Quantum Sensors Fundamental Physics

J. Coleman

Thanks to QSFP Consortium, Shiela Rowan & Peter Knight for input on many of the slides

CALL: Quantum Technologies for Fundamental Physics

On 30 September STFC and EPSRC will open a research call for the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The call has total funding of c.£36m and will look to fund up to seven projects of £2m and above each (80% fEC). Requests for over £5m should contact the office before applying. The call will be for research consortia, i.e. joint proposals with a common research programme from groups of researchers in more than one organisation. Successful applications will require interdisciplinary research teams comprising researchers from both the fundamental physics and quantum technology communities.

The call's fundamental physics remit covers quantum science, astronomy, particle physics, particle astrophysics and nuclear physics. Applications to the call will be expected to show how quantum technologies will enhance or enable their research area of interest.

The call will be open to all individuals and organisations eligible for UKRI funding. PSREs are asked to contact the office to check if they are eligible. Grants will commence on 1 May 2020 and end no later than 30 September 2023. Successful projects will be expected to show tangible outcomes and results within the lifespan of the funding. The standard STFC/EPSRC expectation for Research Organisations to contribute to the cost of equipment at around the 50% level will apply.

Applicants will be required to complete an online Intention to Submit form on the STFC website by 31 October 2019 prior to submitting a full application. The closing date for full proposals will be 3 December 2019. Full details on the call, including the application process and assessment criteria, will be published on the STFC website.

Contact: Rachel Reynolds, QTFP Programme Manager, QTFP@stfc.ukri.org

https://stfc.ukri.org/funding/research-grants/funding-opportunities/quantum-technologies-for-fundamental-physics/

Quantum Sensors for Fundamental Physics

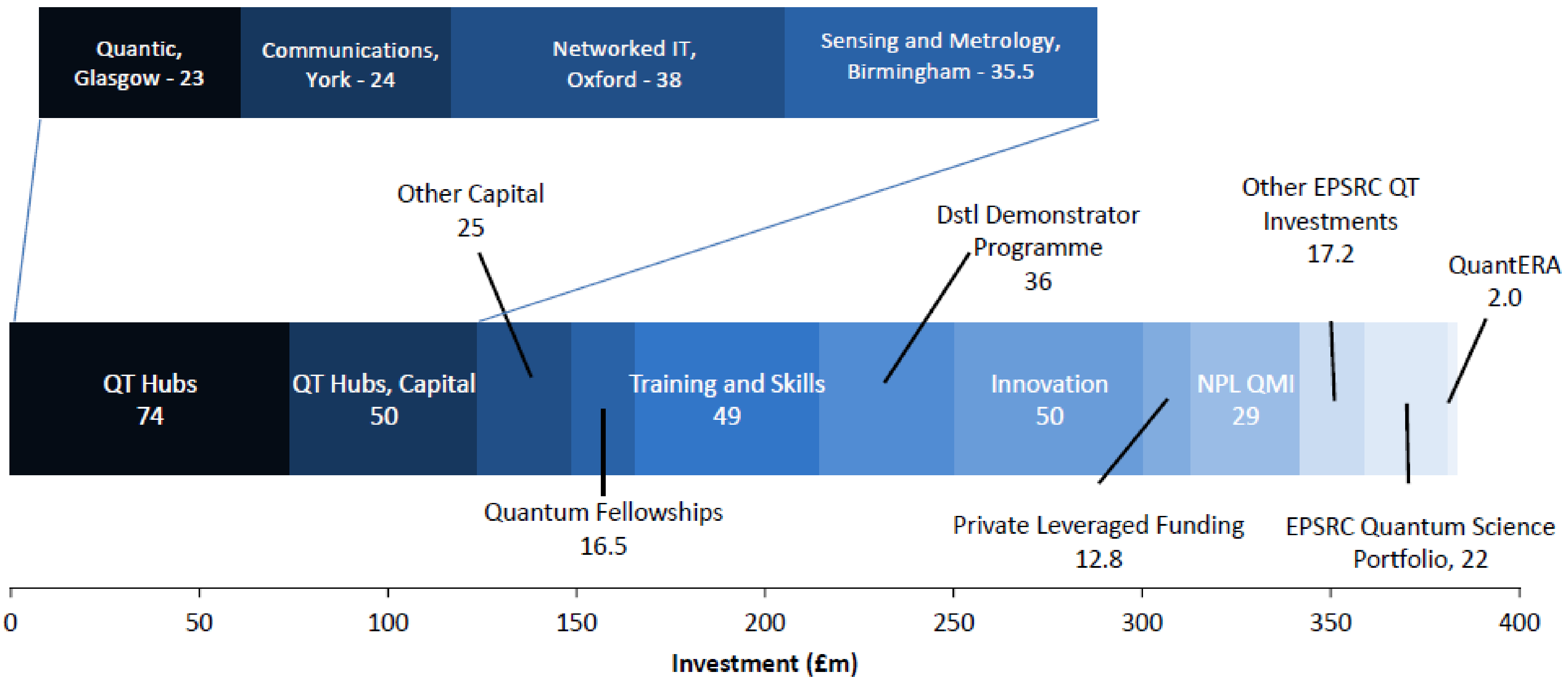
- Why is this good for all the partners?
- The exciting science will benefit all the partners involved: universities, labs & hubs
- Leverage the current Hubs to bring state of the art sensors to this new application.

  There will likely be a tension between performance and "manufacturability" but the Phase II Hubs should be able to deliver research to push performance, and additional support for user communities from STFC that could feed into and benefit from the Hubs activity
- This is a genuinely new *interdisciplinary* partnership between STFC, EPSRC and other partners
- - so plays well to the UKRI era.

Wide range of thoughts and deliverables

Physics Goals
Detector development
Deliverables
Theory
Plan
Competitiveness
Staff internal WP work allocation
Benefit to UK and UK Industry

