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Cavendish Strategy Forum 2018

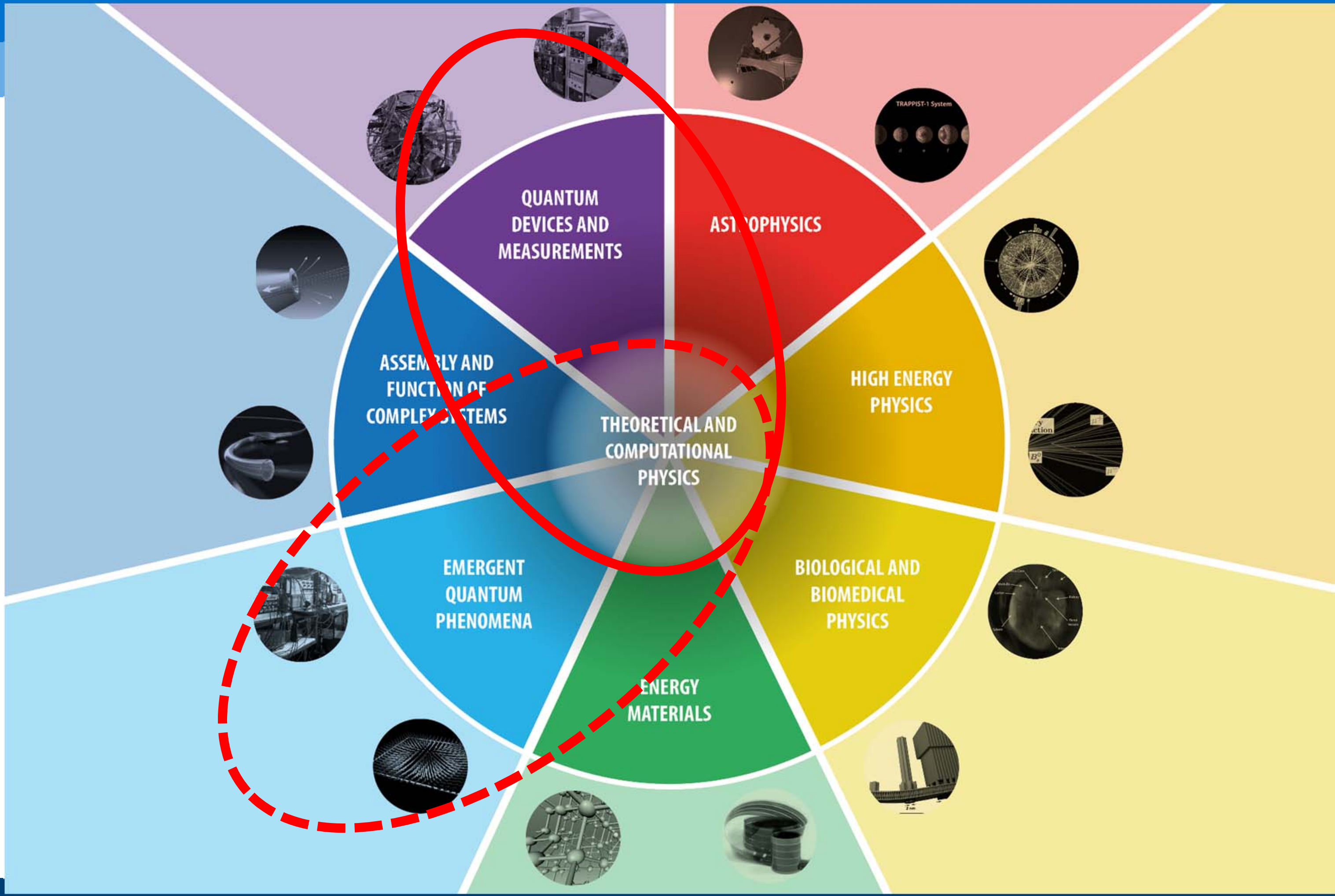
Quantum Devices and Measurements theme

Mete Atature, Crispin Barnes, John Ellis, Chris Ford, Louise Hirst , Andy Jardine, David Ritchie, Henning Sirringhaus, Stafford Withington, Benjamin Berri, Suchitra Sabastian, Ulrich Schneider

Charles G. Smith

Quantum Devices and Measurements theme is strongly linked to Emergent Quantum Phenomena

Emergent quantum phenomena will feed new materials into the Quantum Devices and Measurements theme allowing new sensors and quantum technologies to be realised. In the same way that new quantum devices can be incorporated into instruments that help develop new quantum materials.



Outline

What are we doing?

Funding landscape

What is missing?

What does Quantum Devices and Measurements theme cover

Quantum Sensing

Engineered Quantum States

Quantum Information and Communication

Quantum Simulation

Non-equilibrium Materials (Many Body localisation)

Topological Quantum Systems

Theory of Quantum Circuits

Hybrid Systems at low dimension

Controlling Quantum coherence

Hybrid Quantum Optomechanics

Majorana quantum devices

Quantum energy harvesting

Interactions in quantum systems

Superconducting quantum detectors

Instrumentation

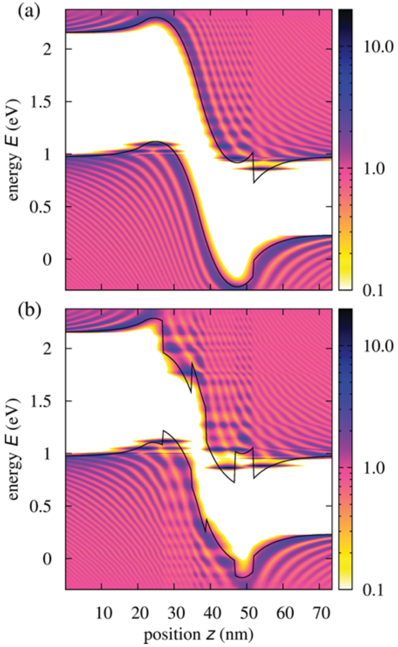
Departmental Strength: III-V Quantum Photovoltaics

Louise Hirst

Tunnel junctions

Quantum confined energy levels:

- Assisted tunneling
- Reduced series resistance

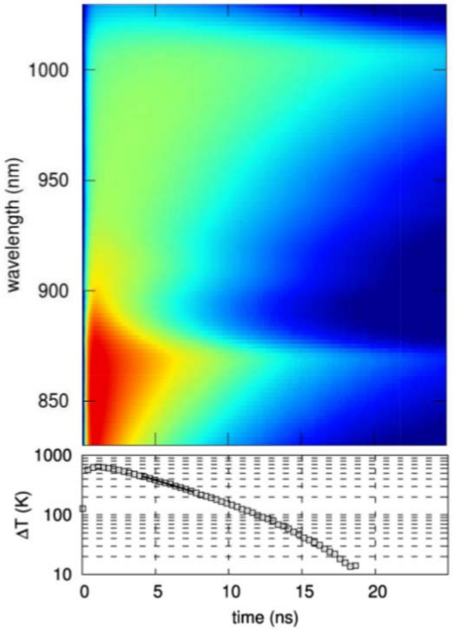


Aeberhard, Phys. Rev. B **87**, 081302(R)(2013)

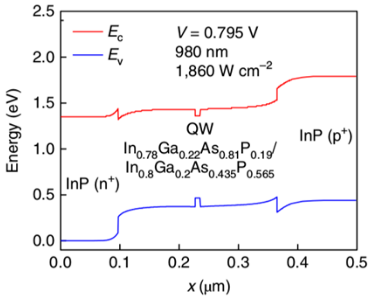
Hot-carrier solar cell

Quantum wells for slow carrier cooling:

- Pathway to fundamental efficiency enhancement



Hirst et al. IEEE Journal of photovoltaics, 4(1) (2014)



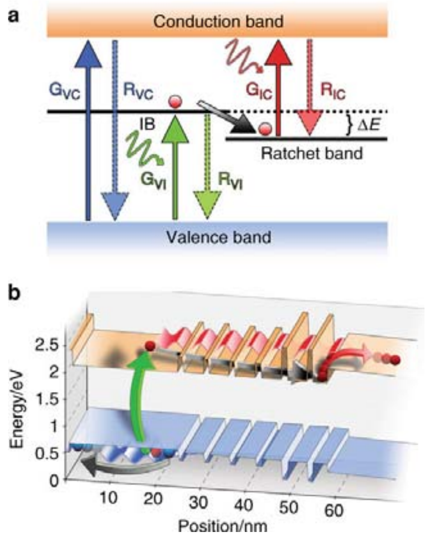
- 2018 demo of room temp HCSC in III-V QW system

Nguyen et al., Nature Energy, **3**, 236–242 (2018)

Photon ratchet intermediate band solar cell

Quantum wells for spatial separation of charge carriers via cascade of confined energy levels

- Analogous to quantum cascade laser

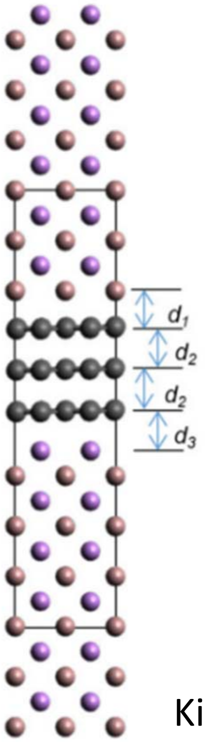


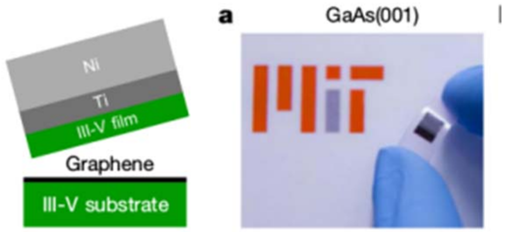
Vaquero-Stainer et al., *Communications Physics* 1(7) (2018)

