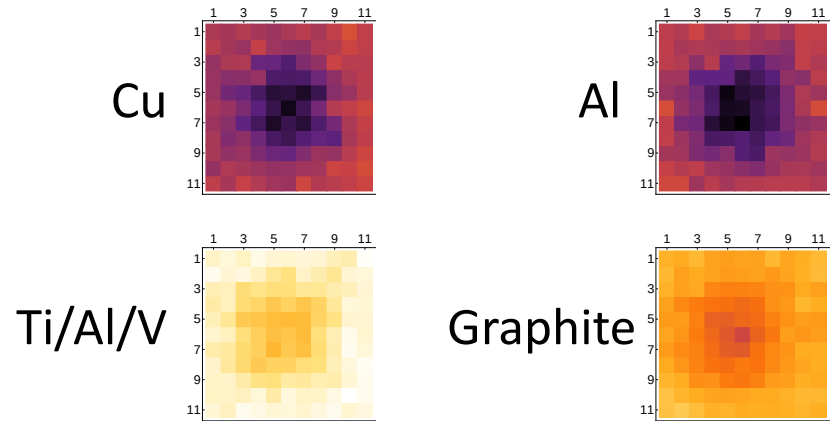
These conventional scanners are limited in sensitivity, and some subject groups are excluded – particularly infants

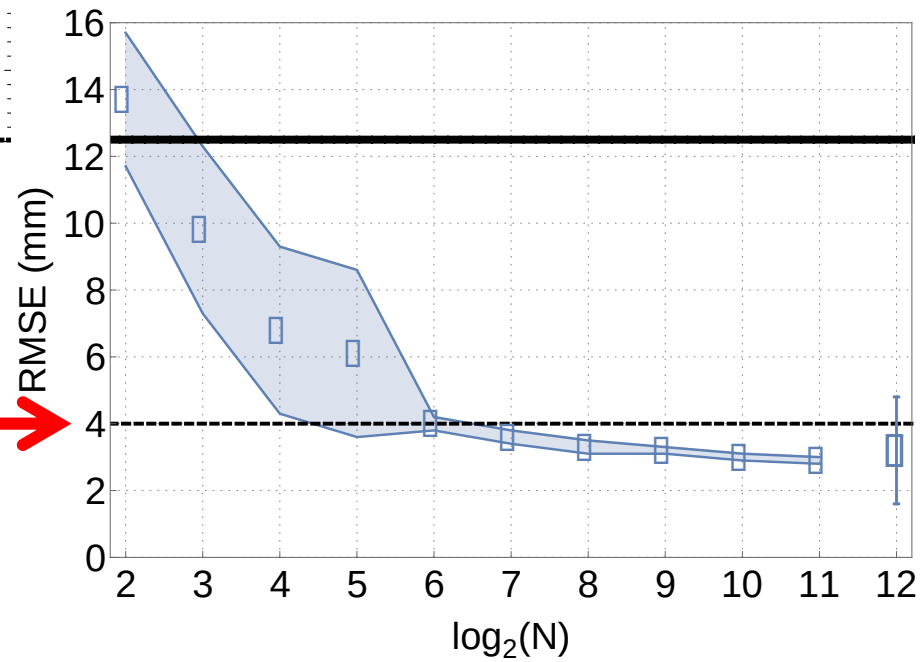
Next generation quantum sensors are allowing a step change in technology – a “wearable” neuroimaging system

Allows scanning of subjects of any age, with free head movement and better sensitivity and spatial resolution compared to conventional systems

