Quantum Computing & Simulation Hub

International State of Quantum Information Technologies Research

Part 2: North America, Asia and Australia

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Publication Information

This is a publication from the **Quantum Computing & Simulation Hub,** an EPSRC funded collaboration of seventeen universities, bringing together academia and industry as part of the **UK National Quantum Technologies Programme.**

This report was authored by Christopher Noble, Dr Keith Norman and Adi Sheward-Himpson under the guidance of the QCS Hub Leadership team.

Acknowledgements

The authors would like to thank Dr Rupesh Srivastava for his invaluable help with the provision of data and preparation of this report.

Methodology

The report summarises grants and publications relating to QIT by country, using Clarivate's Web of Science. A standard search terminology was used here, and in subsequent sections of the report, as follows: `"quantum computing"` OR `"quantum computation"` OR `"quantum computer"` OR `"quantum error"` OR `"quantum circuit"` OR `"quantum simulation"` OR `"quantum architecture"` OR `"quantum compile"` OR `"quantum software"`.

Quantum Computing & Simulation Hub

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Contents

Introduction

Since we published part one of this report on international research in quantum computing, progress has continued at pace. More countries now have national programmes to support research in quantum technologies. More quantum startups have emerged, several of which have seen large investments, and some of which are starting to see revenue flow. More scientific papers have been published in both quantum hardware and software, with promising results. And there is increased involvement from industry, with interest from financial institutions, engineering firms, pharmaceuticals manufacturers, and other commercial organisations.

Many national governments are fully engaged with quantum technologies at a serious level, with support to research and to the burgeoning startup community. While many countries see a sovereign need to build their own quantum devices, national government support is also leading to increased cooperation between nations, with many scientific publications having authors from across borders, and many startups building a global presence.

The major platform providers are also continuing to make clear commitments to quantum technology, with an increasing number of quantum devices now available on the cloud. This enables wider industry to experiment with a variety of quantum hardware, and start to think about how quantum will change business models over the coming years.

As in last year's report on the state of quantum computing in the UK and Europe, I hope that this report on North America, Asia and Australia will be encouraging for those active in the field, and demonstrates the need to continue to invest at a national and global level. Please contact us if you would like further information.

Dominic

Professor Dominic O'Brien
Director, Quantum Computing and Simulation Hub

Australia

Australia has supported quantum engineering, science and technology for more than two decades, and has invested of the order of $1B since 2002 in quantum technologies. In May 2023 it launched a seven year National Quantum Strategy, with five themes:

1. Creating thriving research and development, investment in and use of quantum technologies
2. Securing access to essential quantum infrastructure and materials
3. Building a skilled and growing quantum workforce
4. Ensuring standards and frameworks support national interests
5. Building a trusted, ethical and inclusive quantum ecosystem

It has several national centres of excellence funded by the Australian Research Council that employ more than 500 scientists, running until 2024-2025. It has over twenty quantum startups – as one example, Quantum Brilliance has offices in Germany (Stuttgart) and recently integrated their device into the supercomputer centre at Pawsey (Australia).

Microsoft and Google have both made investments in quantum technology in Australia, specifically Microsoft in their Station Q programme, and Google in general technology, including AI and quantum computing.

There is also National and Regional Government investment to address quantum workforce and commercialization efforts. This includes the Sydney Quantum Academy and Quantum Commercialization Hub.

Australia's approach includes trusted collaborations with international partners, including AUKUS, Japan and India.

National Quantum Strategy: at a glance

Vision for Australia's quantum future

In 2030, Australia is recognised as a leader of the global quantum industry, and quantum technologies are integral to a prosperous, fair and inclusive Australia.

5 Themes

- A skilled and growing quantum workforce
- Thriving research and development, investment in and use of quantum technologies
- Access secured to essential quantum infrastructure and materials
- Standards and frameworks that support national interests
- A trusted, ethical and inclusive quantum ecosystem

Quantum Centres

There are several Australian Quantum Centres of Excellence, funded by the Australian Research Council.