Emerging research opportunity: Remote epitaxy on graphene

Louise Hirst

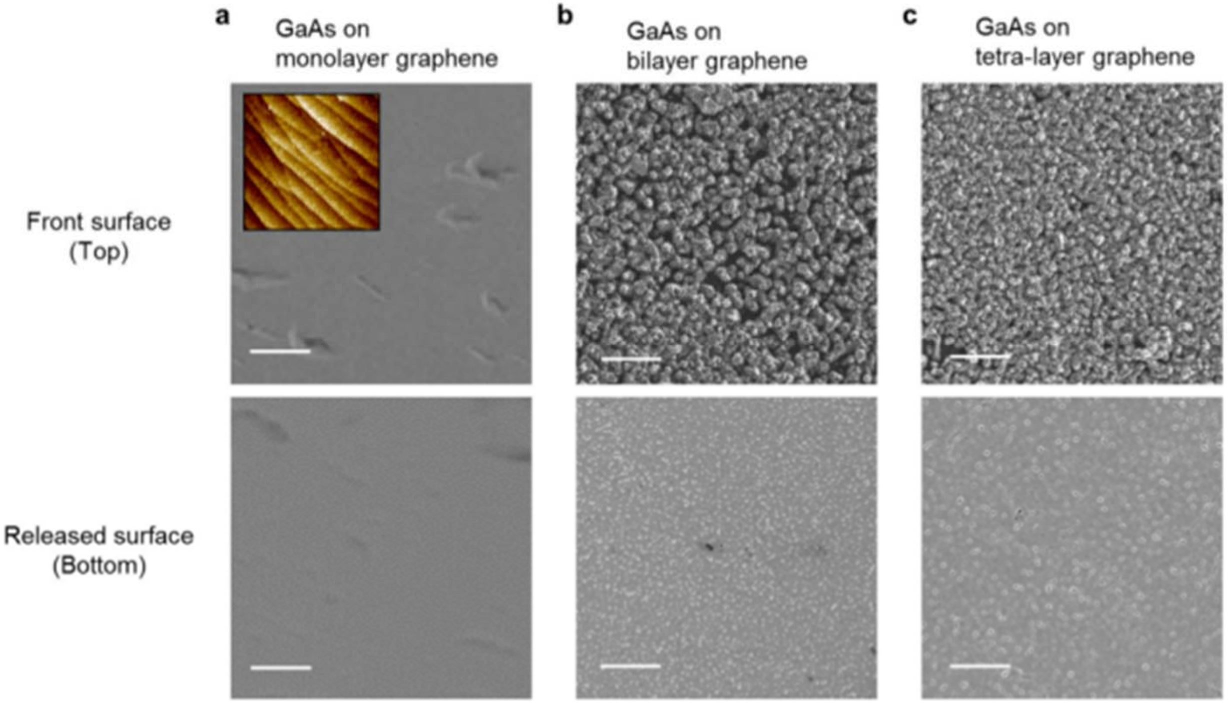
- Opportunity not just limited to Quantum Devices - game changer for **ALL** epitaxially grown devices
  - Reduced costs (substrate reuse)
  - Layering of ultra-thin films for hybrid heterostructures
  - Accessing new lattice constants
  - Fully flexible materials





Graphene layers	Ga – As (Å)	As – As (Å)
1	5.04	6.28
2	8.19	9.44
3	11.35	12.59

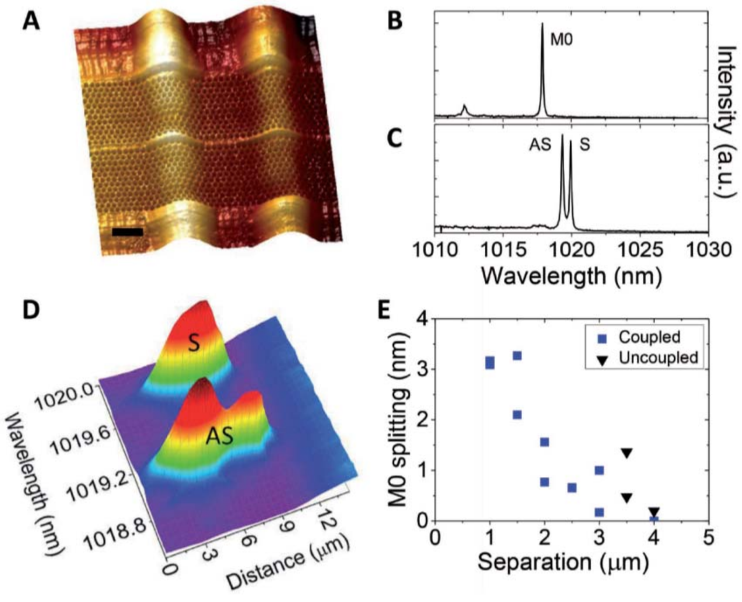
Kim et al. *Nature* 544(340) 7650 (2017)



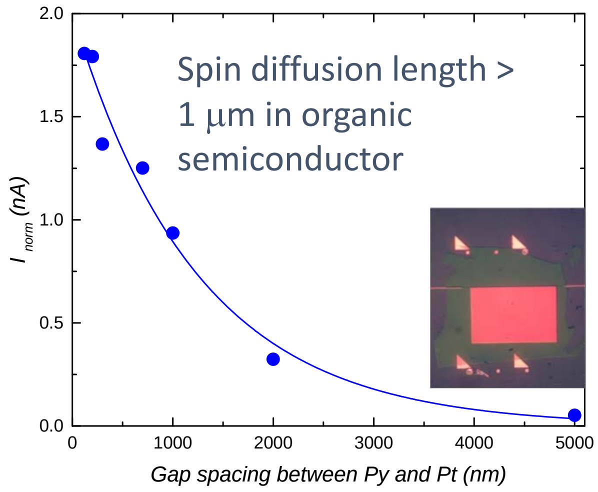
Quantum devices with molecular systems

Henning Sirringhaus

Inkjet printed photonic crystal cavities,
collaboration with Hitachi Cambridge



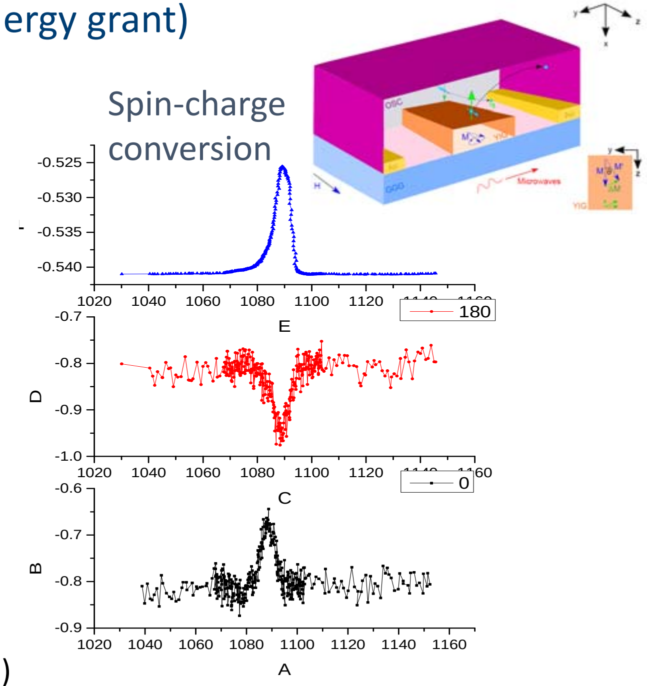
Adv. Mat. 29, 1704425 (2017)



Spin diffusion length > 1 µm in organic semiconductor

Nature Physics **10**, 308 (2014)
Nature Communications 8, 15200 (2017)

Organic spintronics
(ERC Synergy grant)

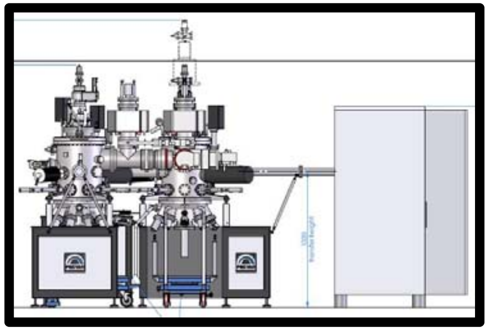


Spin-charge conversion

Nature Materials 12, 622 (2013)

UHV Deposition System

David Ritchie



Two interconnected UHV deposition chambers. 1. for the epitaxial growth of topological insulators and related materials, and 2. for the deposition of a range of metals.

This flexible MBE system is for growth of high-purity epitaxial layers and heterostructures such as topological insulators such as Bi_2Te_3 and Sb_2Te_3, as well as other materials. After growth in this chamber, samples can be transferred under contamination free UHV conditions to the evaporator, described below, for deposition of capping layers.