Electromagnetic Imaging with Atomic Magnetometers and Machine Learning



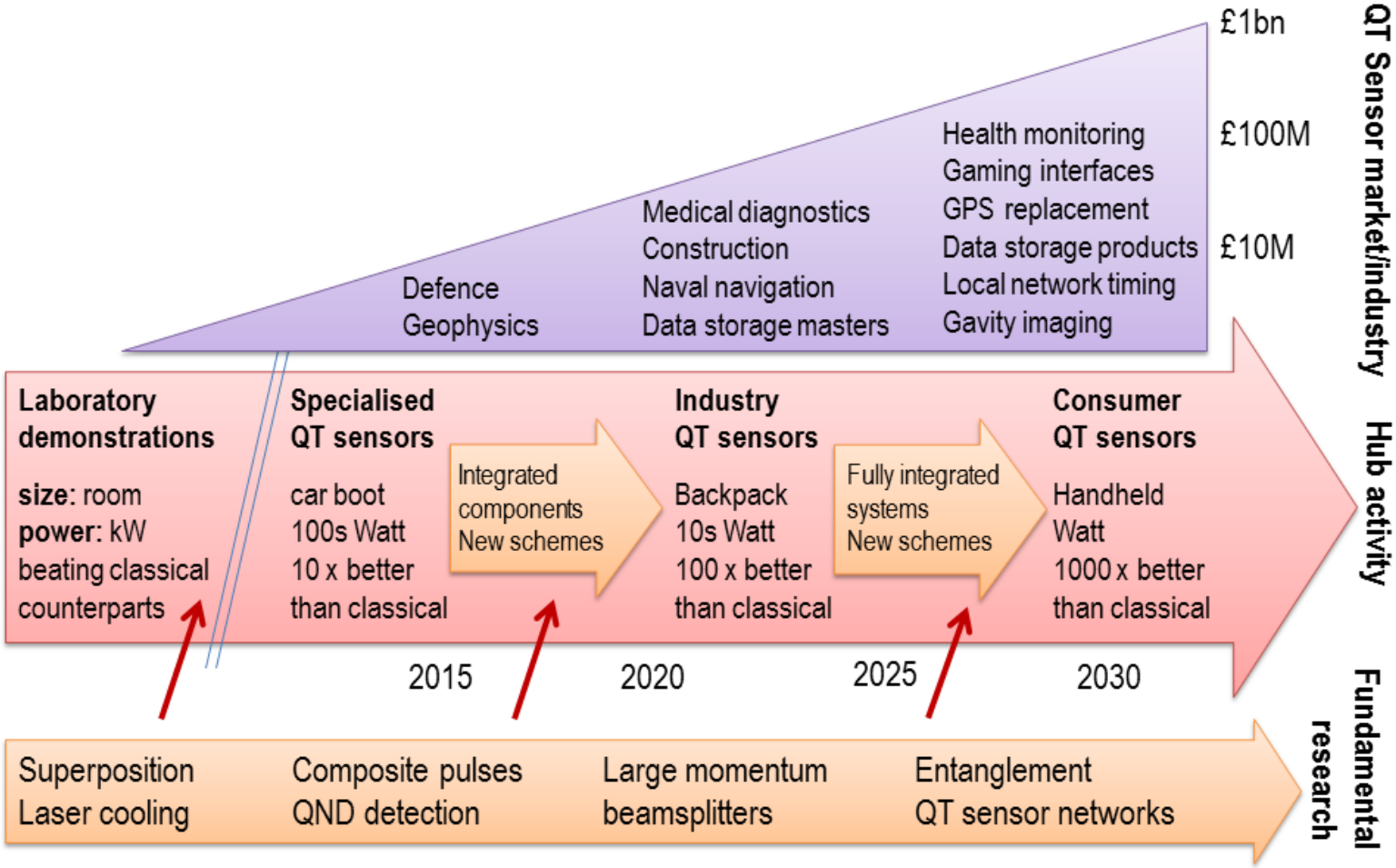




4 mm: Chosen spatial resolution of the imaging system (pixel size)