Engineered Quantum Science (EQUS)

EQUS [1] is administered by the University of Queensland under the directorship of Professor Andrew White. It collaborates with several other Australian and international universities, with associations in Austria, Denmark, UK, France, Germany, Japan, Switzerland and the USA. EQUS aims to build sophisticated quantum machines to harness the quantum world for the future health, economy, environment and security of Australian society. It intends to pioneer the design of quantum materials and solve research problems at the interface of basic quantum physics and engineering.

Quantum Computation and Communication Technology (CQC2T)

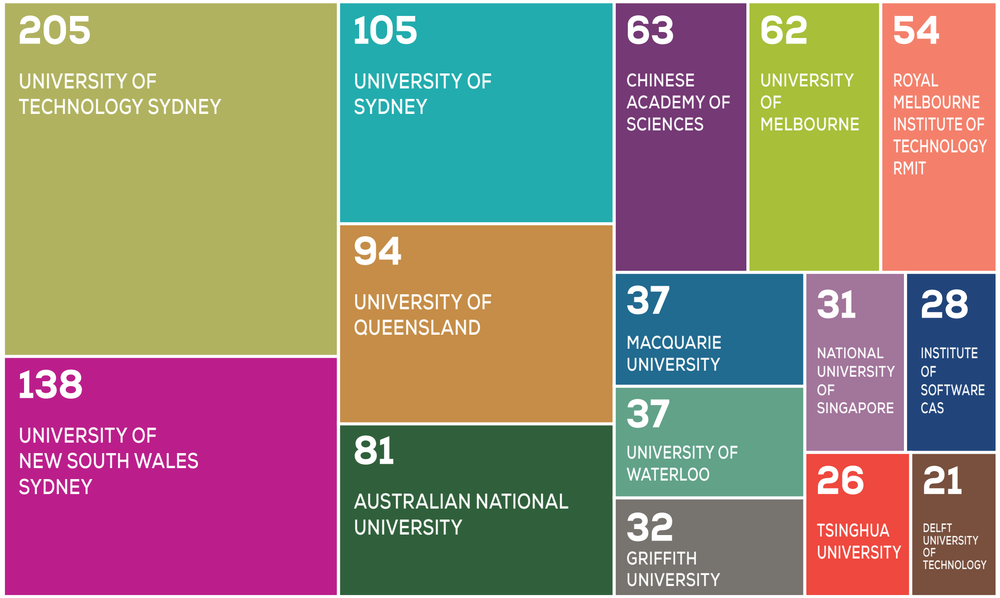
CQC2T [2] is administered by the University of New South Wales under the directorship for Professor Michelle Simmons. It also collaborates with several other Australian and many international universities, working with Belgium, Canada, UK, France, Germany, Japan, New Zealand, Singapore and the USA. CQC2T aims to implement quantum processors able to run error corrected algorithms and transfer information across networks with absolute security. The Centre has developed technologies for manipulating individual atoms and photons, with high-fidelity, long coherence time solid state qubits, the world's longest-lived quantum memory, and the ability to run small-scale algorithms on photonic qubits.

ARC Centre of Excellence in Quantum Biotechnology

The Centre of Excellence in Quantum Biotechnology [3] is administered by the University of Queensland, under the directorship of Professor Warwick Bowen. It has national and international collaborations with the USA, Germany, UK, Canada, Austria, Netherlands and France. It aims to develop quantum technologies to observe biological processes and transform the understanding of life. By building a diverse, multidisciplinary, industry-engaged ecosystem, the Centre means to develop future leaders at the interface of quantum science and biology, and drive Australian innovation across manufacturing, energy, agriculture, health, and national security.

Collaborations

We analysed papers published from 2018 onwards, with some or all the authors based in Australian institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.