UHV evaporator
Has several different sources using both thermal and electron beam evaporation techniques to deposit a range of metals onto samples transferred from the MBE system.

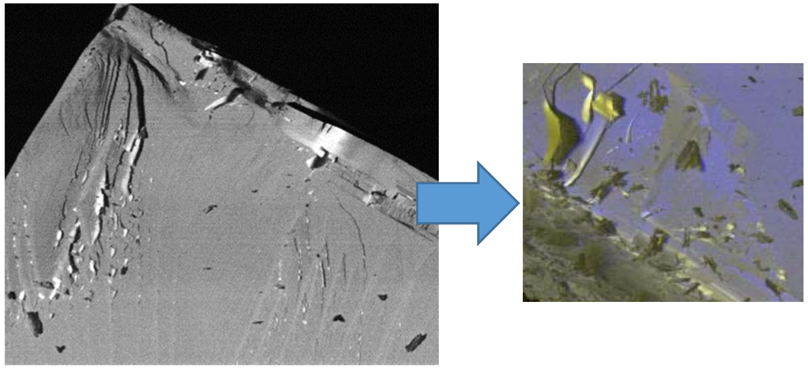
Current research areas
Developing THz SNOM and delivery systems for low temperature cryostats
Positioning InAs quantum dots with Sheffield and Lancaster (2016-2021) for quantum optics experiments and quantum information
Work with Toshiba, the York quantum communications Hub, Sheffield
Work with NPL and European Metrology labs

Neutral Atom Microscopy

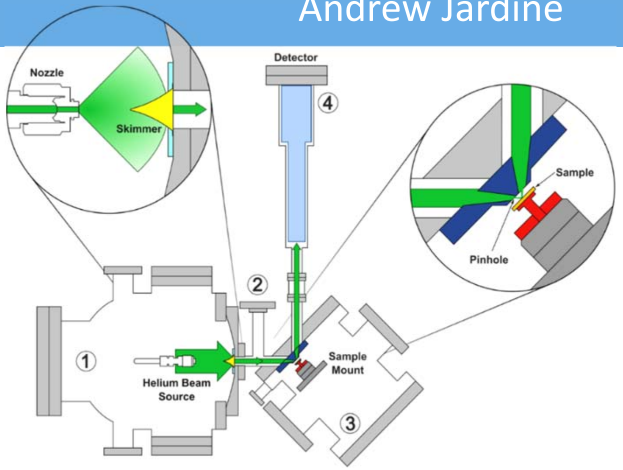
Andrew Jardine

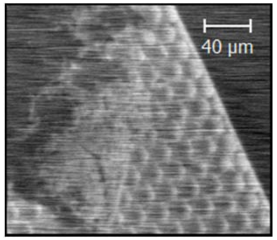
Ongoing £1.5M EPSRC programme to develop neutral atom microscopy; pinhole and Fresnel optics; ultra-sensitive detection; applications.

Characteristics:
Ultra-delicate microscopy – 50meV beam.
No sample preparation / charging
Ultimate resolution ~50nm (currently ~1µm)
New contrast: topological, chemical, wave.

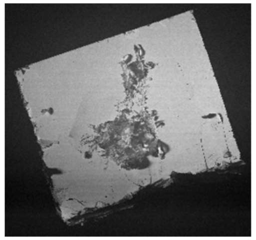


Charge sensitive LiF surface - inset shows topological contrast (brightness) and atomic sensitivity (colour)

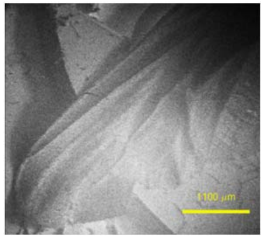




Ultrahydrophobic polymer



Graphitic material



Biological structure

Potential applications:

- Delicate films; organic electronics; ice
- Nanostructured devices; polymers; composite materials.
- Thermoelectrics; Debye-Waller contrast?
- Spot profile helium scattering / spatially resolved growth
- Localised desorption and diffraction

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Nature Communications **7**, 10189 (2016).

Twisted photons and vortex particle beams

Andrew Jardine

Waves containing phase singularities can be used to create photon and particle beams with orbital angular momentum [Nature 464, 737 (2010)].

Multiple approaches to vortex beam formation:
lenses
spiral zone plates
structured surfaces

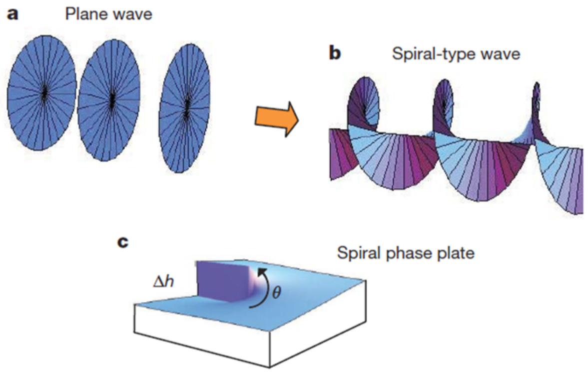


Figure 1 | Conversion from a plane wave to a spiral-type wave using a spiral phase plate. **a**, Wavefronts of a plane wave, which are planes normal to the propagation axis. **b**, Wavefronts of a spiral-type wave. When the wavefronts have a spiral shape so that a $2l\pi$ variation of the phase occurs in a 2π rotation around the beam axis, where l is a topological charge that denotes the winding number of the spiral, there is a phase singularity at the centre. The sign of l represents right-handed or left-handed ramps. **c**, Spiral phase plate with a step height Δh. The thickness increases continuously in proportion to the azimuthal angle θ, but is constant in the radial direction. When a plane wave passes through the spiral phase plate, a spiral wavefront character is imprinted on the plane wave, where a phase singularity at the core of the beam is generated. By changing the step height or material, spiral beams with various l values can be produced.

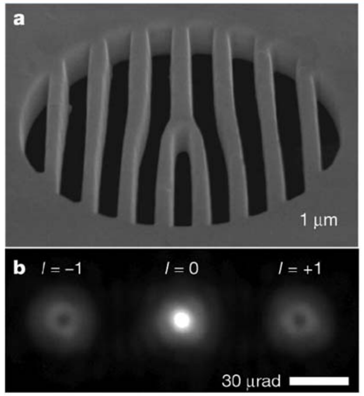


Figure 2 | Experimental realization of the holographic reconstruction technique. **a**, Scanning electron microscope image of a 5-µm phase dislocation aperture made in a thinned Pt foil. **b**, Diffraction pattern obtained in the far field of the vortex aperture when illuminated with a plane wave of 300-kV electrons. The pattern clearly shows the doughnut-shaped sidebands, each carrying opposite angular momentum.

Now opened up many opportunities exploiting these beams as material probes:

- **Photons** – ‘optical spanner’; trapping and rotating colloidal particles; optical data storage & comms; [Nature Physics 3, 305 (2007)].
- **Electrons** – magnetic characterisation of materials with atomic precision, orbital coupling [Sci. Rep. 7, 934 (2017)].
- **Atoms** – chiral scattering and structure, phonon coupling

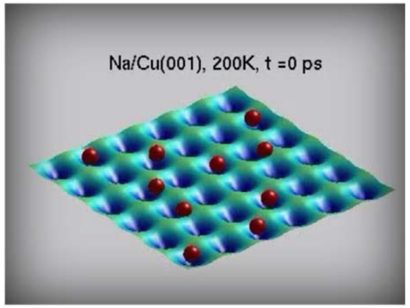
^{3}He Spin Echo: *sub-ps* to *ns* dynamics of atoms/molecules