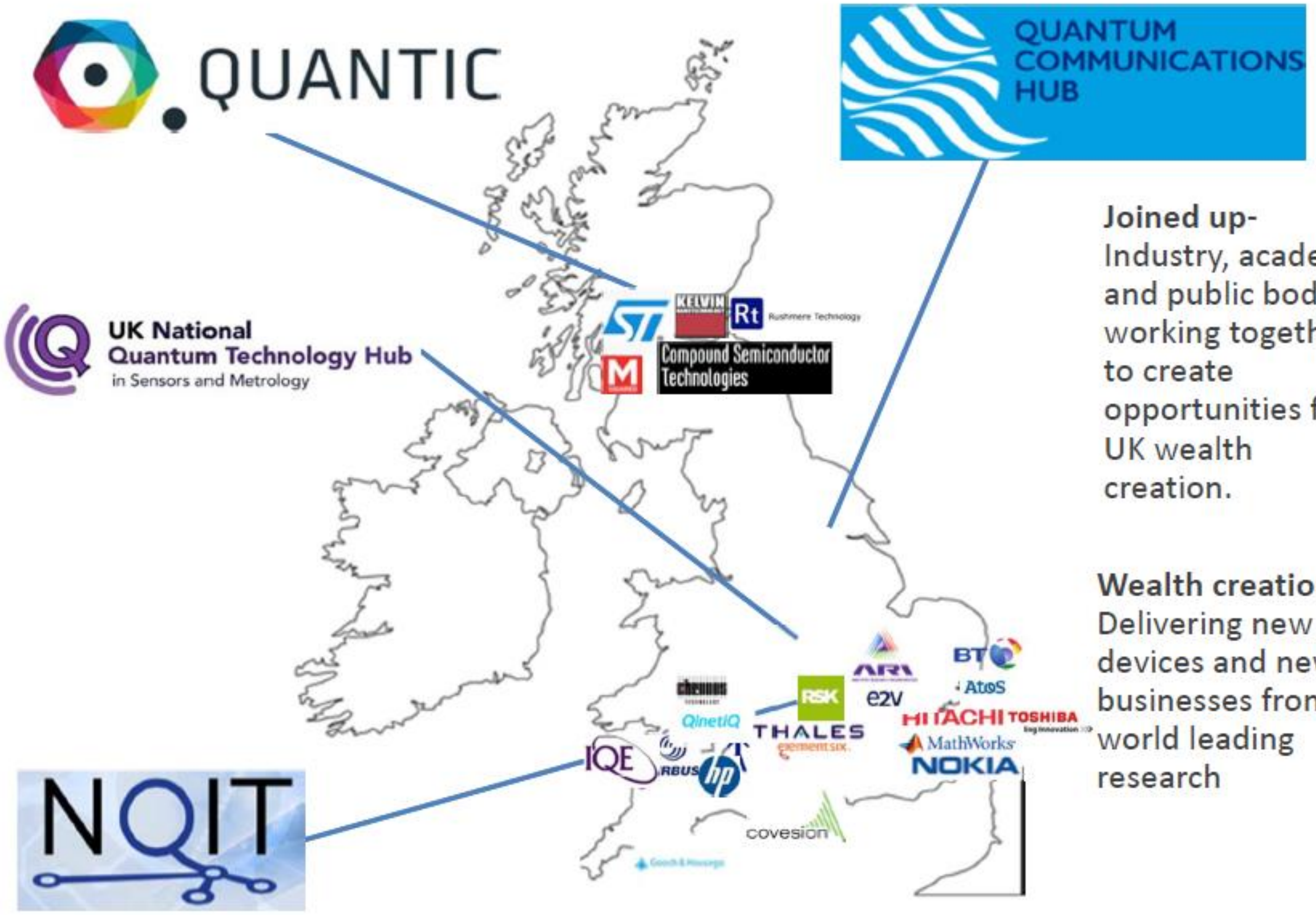
Quantum Research in the UK



Initial £270M investment over 5 years in 2013

The UK Quantum Technologies Eco-System

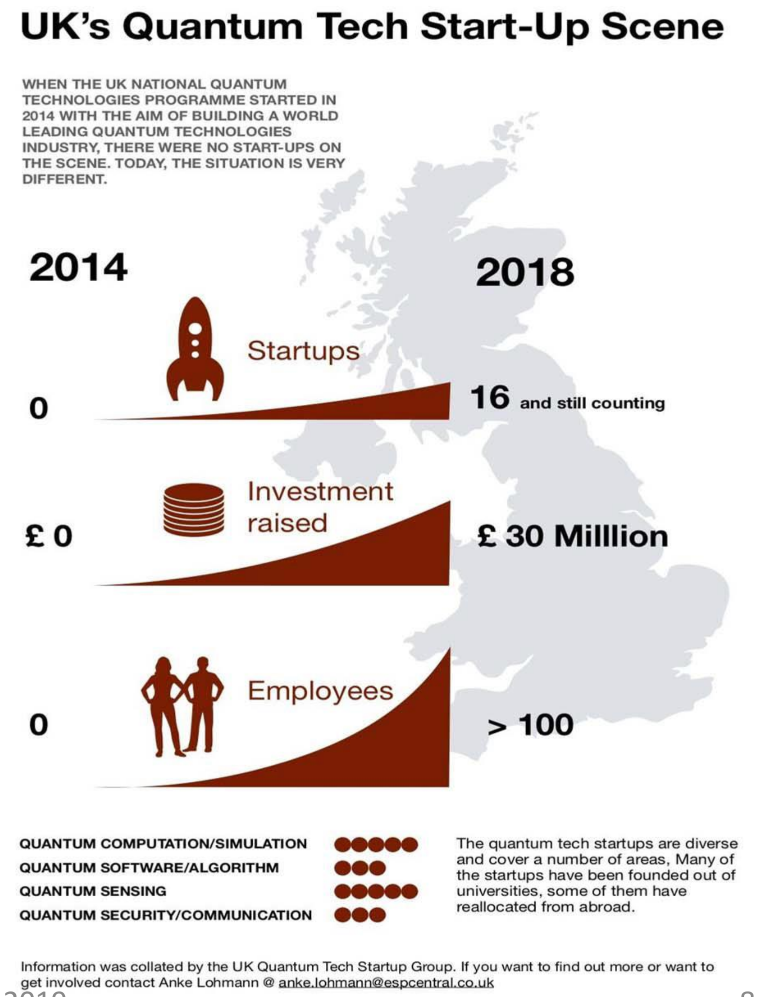
Long term - A 5 year programme with a 10 year vision.



Joined up-
Industry, academia and public bodies working together to create opportunities for UK wealth creation.

Wealth creation-
Delivering new devices and new businesses from world leading research

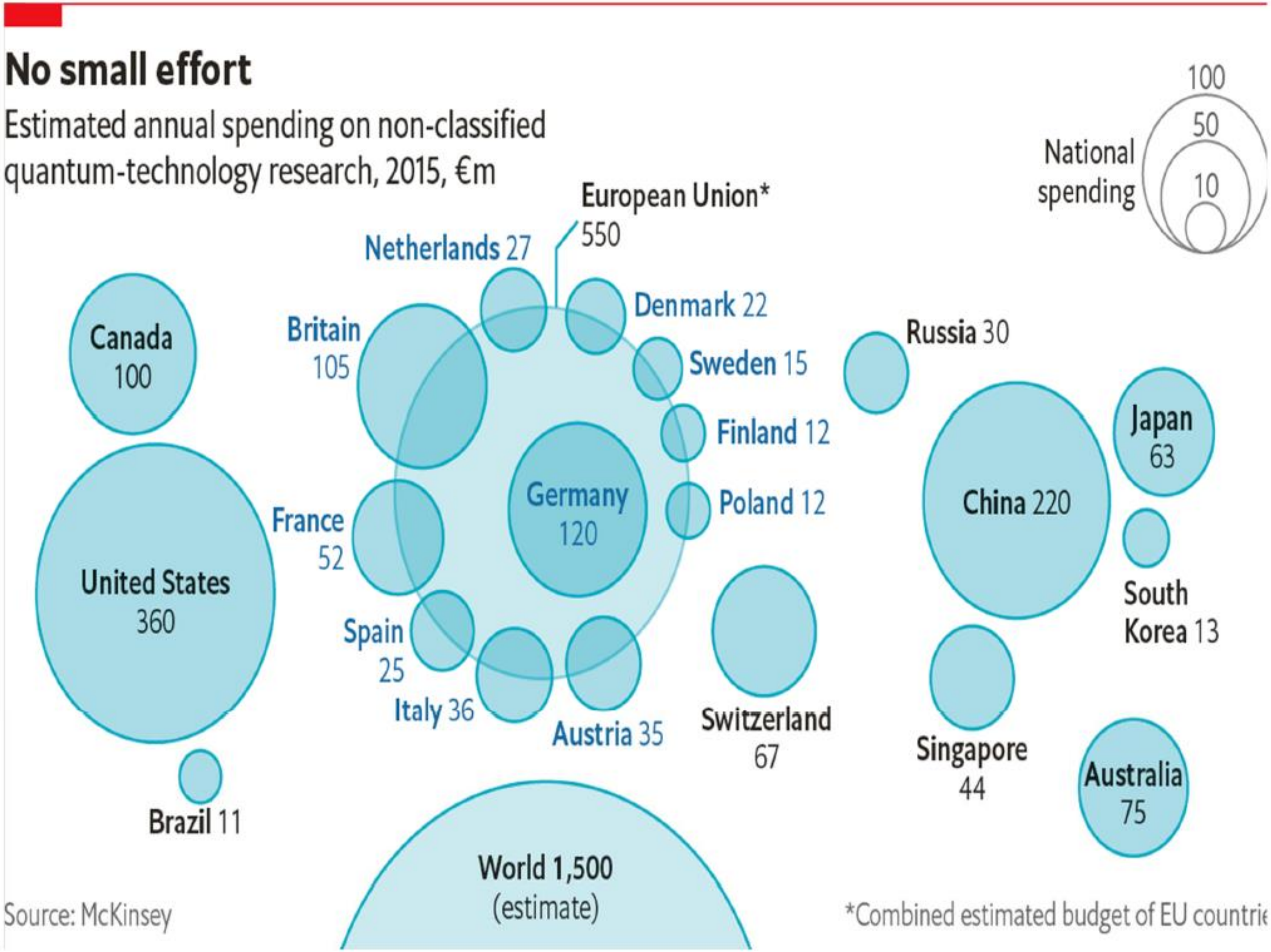
Translation activity: UK Quantum showcase and startups