723 papers from Australian authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	95
PHYSICAL REVIEW B	27
QUANTUM	26
IEEE TRANSACTIONS ON INFORMATION THEORY	25
PHYSICAL REVIEW LETTERS	25
NATURE COMMUNICATIONS	21
NEW JOURNAL OF PHYSICS	21
NPJ QUANTUM INFORMATION	21
PHYSICAL REVIEW RESEARCH	20
PRX QUANTUM	19

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 624 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Argentina	6
Australia	158
Austria	6
Belgium	1
Brazil	3
Canada	26
China	59
Czech Republic	3
Denmark	7
Finland	6
France	14
Germany	20
Hungary	1
Iceland	1
India	1

Country	Number of citations
Italy	17
Japan	18
Malaysia	1
Mexico	3
Netherlands	11
Poland	2
Russia	1
Singapore	1
Spain	39
Sweden	3
Switzerland	15
Thailand	1
UK	47
USA	153
Grand Total	**624**

The lead author's institutional country for these fifty papers is shown below.

Country	Number of papers
Australia	21
Canada	2
China	5
Finland	1
France	1
Germany	2
Italy	1
Japan	1
Netherlands	2
Spain	2
Switzerland	1
UK	6
USA	5
Grand Total	**50**

Canada

Canada has a long history in quantum technology. In 1984, Gilles Brassard at the Université de Montréal and Charles Bennett at IBM Research introduced the first scheme to encrypt information using the properties of quantum mechanics, and Brassard is known as Canada's 'father of quantum information' because of this work. An Institute of Quantum Computing (IQC) based at Waterloo (see Quantum Centres) was established in 2001, following a CA$150m donation by Mike Lazaridis, the founder of Blackberry. Between 2009-19, Canada invested more than CA$1bn in quantum technology [4]. It ranks first among the top 10 nations producing quantum scholarly outputs for the quality and impact of its quantum science [5].

In 2021, a budget of CA$360 million was announced to launch a National Quantum Strategy, and public consultations on the proposal began in July of that year, ultimately receiving over 240 responses [6]. The results of the consultations were published in 2022 [7]. In support of the strategy, a series of grants and investments from the Natural Sciences and Engineering Research Council of Canada (NSERC) were also announced in 2022, as detailed in the table below. NSERC had provided close to CA$384m in quantum research funding over the previous decade [8].

Name	Value (CA$)	Participants
CREATE	5.4m	Supporting efforts to develop, attract and retain top quantum talent in Canada through an annual competition. NSERC to fund at least three CREATE grants in quantum science and technology.
Alliance International Quantum	29.7m	Providing support for researchers in Canada to work with international researchers in the academic sector to establish and grow international research collaborations and projects in quantum science and technology.
Alliance Quantum	62.4m	Reinforce, coordinate and scale up Canada's domestic research capabilities in quantum science and technology through partnerships with organizations in the private, public and not-for-profit sectors.
Alliance Consortia Quantum	40.4m	Develop large-scale research collaborations and enable improved synergy across Canada's regional quantum research and innovation hubs, federal laboratories and other centres and stakeholders.

Canada's National Quantum Strategy was officially launched in January 2023. There are three core missions in the strategy, as shown in the figure below.

Mission: Quantum computers and software

The **Quantum Computers and Software mission** aims to make Canada a world leader in the continued development, deployment and use of quantum computing hardware and software to the benefit of Canadian industry, governments and citizens.

Mission: Quantum communications

The **Quantum Communications mission** intends to ensure the privacy and cyber-security of Canadians in a quantum-enabled world through a national secure quantum communications network and a post-quantum cryptography initiative.

Mission: Quantum sensors

The **Quantum Sensors mission** seeks to enable the Government of Canada and key industries to be developers and early adopters of new quantum sensing technologies.