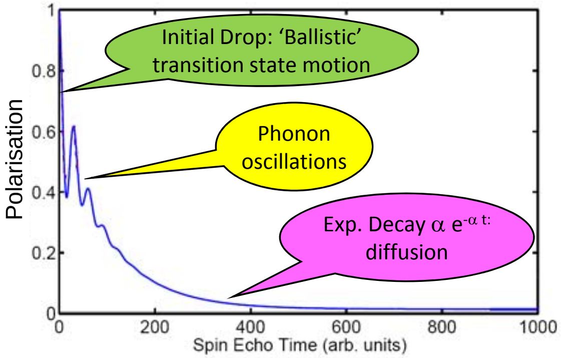
John Ellis

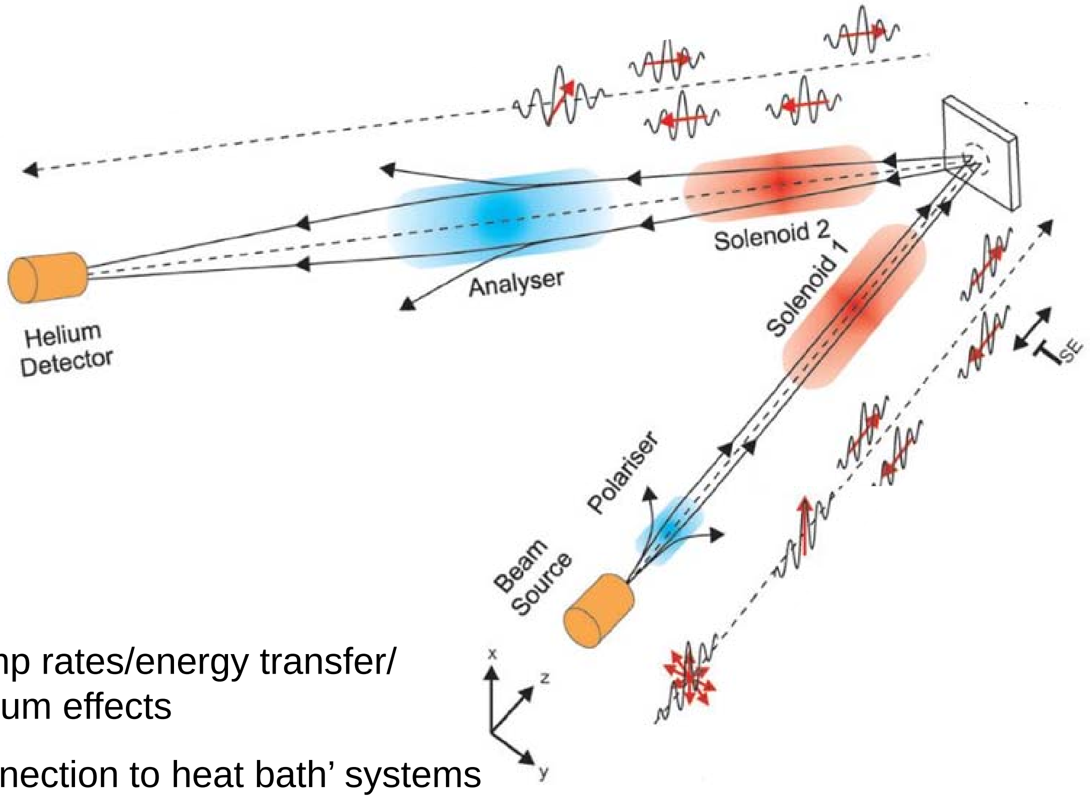
- **He scattering**: everything neutron/x-ray scattering can do at central facility done on a surface with high signal in a lab.

- **He spin echo**: split wavepacket in time – look for changes at surface between impacts.

-In reciprocal space and correlation time ‘watch’ atoms as they move.







Applications:

- Measuring key aspects of dynamics: interaction potentials/ jump rates/energy transfer/ atomic scale friction/ atomic vibration+dephasing/ noise spectrum effects
- Highly detailed measurements of ‘quantum propagation in connection to heat bath’ systems

^{3}He Spin Echo: *Probing quantum propagation at surfaces*

John Ellis

This work deals with ‘Physics Grand Challenge #3’ : methods for treating the static and dynamic quantum mechanics of multi particle systems.

Classical systems: numerically solve for *N*<<10^7 -10^9, depending on complexity of interactions, time scales as *N*

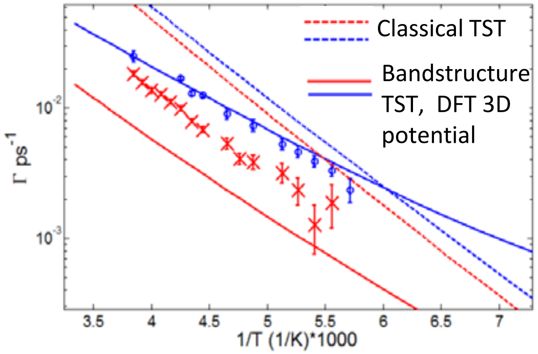
Quantum systems: A good pc might handle *N*=3 interacting particles (many 100 GB just to store wavefunction), time scales as N^N.

An extremely useful concept is the **propagation of a single particle connected to a heatbath** – but a multitude of methods, with little understanding of what approximations have been made or how they relate to each other – and total failure of accurate predictive power.

Calculate band structure of H states in DFT potential – use TST to give jump rate: excellent agreement with data – no variable parameters: works because coupling to heat bath is slow compared to jump rate, but the slower deep tunnelling is a real challenge.

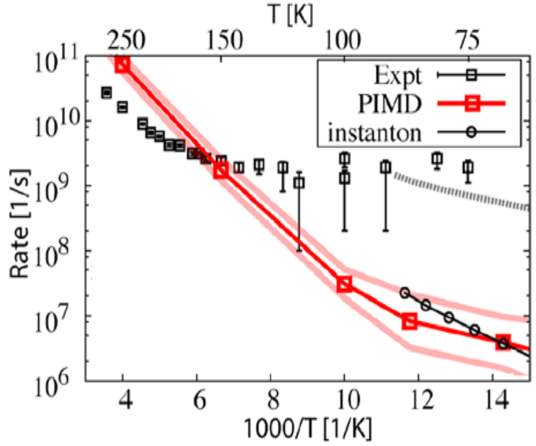
H/D on Cu(111)

Comparison of jump rate data with simple quantum v. classical predictions

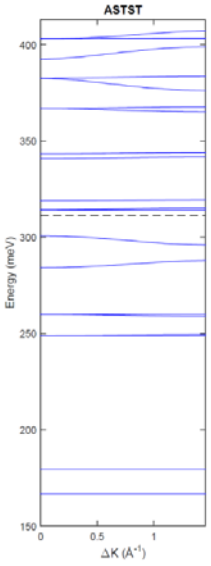


H on Ru(0001)

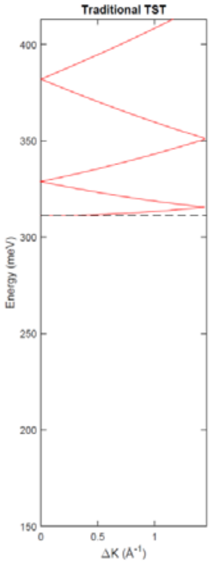
Zillions of hours of HPC time for PIMD: ignore H quantum states



H band structure

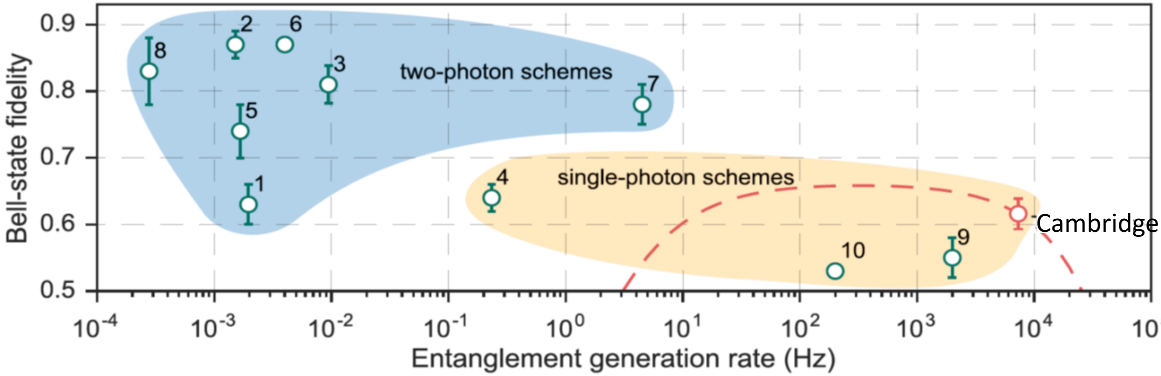


Classical States



Quantum photonic devices for distant networks

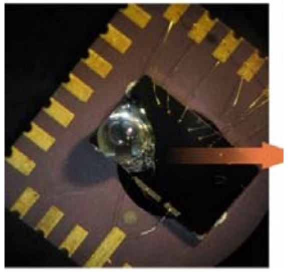
Mete Atature



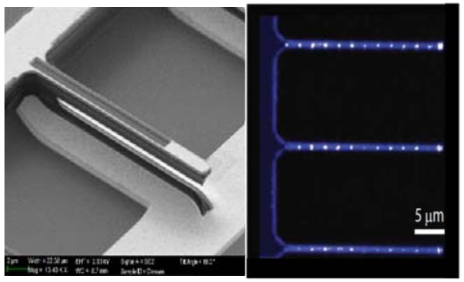
Cambridge has the highest rate of matter qubit entanglement generation among all tested physical systems

1 - D. L. Moehring et al. *Nature* **449** 68-71 (2007) **Ion**
2 - P. Maunz et al. *Phys. Rev. Lett.* **102** 250502 (2009) **Ion**
3 - J. Hofmann et al. *Science* **337** 72 (2012) **Atom**
4 - L. Slodicka et al . *Phys. Rev. Lett.* **110** 083603 (2013) **Ion**
5 - H. Bernien et al. *Nature* **497** 86 (2013) **NV**

Semiconductors



Diamond

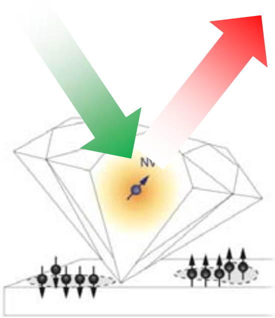


6 - W. Pfaff et al. *Science* **345** 532 (2014) **NV**
7 - D. Hucul et al. *Nature Physics* **11** 37 (2014) **Ion**
8 - B. Hensen et al. *Nature* **526** 682 (2015) **NV**
9 - A. Delteil et al. *Nature Physics* **12** 218 (2015) **Hole spin**
10 - A. Narla et al. *Phys. Rev. X* **6** 031036 (2016) **Transmon**