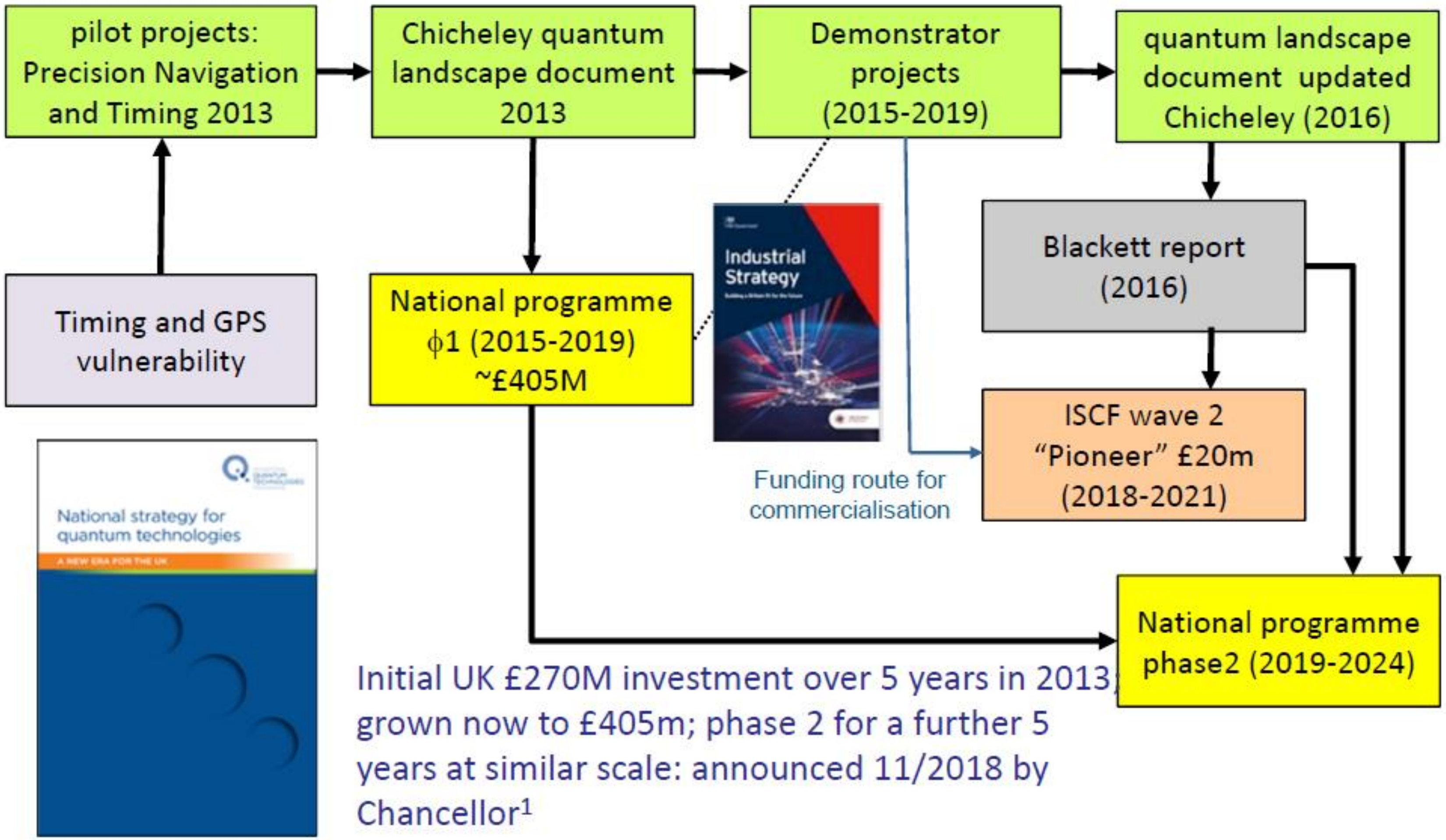
2018 UK developments: £355m

Hub refresh £80m for another 5 years & £15m capital

- £20m plus industry contribution on QT commercializationprojects starting now: total £67m; UK-Aus QT sensors collaboration DSTL-DSTG; UK-Canada collaboration
- House of Commons Science and Technology Select Committee support 6th December 2018
- Budget 2018 commitments:
  - Skills and fellowships: £67m
  - Singapore quantum cubesat £10m plus match
  - National Centre for Quantum Computing £75m
  - Industrial Strategy Challenge Fund £70m for 2019-2021


No small effort
Estimated annual spending on non-classified quantum-technology research, 2015, €m
National spending
100
50
10
European Union* 550
Netherlands 27
Denmark 22
Sweden 15
Finland 12
Poland 12
Britain 105
France 52
Germany 120
Spain 25
Italy 36
Austria 35
Canada 100
United States 360
Brazil 11
Russia 30
China 220
Japan 63
South Korea 13
Switzerland 67
Singapore 44
Australia 75
World 1,500 (estimate)
Source: McKinsey
*Combined estimated budget of EU countrie

UK Quantum technology investment plan



Initial UK £270M investment over 5 years in 2013; grown now to £405m; phase 2 for a further 5 years at similar scale: announced 11/2018 by Chancellor[1]

1 https://www.gov.uk/government/news/new-funding-puts-uk-at-the-forefront-of-cutting-edge-quantum-technologies