C. Deans, L. D. Griffin, L. Marmugi, F. Renzoni, **ArXiv:1710.06629** (2017)

Quantum Sensor Roadmap



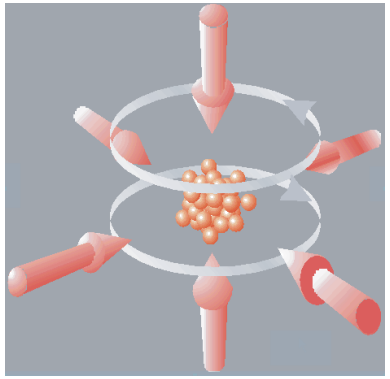
Optics Challenges

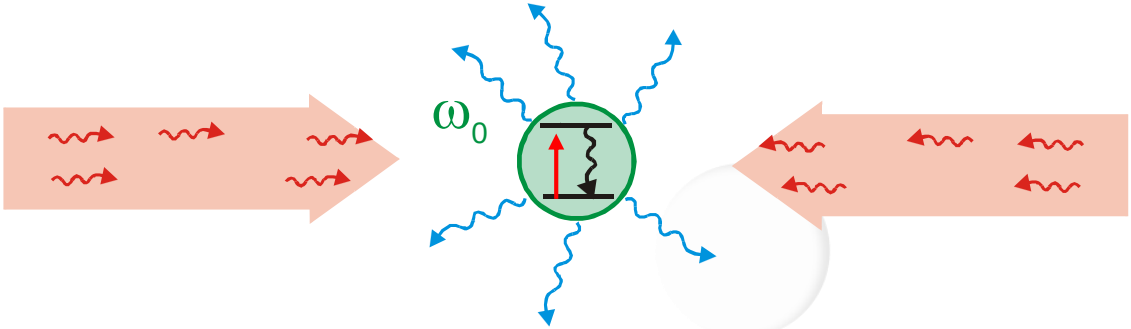
Laser cooling

The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

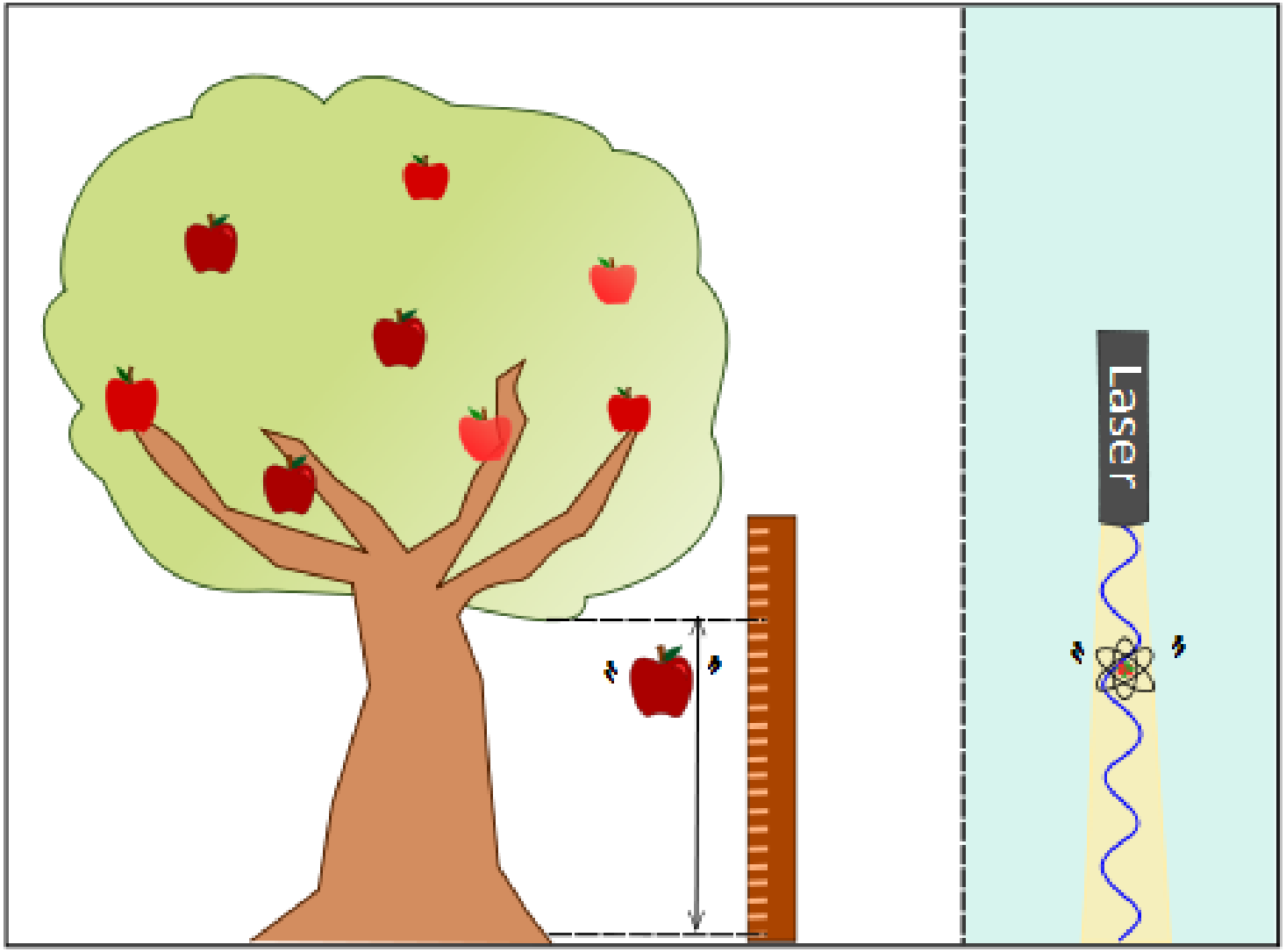
S. Chu **C. Cohen-Tannoudji** **W.D. Phillips**