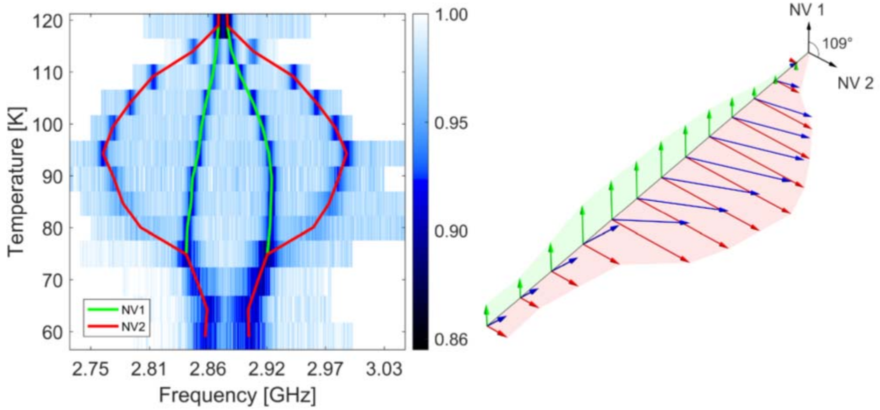
Local imaging of emergent magnetism in thin-film devices

Mete Atature

Local sensing of emergent magnetism



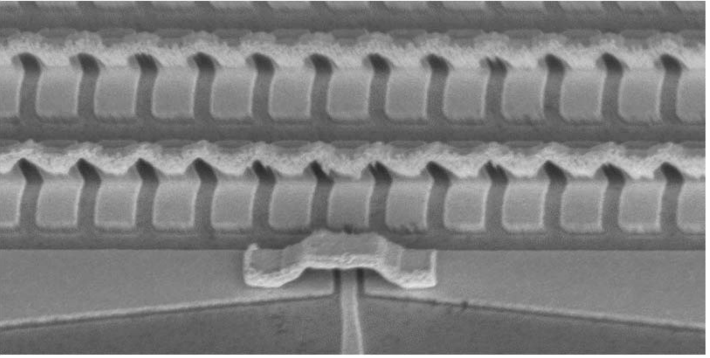
Praseodymium Calcium Manganese Oxide (PCMO) film on Strontium Titanium Oxide (STO) substrate

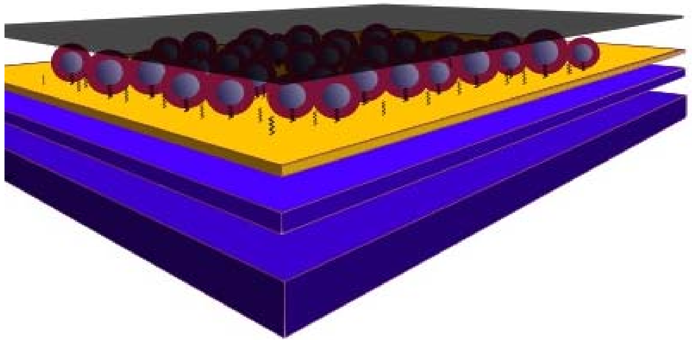


Supported by EPSRC NQTP (QUES2T) and the Royce Institute.

Harnessing patterned confined quantum systems

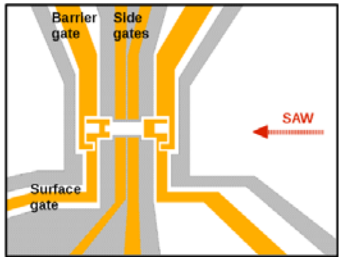
Chris Ford

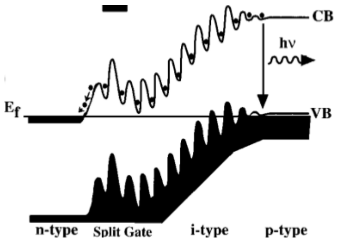




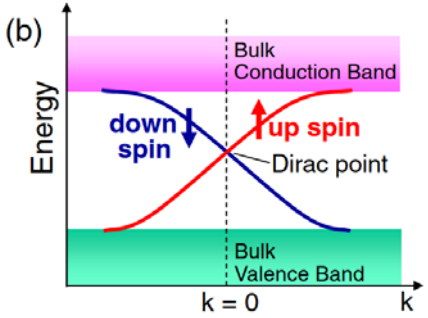
We are developing a thermoelectric energy-harvesting device using monolayers of designer molecules based on room-temperature quantum interference, phonon reflection, together with a graphene top electrode

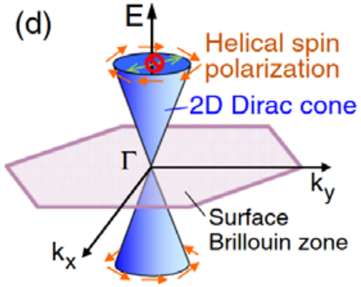
We use advanced fabrication to measure spectral funct systems to investigate interaction effects beyond the Luttinger-liquid regime, mapping out spin-charge separation and testing new theories





We drive electrons and holes through undoped lateral p-n junctions for high-speed single-photon sources and detectors





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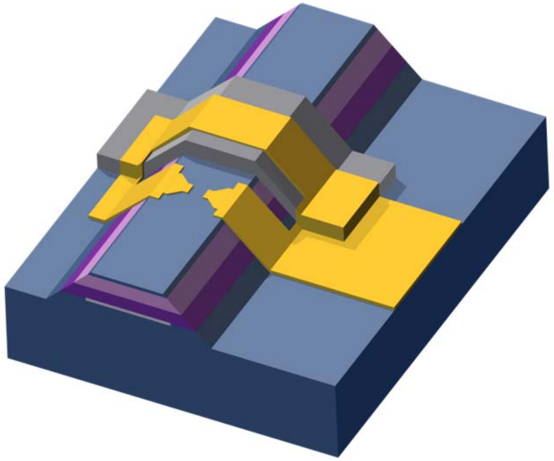
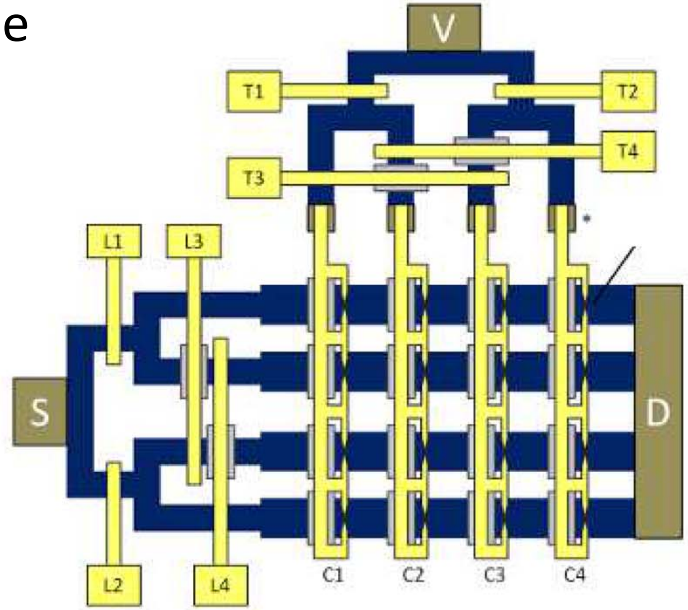
We will control and exploit 0D, 1D and 2D states in topological insulators using heterostructures and patterned structures

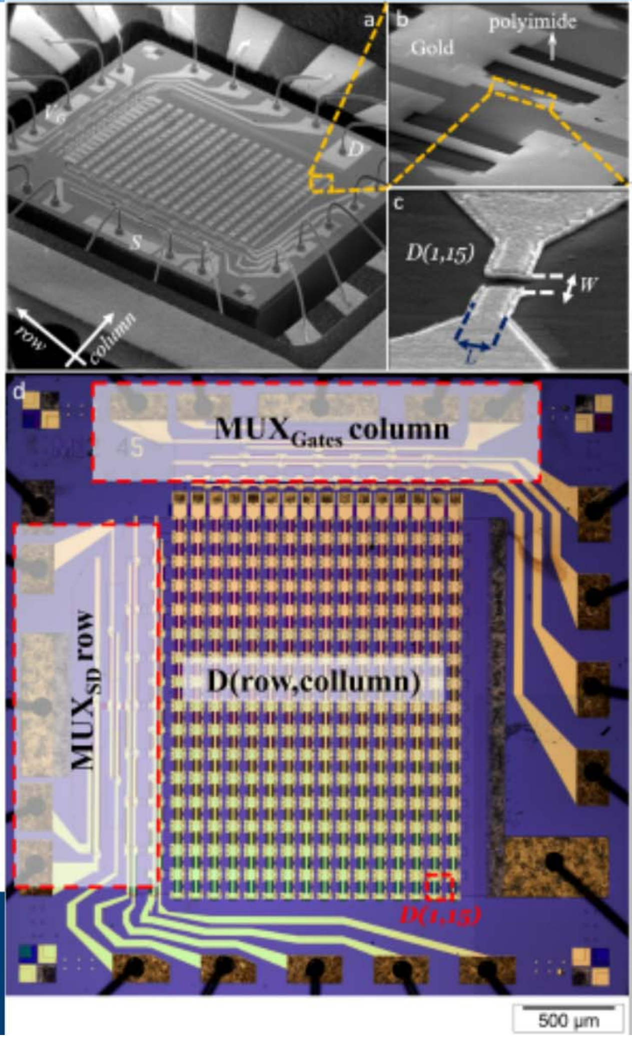
Low temperature multiplexer for scaling up quantum devices