Each of the missions are underpinned by three pillars – Research, Talent and Commercialization. In the Research pillar, the National Research Council of Canada (NRC) launched a new program, the Quantum Research and Development Initiative (QRDI), to advance shared quantum priorities of federal departments and agencies. In the Talent pillar, new quantum work placements were announced through Mitacs, a nonprofit national research institution that operates research and training programs in partnership with industry and academia. Finally, the Commercialization pillar included an Applied Quantum Computing Challenge program from the NRC, forging connections between industry and academia and focussing on applications and simulations, enabling technologies, and models and architecture. In addition, Canada's Global Innovation Clusters were designated to help further the adoption of made-in-Canada quantum technologies by business, whilst Innovative Solutions Canada was to move quantum solutions to the marketplace by matching Government of Canada clients with Canadian SMEs [9].

There are also various regional initiatives throughout Canada's provinces. One such example is the Regional Quantum Initiative (RQI) in southern Ontario, with over $23 million available between 2022 and 2027 to help companies commercialize their quantum products [10]. Canada also has its own industry body – Quantum Industry Canada - a consortium of Canadian quantum technologies companies aiming to ensure that Canadian quantum innovation and talent is translated into Canadian business success.

Quantum Centres

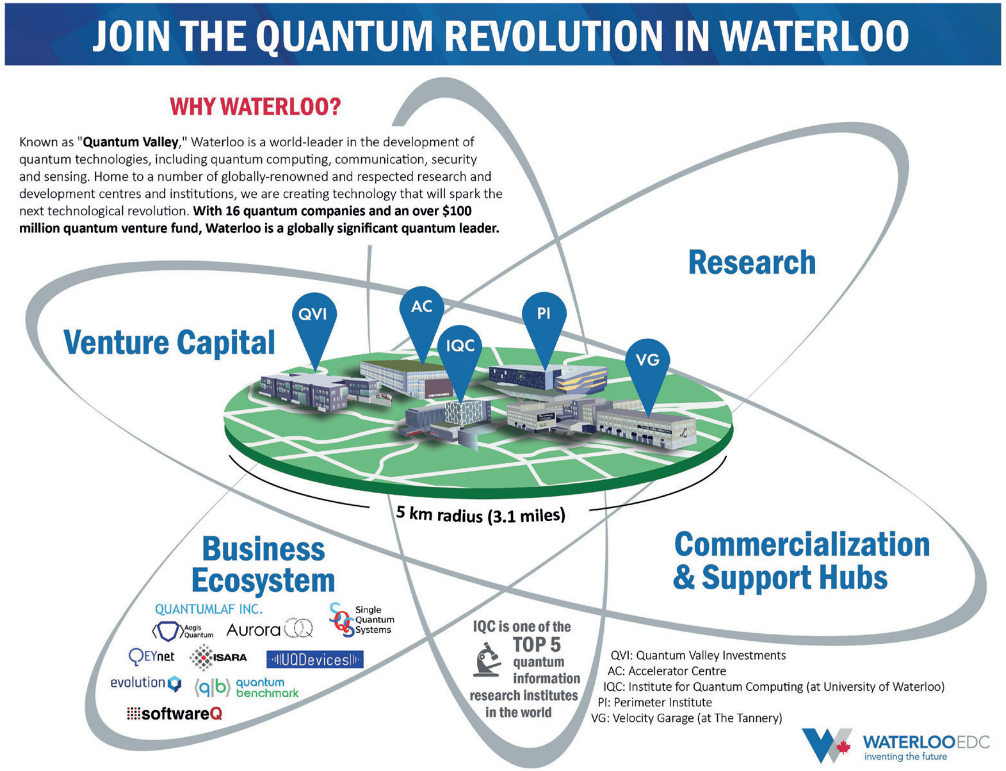
Waterloo

The IQC at the University of Waterloo is over two decades old, and has published over 2,000 papers in that time, and has trained over 2300 researchers in QIT [11]. It currently houses 29 faculty members and over 300 researchers. A selection of research groups are shown in the figure below.