Worldwide quantum technologies activities

Current/planned Quantum Tech investments exceed $15bn

£400M
UK National QT Programme

$2.4bn
US QT Programme

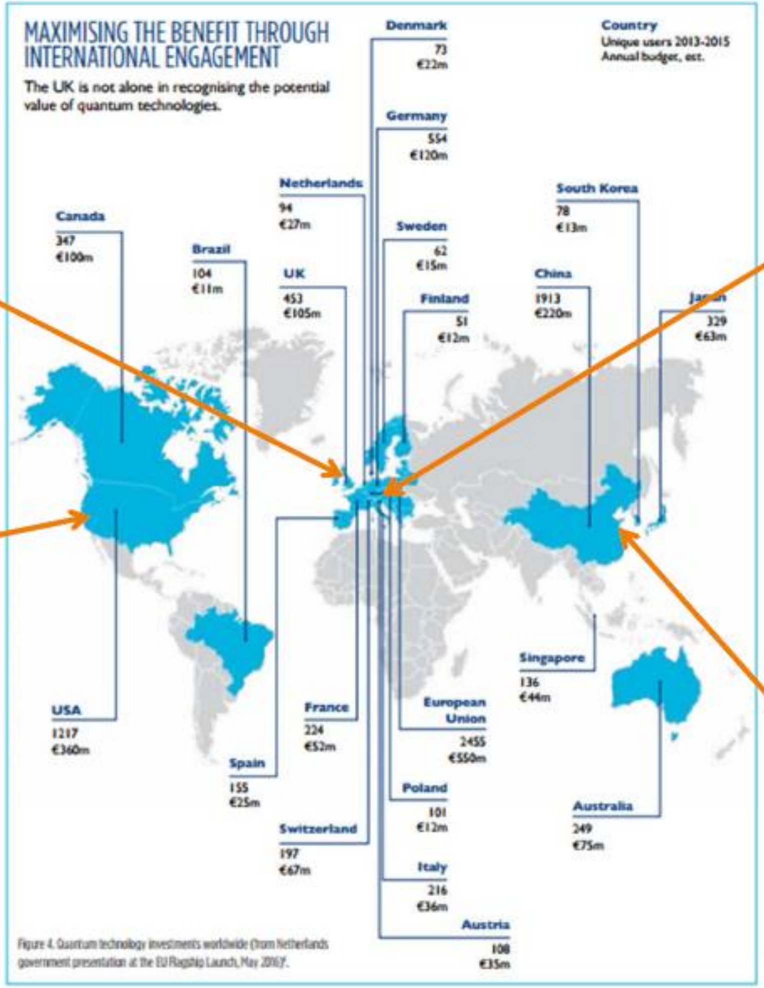


Figure 4. Quantum technology investments worldwide (from Netherlands government presentation at the EU Flagship Launch, May 2016)[*].

€1bn
Quantum Technology Flagship

$10bn
National Laboratory for Quantum Information Science

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

H. R. 6227

(Bill Passed Dec 2018)

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

National Quantum Initiative Act

This bill directs the President to implement a National Quantum Initiative Program to, among other things, establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications.

The bill defines "quantum information science“ as the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics.

The National Science and Technology Council shall establish a Subcommittee on Quantum Information Science, including membership from the National Institute of Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA), to guide program activities.

The President must establish a National Quantum Initiative Advisory Committee to advise the President and subcommittee on quantum information science and technology research and development.

NIST shall carry out specified quantum science activities and convene a workshop to discuss the development of a quantum information science and technology industry.

The National Science Foundation shall: carry out a basic research and education program on quantum information science and engineering, and award grants for the establishment of Multidisciplinary Centers for Quantum Research and Education.

The Department of Energy (DOE) shall carry out a basic research program on quantum information science. The Office of Science of DOE shall establish and operate National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology.

QSFP Opportunities Funding from STFC

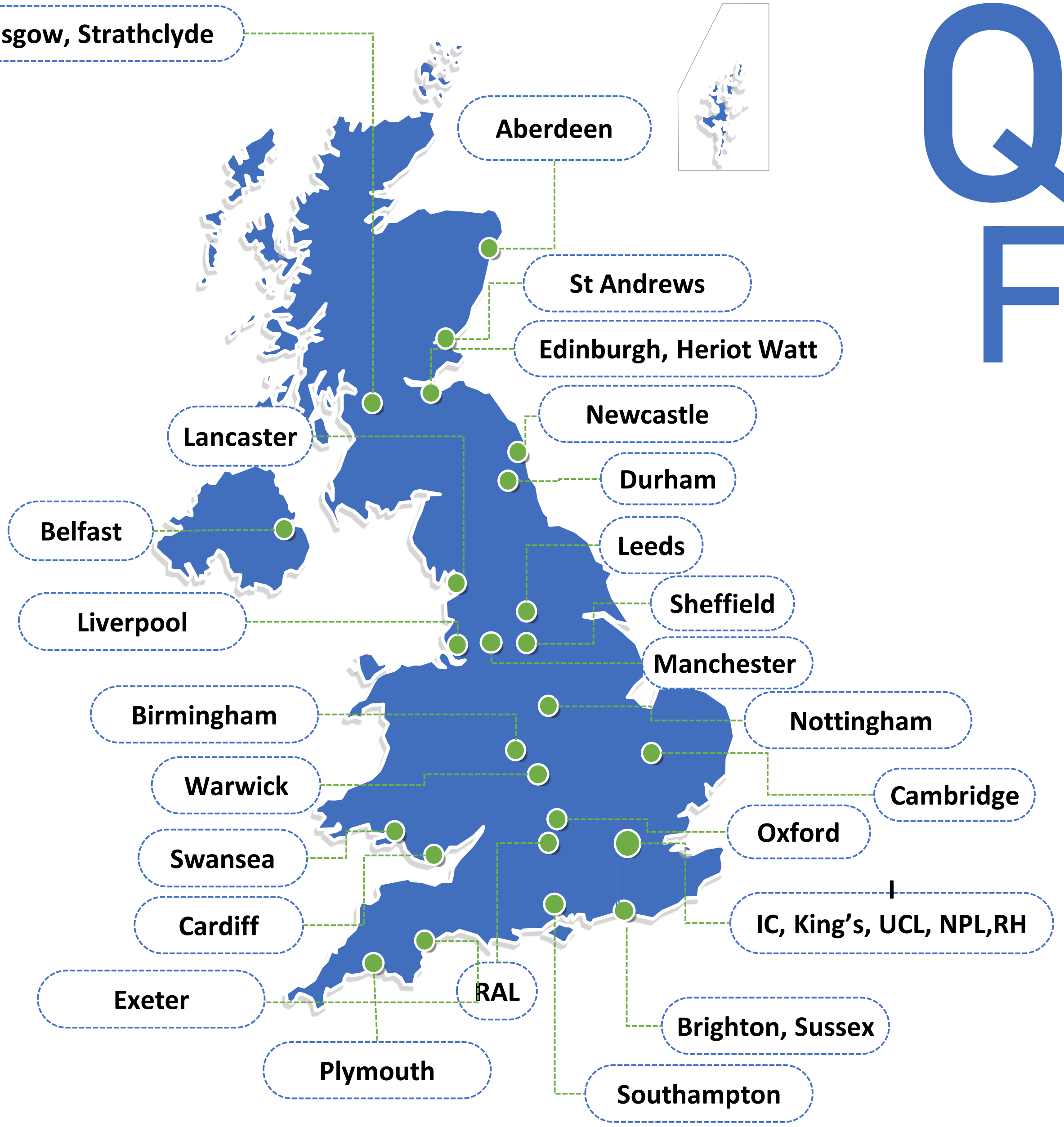
was awarded to build a community and consortium to prepare for the call. Supporting workshops that facilitate formation of teams and proposals around key experiments that would be funded by QSFP.

Workpackage Summary

1. Hidden Sector Facility
2. Macroscopic Superposition
3. AION
4. Neutrino Mass
5. Simulators
6. Networked Sensors
7. 5^{th} Force & Dark Matter
8. Exotic Atoms
9. Lorentz Invariance
10. Collective quantum excitations - new

UK

- 32 institutes
- Multiple companies
- Scientists....



		WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	WP9
Aberdeen	1									
Belfast	1									
Birmingham	3									
Brighton	1									
Cambridge	5									
Cardiff	1									
Durham	2									
Edinburgh	1									
Glasgow	2									
Heriot Watt	1									
Imperial	3									
Kings	2									
Lancaster	1									
Leeds	1									
Liverpool	3									
Manchester	1									
Newcastle	1									
Nottingham	3									
NPL	4									
Oxford	4									
Plymouth	1									
RAL	1									
RH	2									
Sheffield	1									
Southampton	1									
St Andrews	1									
Strathclyde	2									
Sussex	4									
Swansea	2									
UCL	6									
Warwick	2									
		11	15	7	5	7	8	3	4	3

WP1: Quantum Sensors for Hidden Sector Physics

Decided not to focus on building a specific instrument during the first phase of the project

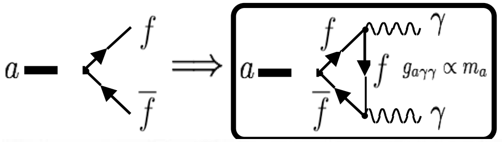
Yr 1-2: Build the team and institutional interfaces. Develop an optimised science case

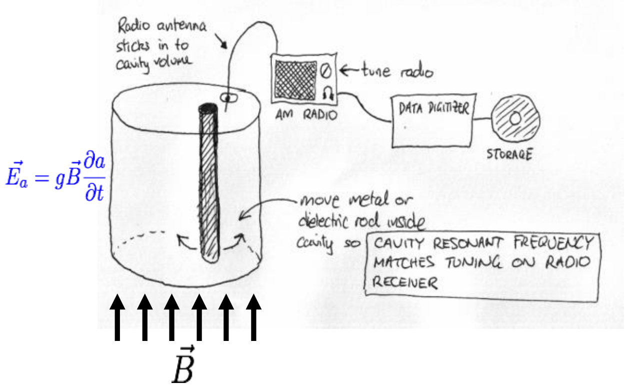
Yr 2-3: Component technology development - superconducting electronics, etc.

Yr 3: Complete end-to-end signal-chain demonstrations through pathfinder – early science

Conceptual design study of national facility. Submit a comprehensive proposal.

Axions





UK Idea Improve hidden sector searches with feedback resonators arXiv:1805.11523.

WP2: Macroscopic quantum superpositions for physics beyond the standard model

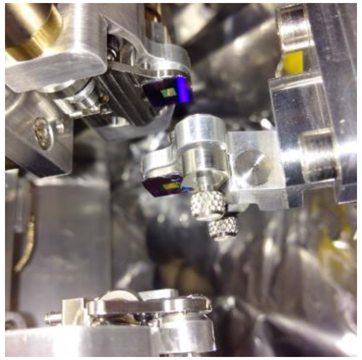
Subpackage 1: Silica spheres
Subpackage 2: Diamonds NV^- centres
Subpackage 3: Clamped oscillators
Subpackage 4: Theory

Simulate the proposed experiments
Dark matter and neutrino detection
Short-range force tests
Relativistic effects
Non-equilibrium mesoscopic quantum mechanics
Gravitational wave detection

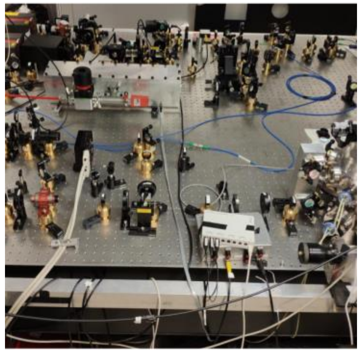
Strengths:

Results come with/without spontaneous collapse
Leverages investment in three QT Hubs
Many years of work by us to propose this work
Community already working together

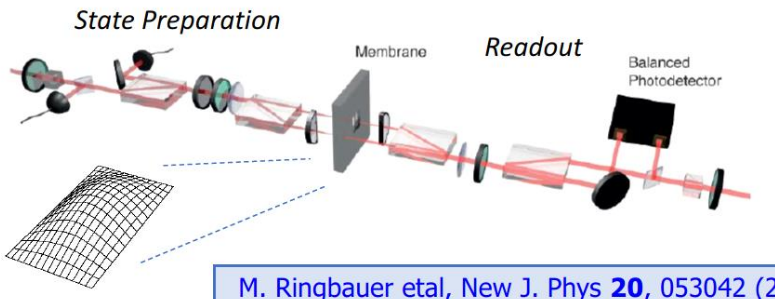
sp1



sp2



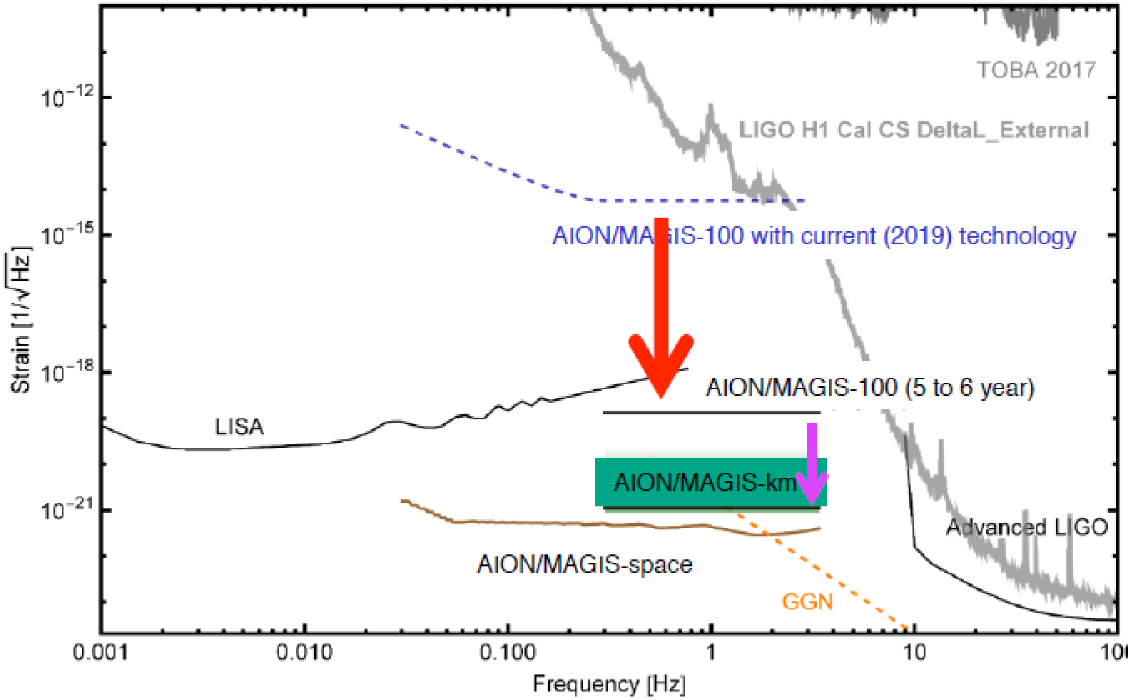
sp3



M. Ringbauer etal, New J. Phys **20**, 053042 (2

WP3: AION

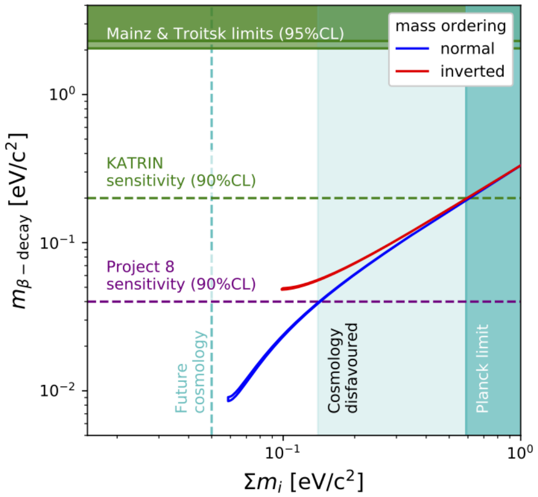
- Atomic Interferometric Observatory Network (AION) in the UK
  - Ultralight (<1 eV) dark matter searches
  - gravitational waves in the mid-frequency band
- Networked with MAGIS
  - •a'la LIGO and VIRGO