Charles smith

Cryogenic on-chip multiplexer for the study of quantum transport in 256 split-gate devices





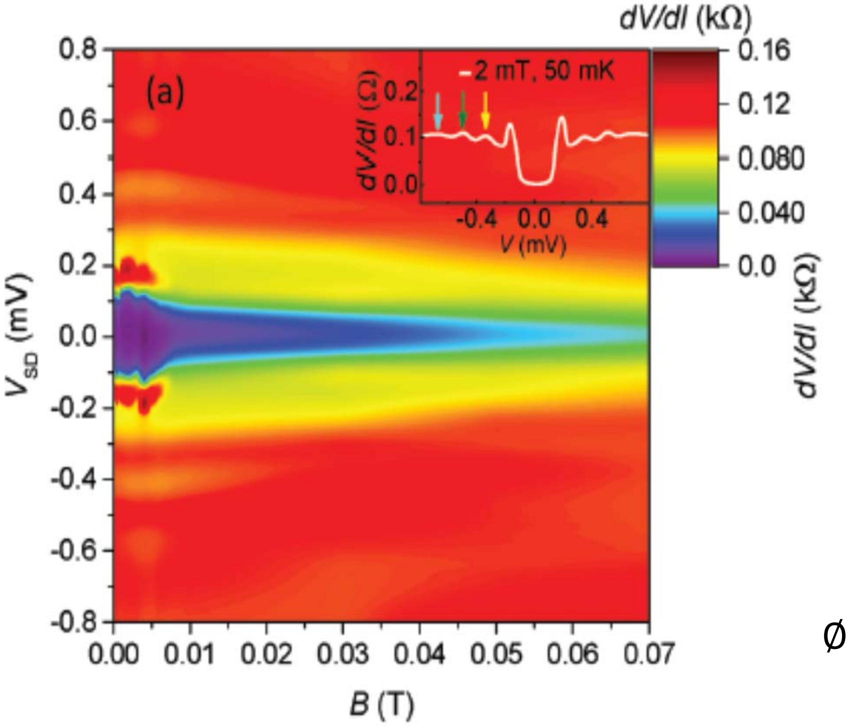


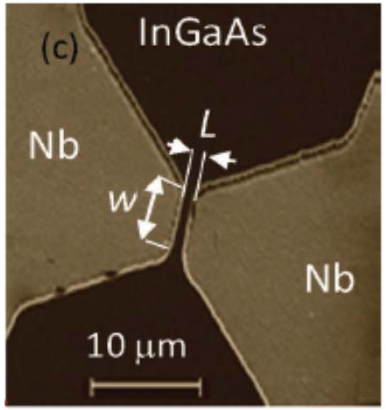
L. W. Smith *et al* Phys. Rev. B **90**, 045426 (2014)
LW Smith, et al. Phys. Rev. App. 5 (4), 044015 (2016)

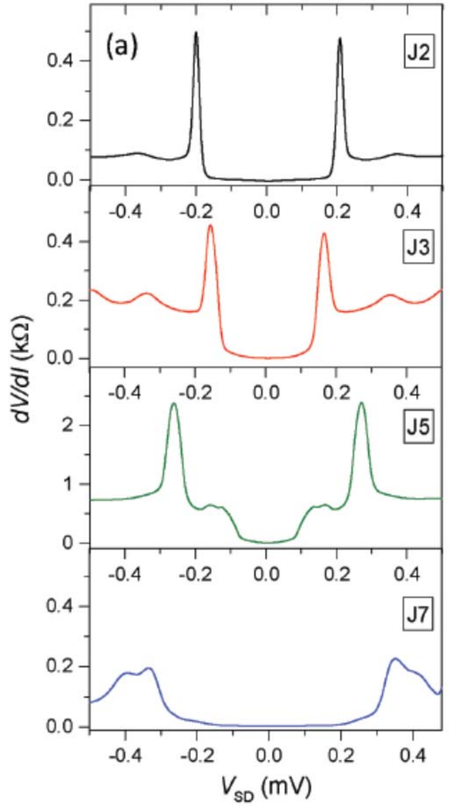
Magnetic field dependence induced superconductivity hybrid semiconducting superconducting nano-devices- towards Majorana

Charles Smith

K. Delfanazari et al *Advanced Materials*, 2017, 1701836







$$\emptyset = \frac{h}{e}$$

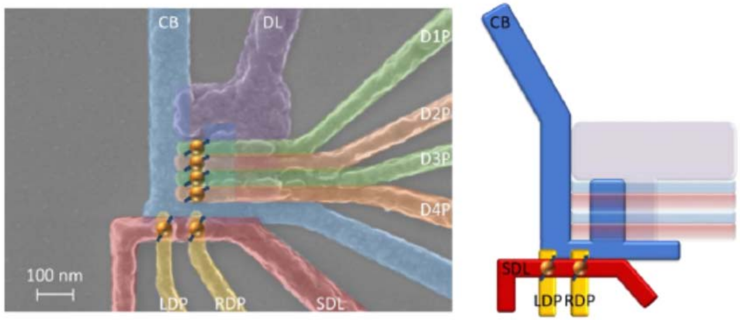
$\Delta B \approx 0.8$ mT

$A = \Delta\Phi/\Delta B \approx 2.5\ \mu m^2$

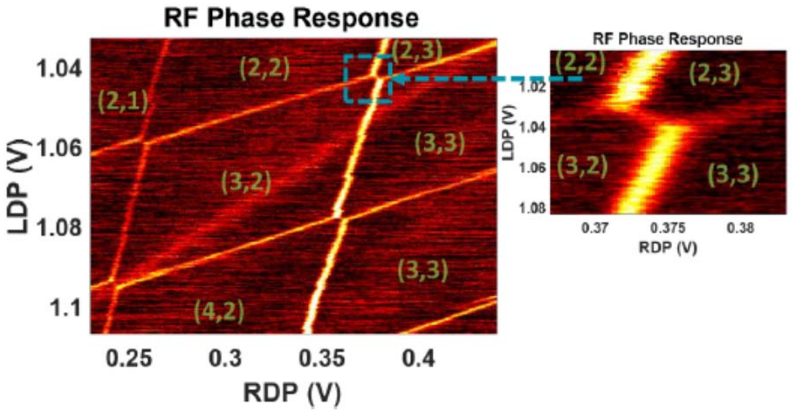
Estimated area A = 3.6 μm^2

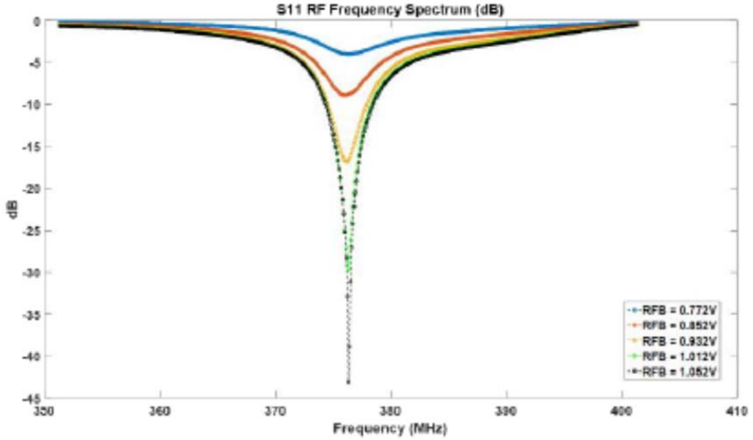
Silicon QUBIT double quantum dot with tuning (Collaboration with UNSW)

Charles smith



Figu





C.M. Cheng* , C.H. Yang**, J.C.C. Hwang**, M. Veldhorst**, F.E. Hudson** , K.M. Itoh***, A.S Dzurak** and C.G Smith*

Quantum Sensors Group at the Cavendish Laboratory

Stafford Withington

Physics of extreme measurement:

- Tackling demanding problems in *ultra-low-noise* measurement for fundamental physics
- Astronomy and atmospheric science
- Ground-based and space-based applications
- *Moving into* Quantum computing and communications
- Develop and deploy both research-grade and science grade technologies
- Good facilities for modelling, manufacturing and testing (65 mK – 4 K) ultra-low-noise microwave, THz, FIR, optical and x-ray devices
- Extensive capability in device modelling, test and characterisation

Thin-film superconducting materials science and UHV device processing: repertoire includes

Nb, Ta, β-Ta, Al, NbN, TiN, NbTiN, Mo, Hf, Ir, Cu, Au, AuCu, AuPd, SiO_2 SiO

Quantum Sensors Group at the Cavendish Laboratory

Stafford Withington

Example, we are the preferred supplier for superconducting focal plane technology for SPICA: ESA-JAXA-NASA mission operating at Lagrange Point L2

- Cooled primary telescope (~3 K) to eliminate thermal radiation from mirror
- SAFARI grating / Fourier-transform spectrometers
- L-band 210-110 µm, M-band 110-60 µm, S-band 60-34 µm imaging arrays
- Several thousand superconducting pixels operating at 50 mK
- Pixel NEP ~2×10^{-19} $\mathrm{WHz}^{-1/2}$
- Readout multiplexing also based entirely on superconducting electronics
- Currently working with Airbus to create a space-qualifiable technology