Research Group	Description
Digital Quantum Matter Lab	The Digital Quantum Matter laboratory is dedicated to researching and designing quantum information processing devices. The goal of the group will be to build a fully general quantum computer.
Quantum Information with Trapped Ions	The Laboratory for Quantum Information with Trapped Ions (QITI) studies interaction between quantum degrees of freedom in a laser-cooled trapped ion system. QITI aims to create a flexible quantum system, with control at the level of individual particles for studying problems in quantum many-body physics and computation.
Quantum Photonic Devices Laboratory	The Quantum Photonic Devices Laboratory is focused on advancing quantum information science and technologies through the development of novel quantum light sources and solid-state quantum devices. The researchers also test fundamental questions in quantum photonics. The group aims to 1. Realise a quantum repeater – a quantum device that extends the distance for transferring quantum information 2. Perform quantum optics and algorithms on a semiconductor chip 3. Realise an efficient interface between stationary and flying quantum bits, an important milestone towards the Quantum Internet 4. Develop a "plug and play", tuneable quantum light source – an essential component needed in advanced quantum information schemes.
Quantum Photonics Laboratory	The Quantum Photonics Laboratory (QPL) centres on the applications of quantum photonics and quantum optics, as well as the fundamental aspects of the quantum world. They are involved in the experimental design of devices based on quantum photonics suitable for communication and computing with photons, and the development of ultra-long distance quantum communication systems using terrestrial and satellite-based systems. QPL is currently building a quantum ground station to connect to a satellite (the Quantum EncrYption and Science Satellite - QEYSSat).
Quantum Software Group (Qsoft)	The focus of Qsoft: The Quantum Software group, is to develop a range of tools for the synthesis and optimization of quantum software to be run on fault-tolerant quantum computing hardware.
Superconducting Quantum Devices Group	The Superconducting Quantum Devices (SQD) Group focuses on experimental research with superconducting devices, ranging from quantum bits for quantum information experiments, to superconducting resonators for loss characterization.

The IQC has a number of industrial partners, and has spun out 17 startups since its inception [12].

The wider city of Waterloo is referred to as "Quantum Valley" in Canada. As well as the IQC, there are other research institutions active in QIT such as the Perimeter Institute for Theoretical Physics. There are over a dozen quantum technology companies based in Waterloo, as well as a quantum venture fund. An illustration of Waterloo's quantum cluster activity is shown below [13].



Institut Quantique

The Université de Sherbrooke was awarded a Canada First Research Excellence Fund (CFREF) grant of $33.5 million, leading to the establishment of Institut Quantique in 2016, which brings together experts in quantum materials, quantum information and quantum engineering. The initiative also seeks to take advantage of the micro-nanofabrication and quantum engineering expertise at the Université de Sherbrooke's Interdisciplinary Institute for Technological Innovation and MiQro Innovation Collaborative Centre [4], [14]. The Insititut has a number of active research areas in QIT, including in metal oxide semiconductor based silicon quantum dots, where they recently demonstrated a new split accumulation gates concept, and are working on fabrication pathways for the technology [15].

26 Professors-Researchers

138 Graduate Students

37 Postdocs

22 Research Staff

67 Publications

6 Adjunct Professors

The Gouvernement du Québec designated Sherbrooke as an Innovation Zone in Quantum Science and Technology. In 2022, IBM chose Quebec as the region to house its first System One in Canada [16].

Quantum City

In June 2022, the provincial government of Alberta announced CA$23 million in funding for the University of Calgary to create a new quantum science technology hub called Quantum City, with researchers working across a variety of quantum technologies, including QIT. The government reported that the Hub would accelerate the development of Alberta-grown quantum technologies, with the intent to develop skills and talent and attract companies interested in commercializing quantum technologies to Alberta. The University of Lethbridge and the University of Alberta also partnered in the program, as well as Mphasis, an IT solutions provider [17].

The University of Calgary is also home to the Institute for Quantum Science and Technology (IQST), a multidisciplinary group of researchers from the areas of computer science, mathematics, chemistry and physics, with research activity in QIT-relevant fields such as trapped ions and practical quantum computation. A list of recent national and international collaborations of IQST are shown in the figure below.