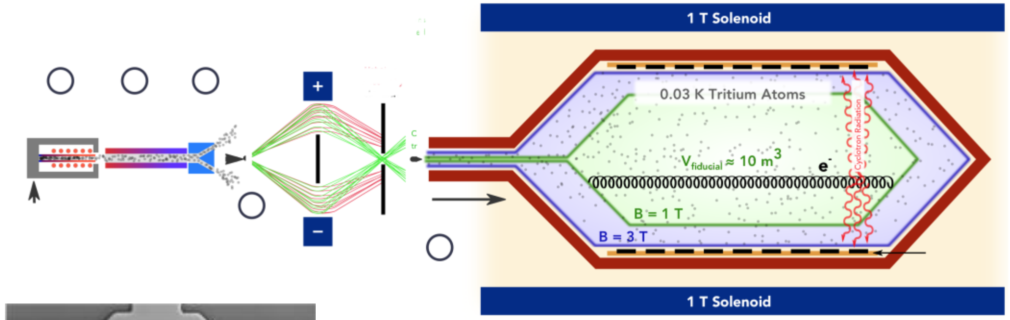
WG-Physics: Theory and Analysis
WG-AION-10: 10 m interferometer
WG-MAGIS: Collaboration with the Fermilab program
WG-AION-100: Site Planning & Preparation
WG-AION-Upgrades: reaching the ultimate sensitivity

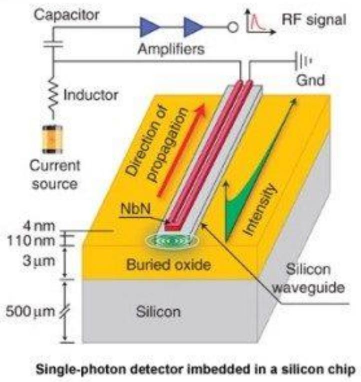
WP4: Quantum Sensors for Neutrino Mass

Guaranteed observation
Deliverable: trapping 10^{20} D/T atoms
Cyclotron Radiation Emission Spectroscopy
Beyond Bolometers (det. dev.)

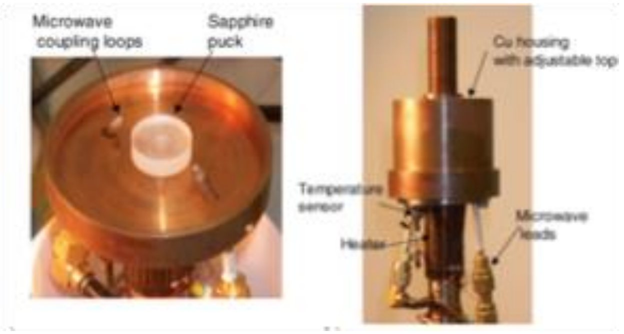


Sensitivity to
9mev





Single-photon detector imbedded in a silicon chip



Nanowire bolometers

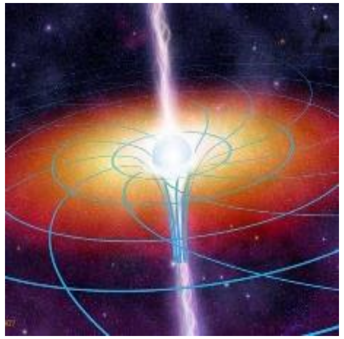
WP5: Quantum Simulators of Fundamental Physics

Deeping our understanding of dynamics of the early universe and black holes

Bose-Einstein Condensates, superfluid Helium and optical systems.

2-component Bose-Einstein cond. in 2D box trap: under development (Cambridge)

Superfluid Helium 4 bathtub vortex flow (Nottingham, UK). Proof of principle under construction.



Black holes

Space-time

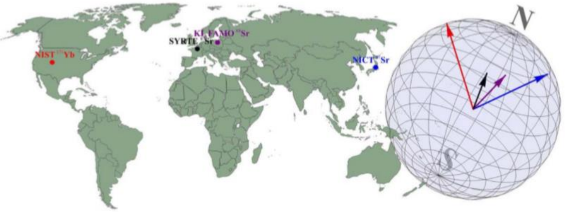
Vacuum

Our approach: to study these processes in theory & experiment in analogue quantum simulators

WP6: Networked Sensors

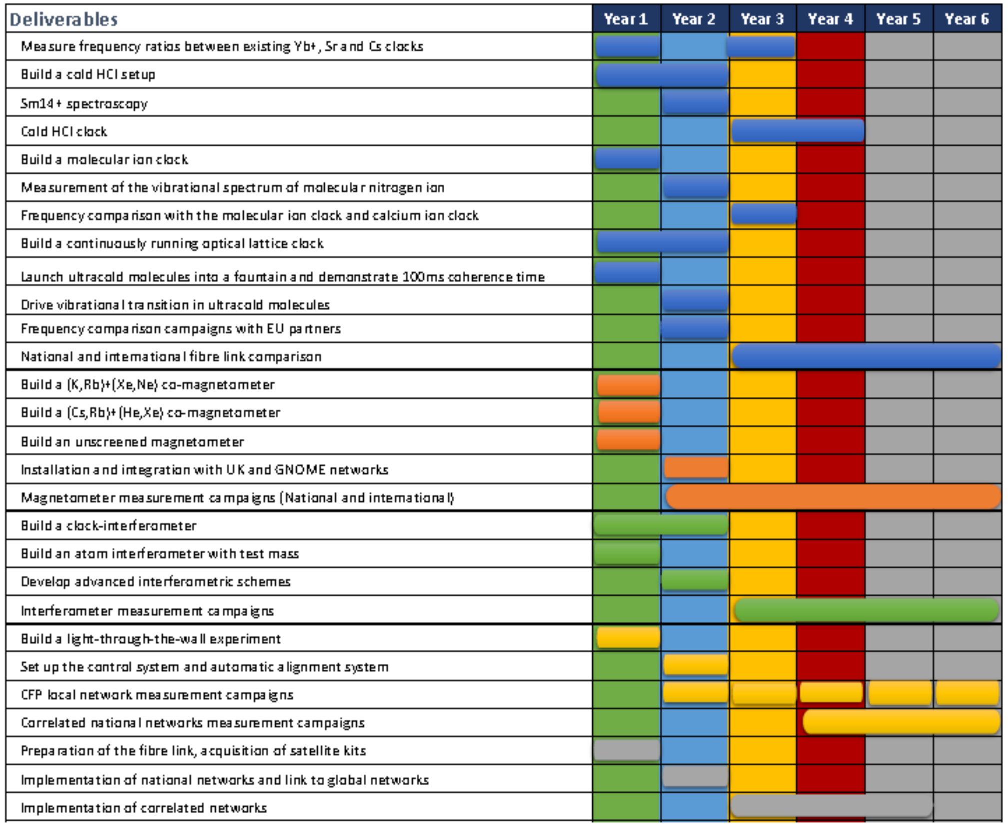
"Each node/element will deliver disruptive results in the search for variations in fundamental constants, Lorentz symmetry breaking, new forces, tests of the equivalence principle"