Quantum tech work

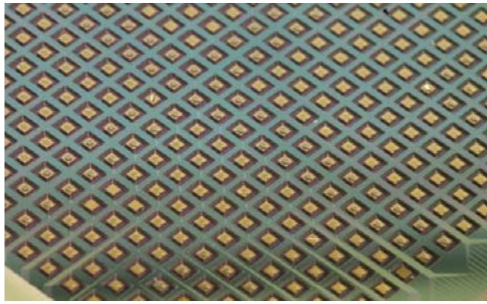
Stafford Withington

We study a wide range of device types:

- TESs, KIDs, SIS mixers, SQUIDs, superconducting resonators, superconducting parametric amplifiers
- Lab-on-a-chip type devices – conductance, heat capacity, NMR
- Ultra-low-noise amplification
- High functionality - single chip submillimetre-wave spectrometers for Earth Observation (ice-cloud monitoring)
- Optical and x-ray time-resolved optical photon counting

This includes the development of measurement and characterisation techniques

A major strength is that the modelling–fabrication-test cycle all takes place in house

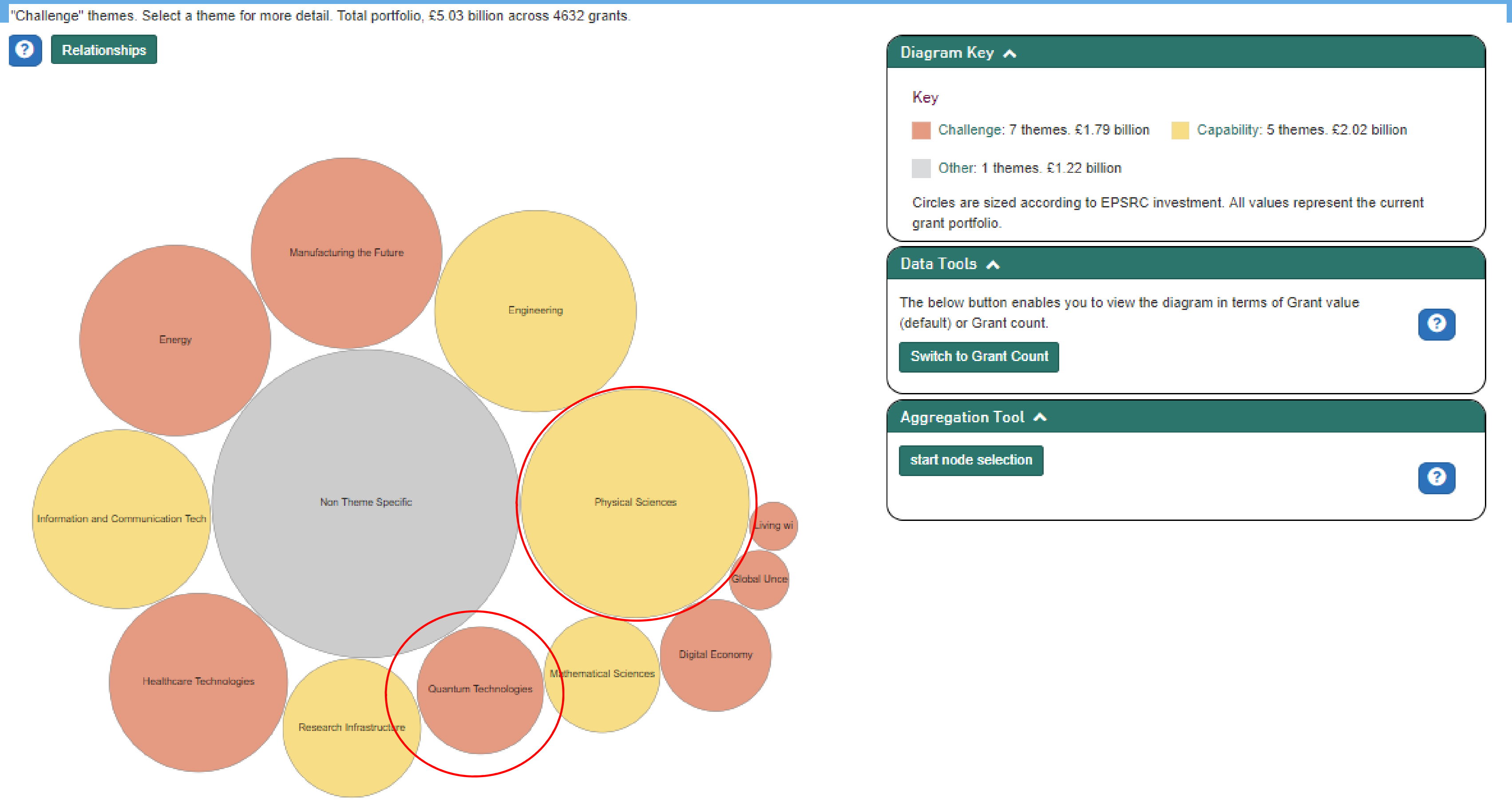


Equipment from Quantum Technology Initiative

New £700,000 UHV deposition system for superconductors and high quality barriers for quantum devices.

New dilution refrigerator (joint with Mete Atature)

EPSRC funding landscape, which ponds do we fish in



"Challenge" themes. Select a theme for more detail. Total portfolio, £5.03 billion across 4632 grants.

Key

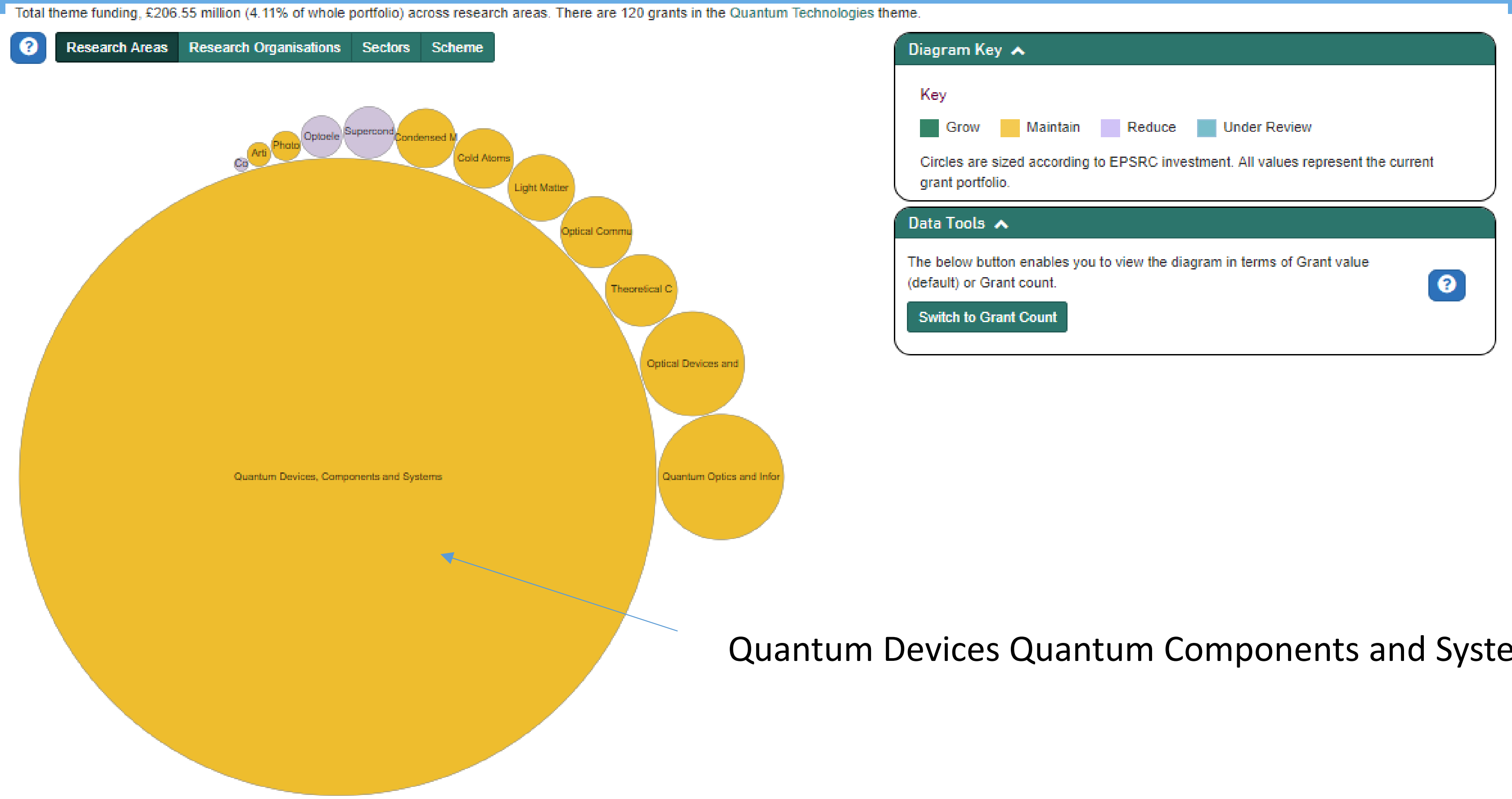
🟥 Challenge: 7 themes. £1.79 billion 🟨 Capability: 5 themes. £2.02 billion

⬜ Other: 1 themes. £1.22 billion

Circles are sized according to EPSRC investment. All values represent the current grant portfolio.

The below button enables you to view the diagram in terms of Grant value (default) or Grant count.