INTERNATIONAL INSTITUTIONS

- Aarhus University, Denmark
- Ben-Gurion University of the Negev, Israel
- California Institute of Technology, United States of America
- Carl von Ossietzky University of Oldenburg, Germany
- Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico
- Cockcroft Institute, United Kingdom
- European Organization for Nuclear Research (CERN), Switzerland
- Harvard University, United States of America
- Humboldt-Universität zu Berlin, Germany
- Indian Statistical Institute, India
- Institut Néel, Grenoble, France
- Jagiellonian University Krakow, Poland
- Korean Institute of Science and Technology, South Korea
- Missouri University of Science and Technology, United States of America
- National Institute of Nuclear Physics - Pisa (INFN), Italy
- University of Brescia, Italy
- University of Bristol, United Kingdom
- University of California at Berkeley, United States of America
- University of Electronic Science and Technology of China
- People's Republic of China University of Gdańsk, Poland
- University of Hong Kong, People's Republic of China
- University of Liverpool, United Kingdom
- University of Manchester, United Kingdom
- University of Oxford, United Kingdom
- University of Science and Technology of China
- People's Republic of China
- University of Science and Technology, South Korea
- University of Strathclyde, United Kingdom
- University of Technology Sydney, Australia
- University of Warsaw, Poland
- Western Michigan University, United States of America
- National Institute of Standards and Technology, United States of America
- Nova Southeastern University, United States of America
- Polish Academy of Sciences, Poland
- Politecnico di Milano, Italy
- Purdue University, United States of America
- Qingdao Institute of Marine Geology, People's Republic of China
- Radboud University, the Netherlands
- Soreq Nuclear Research Centre, Israel
- Stockholm University, Sweden
- Swansea University, United Kingdom Tampere University, Finland
- Trinity College Dublin, Ireland
- Università Ca' Foscari Venezia, Italy
- Universität Ulm, Germany
- Université catholique de Louvain, Belgium
- Université Paris-Saclay, France
- Universidade Federal do Espírito Santo, Brazil
- Universidade Federal do Rio de Janeiro, Brazil
- University College Dublin, Ireland

NATIONAL INSTITUTIONS

- British Columbia Institute of Technology Institut National d'Optique (INO)
- Lakehead University
- Queen's University
- Simon Fraser University
- University of Alberta
- University of British Columbia
- Université de Sherbrooke
- University of Victoria
- University of Waterloo
- York University

Calgary is also home to Quantum Alberta, an academic-industrial network of people aiming to elevate Quantum Science research, development and commercialisation in Alberta.

Quantum Algorithms Institute (QAI)

The QAI was established in 2019 as a collaboration between industry, academia and government, in British Columbia. The institute was founded by Simon Fraser University, the University of British Columbia and University of Victoria, alongside the Government of British Columbia. Amazon Web Services, D-Wave, IBM, Microsoft, Photonic, and 1-QBit were the named industrial partners. Its research focusses on the design and application of new quantum algorithms, or novel hybrid approaches utilizing both quantum and classical computing, to tackle the scale of real-world problems and demonstrate those new approaches on industrial and governmental challenges [18]. By 2022 there were 11 affiliate QAI fellows from the various academic institutions involved.

In June 2021 QAI received CA$2.2 million in federal funding from Western Economic Diversification Canada (WD) to help it accelerate the innovation and commercialisation of quantum technologies [19].