Magnetometers (GNOME)
[https://budker.uni-mainz.de/gnome/]



Optical atomic clocks
[Science Advances 4, eaau4869 (2018)]

"assemble a new tool" to enable completely new capabilities



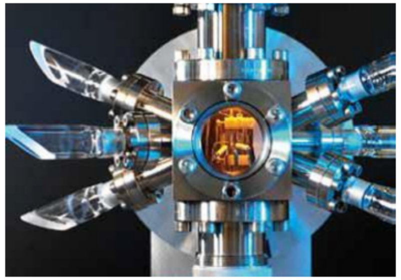
WP7: Searches for a Fifth Force and Dark Matter Using Precision Atomic Spectroscopy

$$Z\frac{\alpha}{r} \rightarrow Z\frac{\alpha}{r} + \frac{y_i y_j}{4\pi}\frac{e^{-m_\phi r}}{r}$$ **Yukawa potential**

WP7: Programme of Work (Years 1 – 3)

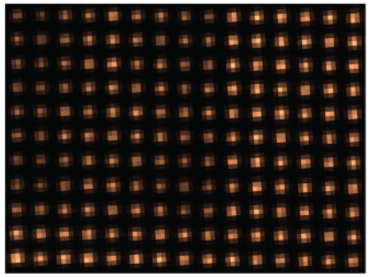
Experiments

Sussex (Keller)



Two Ca^+ ion clocks. Compare for isotope shifts

Durham (Jones/Adams)



Rydberg spectroscopy on Sr atom tweezer array

Durham (Carty/Jones/Adams)

Rydberg spectroscopy on ultracold H/D-atom fountain

Deliverabes

Sussex (Keller):

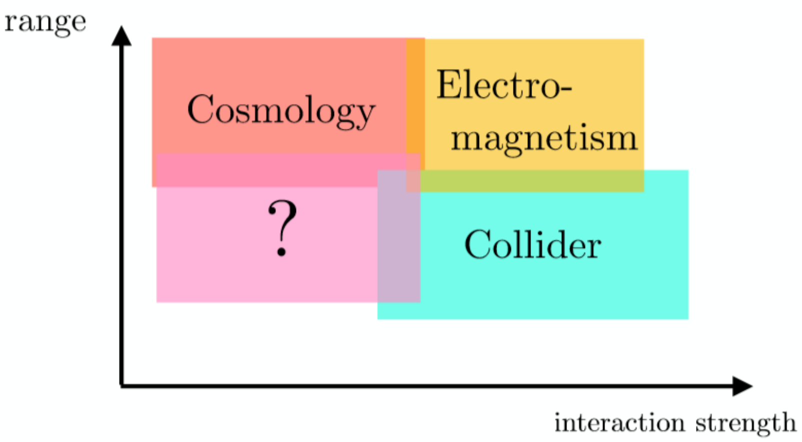
- A second Ca^+ ion clock.
- Measure relative isotope shift of the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ transition between $^{40}Ca^+$, $^{42}Ca^+$, $^{44}Ca^+$ and $^{48}Ca^+$ at Hz level.
- **Constraints within 3 years.**

Durham (Jones/Adams):

- Absolute frequencies of Sr Rydberg states, n = 35-100 with <1 kHz accuracy (>10^3 increase over state of art).
- Testbed for methods to control statistical and systematic errors for other experiments.
- **Constraints within**

Durham (Carty/Jones/Adams):

- Investigate H/D + Li collisions for sympathetic cooling H/D to μK.
- Develop set up for precision Rydberg spectroscopy of H/D atoms



WP8: Fundamental Physics with exotic atoms

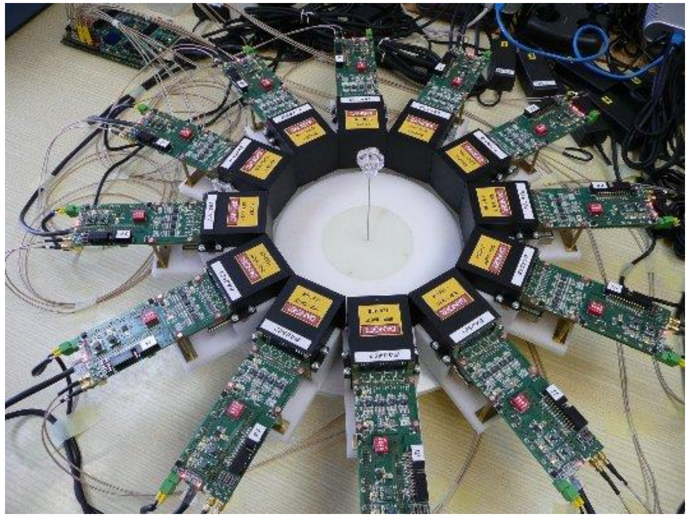
Antihydrogen

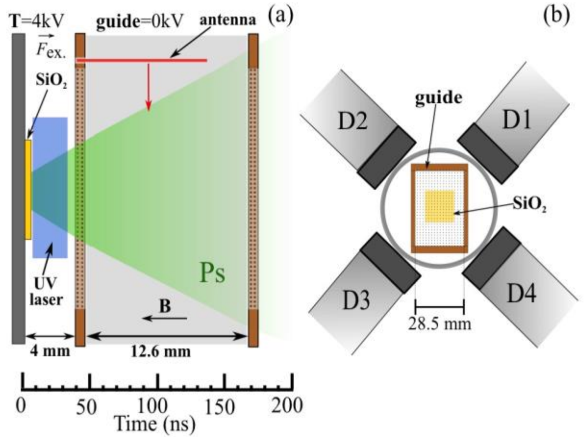
trapping efficiency will go up by an order of magnitude,

never been a better time to support this field

Positronium…

Production of slower focused beams [via Rydberg Stark deceleration/manipulation methods]
Construction of new detector(s)
Integration of Rydberg He spectroscopy into Ps experiments for high precision field characterization
Spectroscopic measurements of energy intervals and Rydberg constant
Demonstration of Rydberg Ps interference effects
“up or down” measurement of Ps gravity