EPSRC quantum technology funding £207 Million


Total theme funding, £206.55 million (4.11% of whole portfolio) across research areas. There are 120 grants in the Quantum Technologies theme.

Key

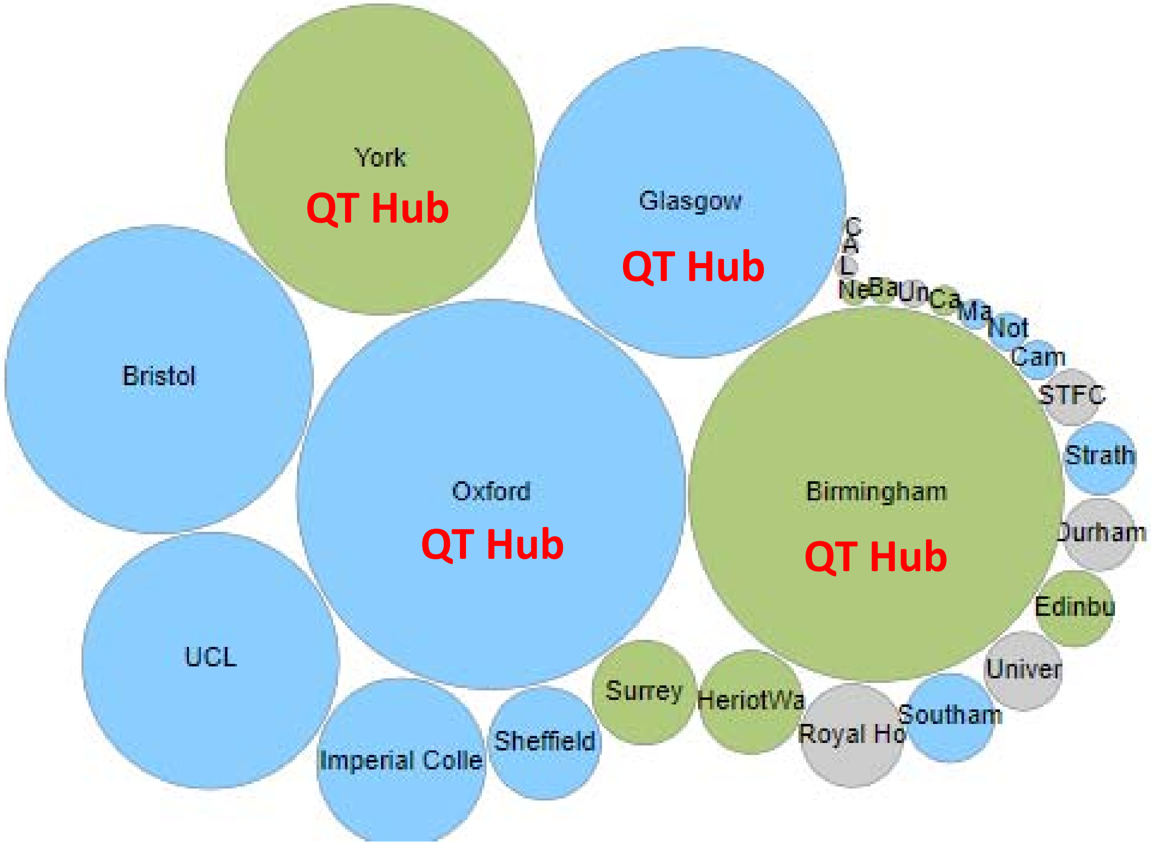
🟩 Grow 🟨 Maintain 🟪 Reduce 🟦 Under Review

Circles are sized according to EPSRC investment. All values represent the current grant portfolio.

The below button enables you to view the diagram in terms of Grant value (default) or Grant count.

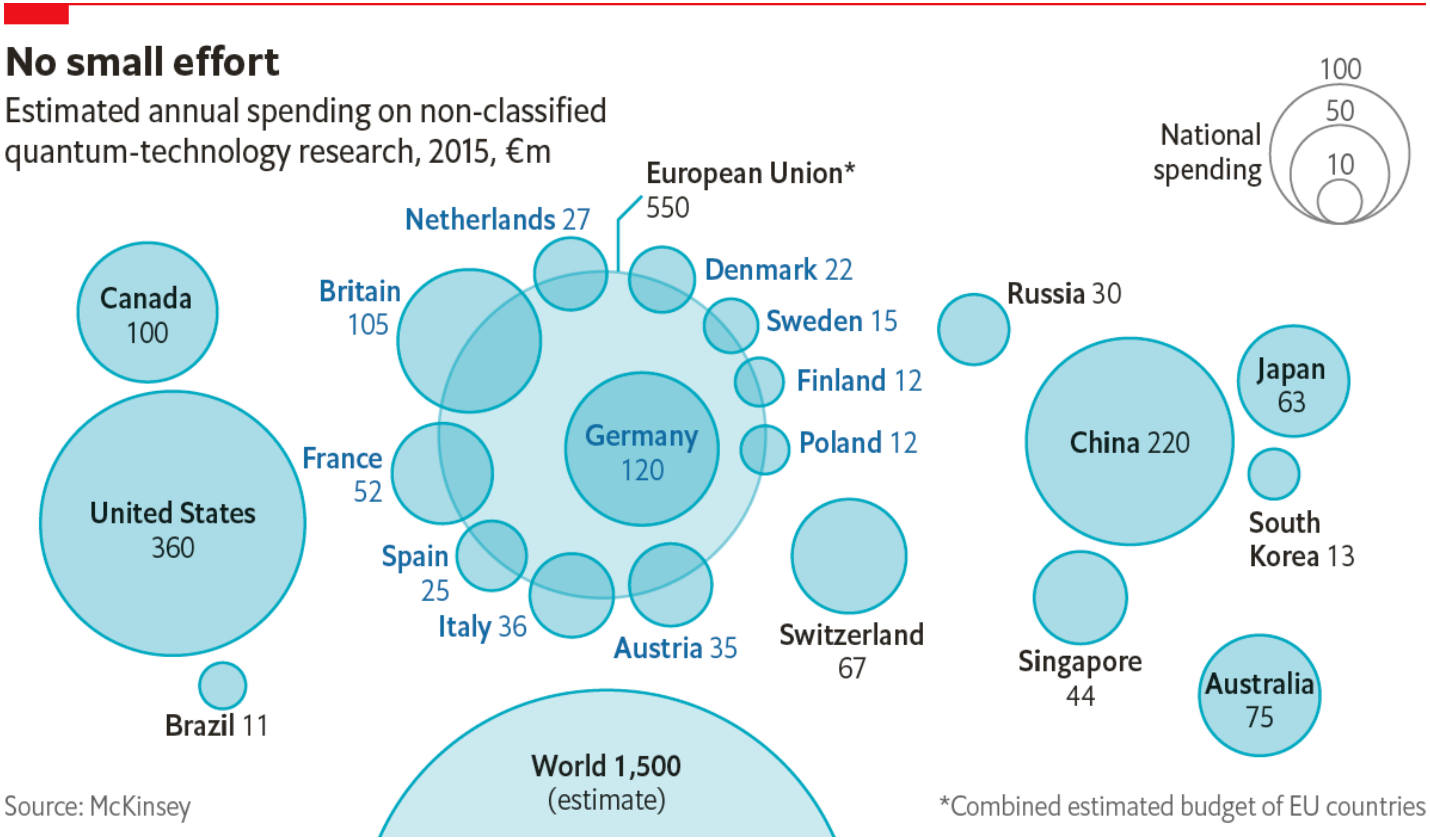
Quantum Devices Quantum Components and Systems

The cavendish does not have critical mass in quantum technology research



nbridge is way down the list
is actually doing better than this
nany Cis have funding from the quantum
s. Funding closer to £4 million (somewhere
ween Imperial College and Sheffield.

Economist estimate of Quantum technology spending world wide 2015 (probably double this now)



Source: McKinsey

*Combined estimated budget of EU countries

https://www.economist.com/news/essays/21717782-quantum-technology-beginning- come-its-own

IBM sees quantum computing going mainstream within five years

https://www.cnbc.com/amp/2018/03/30/ibm-sees-quantum-computing-going-mainstream-within-five-years.html?__twitter_impression=true

Jessa Tan, Special to CNBC.com
Published 12:14 AM ET Fri, 30
March 2018CNBC.com

HARRIET GREEN
CHAIRMAN & CEO, IBM, APAC

Infrastructure

Royce funding for new MBE growth of quantum materials (TI etc) 20 cells in two chambers

One of the best e-beam facilities in Europe

Clean room facilities

Wide range of cryostats working down to 10mK and with B fields up to 18 Tesla

Low temperature scanning probe systems (NV centres in Diamond, Scanning Capacitance, THz SNOM etc)

Atom and ion microscopes (Instrument development)

Thin-film superconducting materials science and UHV device processing: repertoire includes

Nb, Ta, β-Ta, Al, NbN, TiN, NbTiN, Mo, Hf, Ir, Cu, Au, AuCu, AuPd, SiO_2 SiO

Quantum Devices and Measurements theme

- This is a fast growing area of research in many leading physics departments around the world
- There is an opportunity for the Cavendish to bid into the increased levels of funding in quantum technology both from the EPSRC and the European Union
- Investing in a critical mass of researchers working in this field can allow an increase in funding for the department in this fast growing area
- We have a great deal of infrastructure that make would allow new hires to get up and running quickly