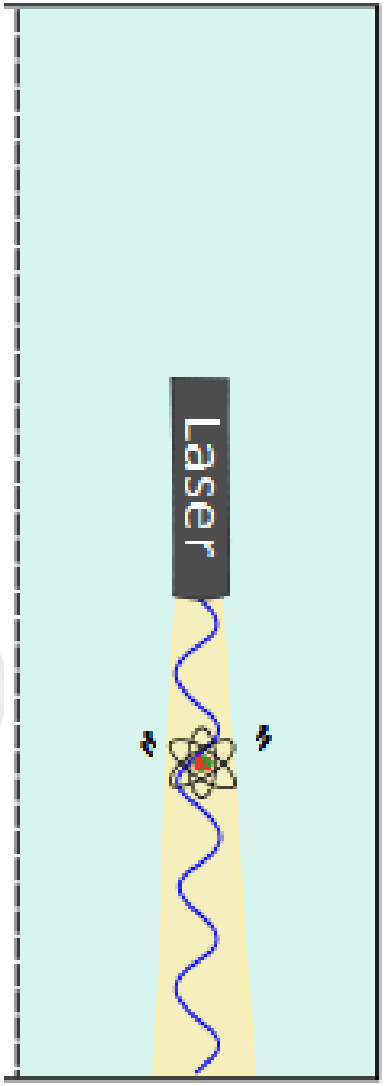
Laser linewidth and absolute frequency stability < MHz (<natural linewidth)
For red cooling transition in Sr <kHz !

How Quantum Sensors work: Gravity



Measuring Gravity

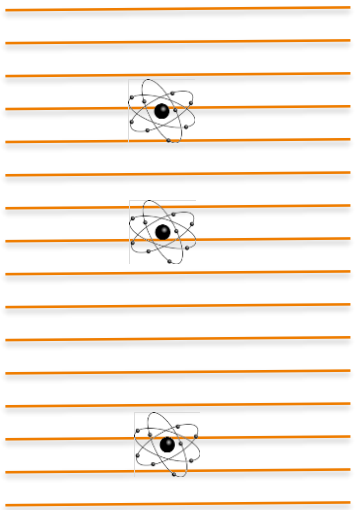
$$k_z T^2 g_z = 2\pi \frac{\Delta z}{\lambda}$$



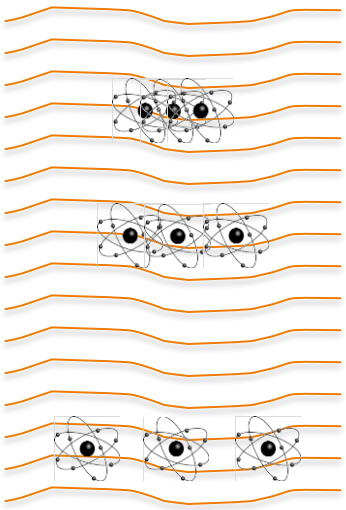
- ➔ Dropping object next to laser ruler
- ➔ Accuracy of 1 part in 10^{10} requires a ***1 in 10^{10} accuracy in laser wavelength!!!***
- ➔ ***Laser linewidth < 10 kHz***
- ➔ ***Gravity gradiometers have similar requirements***
- ➔ ***Also think of power!!!***

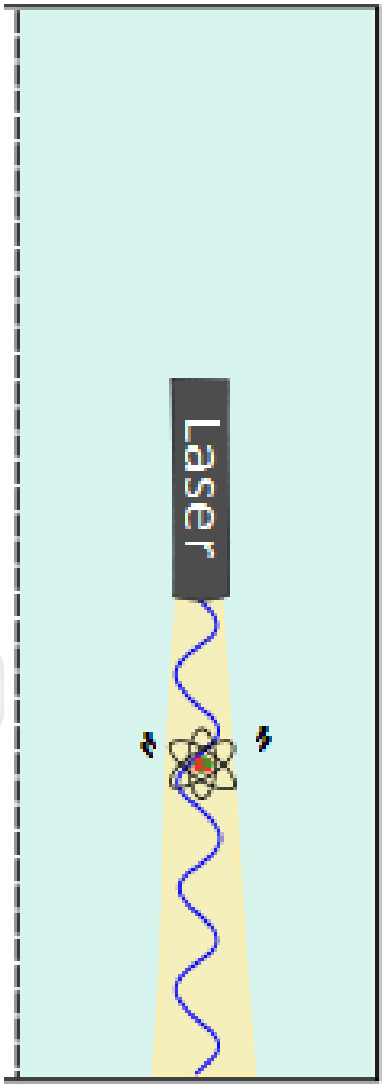
Wavefront Effects

Ideal case



Realistic case





Detecting 10^6 atoms delivers shot noise of 1mrad or $\lambda/1000$

Using Entanglement would make this $\lambda/1000000$!

Optics Challenges

- Stable lasers – step-change in SWAP-C
- Robust optical delivery (polarisation in fibres vs complexity in free space)
- Low-loss integrated optical components (in particular μs, 100dB switches)
- Recycle optical power and stay frequency agile?
- Ultra-flat wavefront optics (inside or through vacuum)
  - Could I have those with flat intensity as well, please?