New detector system for positronium

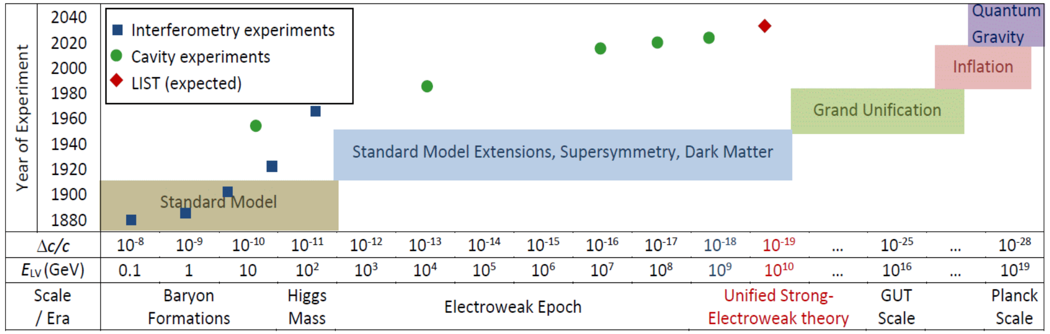
WP9: Lorentz invariance Space Test

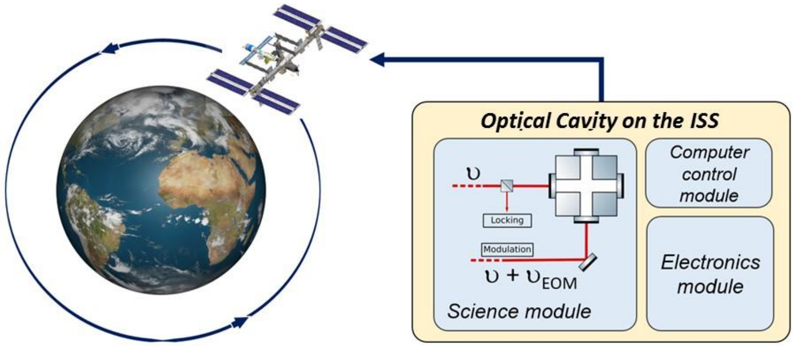
A Michelson-Morley-type of experiment in microgravity

LIST: 1st of kind

Earth-bound experiments limited

LIST aim is to **improve precision by an order of magnitude**



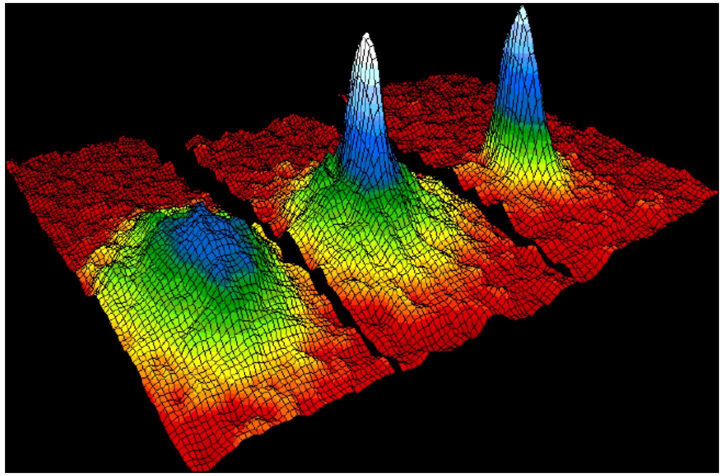


[k£]	Y1	Y2	Y3	Y4	Y5	Y6	SUM
Design & Build phase	1,403	1,939					3,341
Qualification & pre-Launch			926				926
Launch & Data analysis				296	216	206	718
TOTAL							4,985

WP10: Collective quantum excitations as quantum sensors

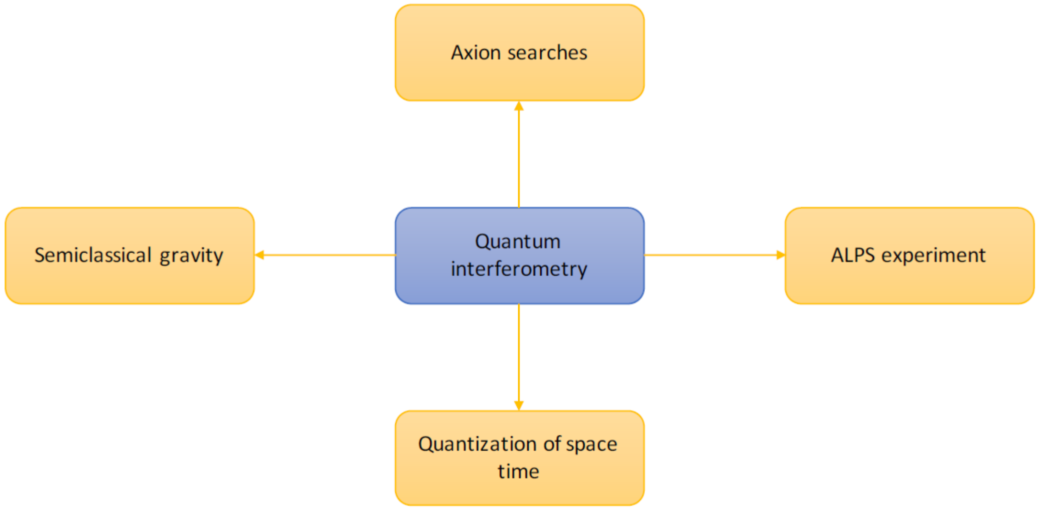
- screened scalar fields
- high-frequency gravitational waves
- gravimetery and gradiometery

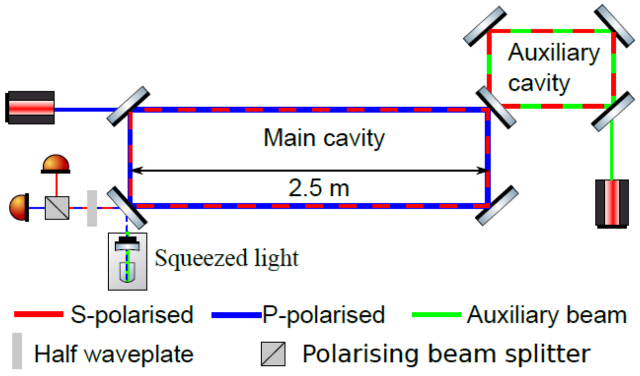
1. Phonic field measurement to provide info on the temp of system
2. quantum dots as temp sensors
3. Build a BEC with quantum dots inside

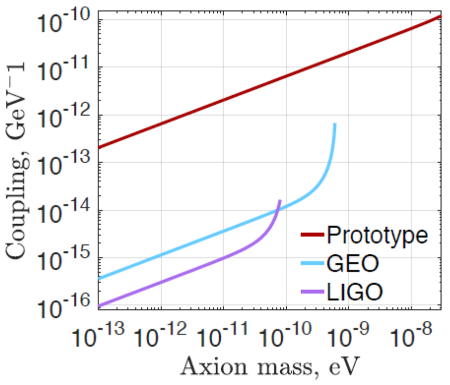


WP11: Quantum-enhanced Interferometry for New Physics

- three table-top experiments to search for
- (i) axion-like particles,
- (ii) quantization of space-time,
- (iii) semiclassical gravity, and
- (iv) to enhance the sensitivity of the Any-Light- Particle-Search (ALPS) detector using quantum technologies.







QSFP school 2020

- First QSFP school from Jan 6-10 in Durham
- The first school on Quantum Sensors for Fundamental Physics will cover the diverse and promising field of quantum technology applications to advance fundamental physics. Experts on the fundamental questions in physics today and on current and future quantum devices will present lectures to an audience of students, postdocs and senior members of both communities.
- 6 – 10 Jan 2020
- https://conference.ippp.dur.ac.uk/event/831/

Summary

- In the US the Quantum/Fundamental Science interface area acts as a major attractor for creative, original young experimentalists and theorists. We believe this will be true in the UK as well. The programme will be world-leading, and highly complementary to the US programme and those of other nations
- In this competitive area it is important to quickly develop the community that can launch the proposed programme. To do this expeditiously it will build on expertise, selected existing activities within the UK and exploitation of existing resources.
- As the EPSRC, STFC and Space communities come together, and working with the quantum hubs, and NPL and US partners we anticipate entirely new and exciting science will emerge.