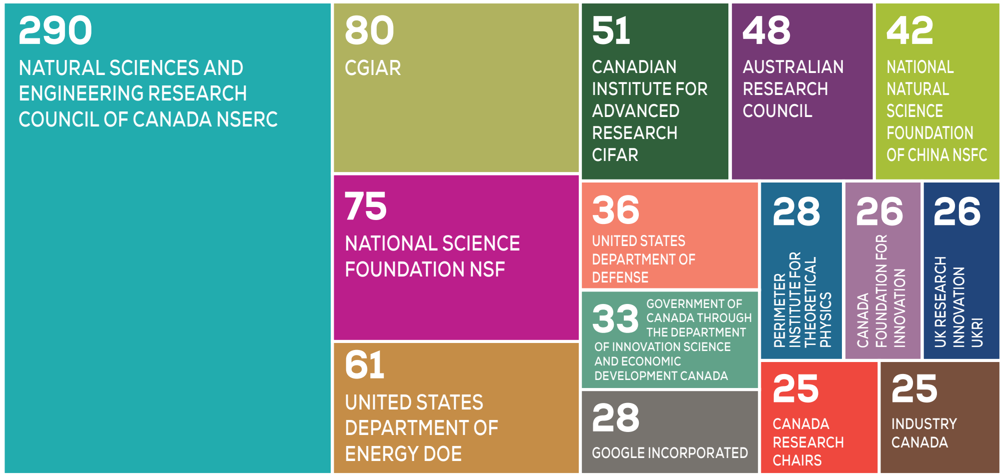
Collaborations

In September 2017, Canada and the UK signed a ten-year Memorandum of Understanding (MoU) on science, technology, and innovation, with quantum technologies listed as one of the focus areas. The MoU aimed to strengthen ties between the UK's and Canada's government bodies, businesses and more. Its goal is to accelerate the commercialisation of emerging technologies, grow domestic firms, and create jobs in both countries [20]. In 2022, the CRC and Innovate UK announced CR&D funding of up to £6m to fund both Canadian and UK businesses seeking to commercialise quantum technologies [21]. 2023 will also see the UK's four Quantum Technology Hubs host a quantum technologies summer school, open to both UK and Canadian early career researchers [22].

In July 2018, following a Data Science and Quantum Computing Workshop in June, Canada's TRIUMF, TRIUMF Innovations, D-Wave Systems and 1QBit signed an MoU with Germany's Helmholtz Association centres, DESY and Forschungszentrum Jülich. The MoU sought to establish quantum computing and machine learning networks and to collaborate on applied quantum computing and machine learning initiatives of mutual interest. Four joint working groups were established, around Quantum Computing, Large Scale Computing, Machine Learning, and Big Data Analytics [23].

Finally, in January 2023, Quantum Industry Canada (QIC), the Quantum Economic Development Consortium (QED-C), the Quantum Strategic Industry Alliance for Revolution (Q-STAR) and the European Quantum Industry Consortium (QuIC) signed an MoU to formally establish the International Council of Quantum Industry Associations. The council aims to strengthen communication and collaboration among the participating consortia on goals and approaches to the development of quantum technologies [24].

We analysed papers published from 2018 onwards, with some or all the authors based in Canadian institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown,



Over 700 papers from Canadian authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	69
PHYSICAL REVIEW LETTERS	32
QUANTUM SCIENCE AND TECHNOLOGY	30
PRX QUANTUM	27
QUANTUM	27
PHYSICAL REVIEW RESEARCH	21
NEW JOURNAL OF PHYSICS	20
PHYSICAL REVIEW B	18
NPJ QUANTUM INFORMATION	13
PHYSICAL REVIEW D	13

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 579 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Algeria	1
Australia	16
Austria	9
Belgium	4
Brazil	4
Canada	186
Chile	1
China	8
Czech Republic	2
Denmark	1
France	14
Germany	13
Iceland	1
India	1
Israel	1
Italy	1
Japan	5

Country	Number of citations
Mexico	2
Netherlands	13
Poland	2
Portugal	1
Russia	9
Slovenia	1
South Africa	1
Spain	11
Sweden	2
Switzerland	42
Thailand	5
UK	20
USA	200
Korea	1
Singapore	1
Grand Total	**579**

The lead author’s institutional country for these fifty papers is shown below.

Country	Number of papers
Algeria	1
Australia	1
Austria	1
Belgium	1
Canada	18
China	1
Germany	2
Netherlands	1
Russia	1
Singapore	1
Switzerland	4
UK	4
USA	14
Grand total	**50**

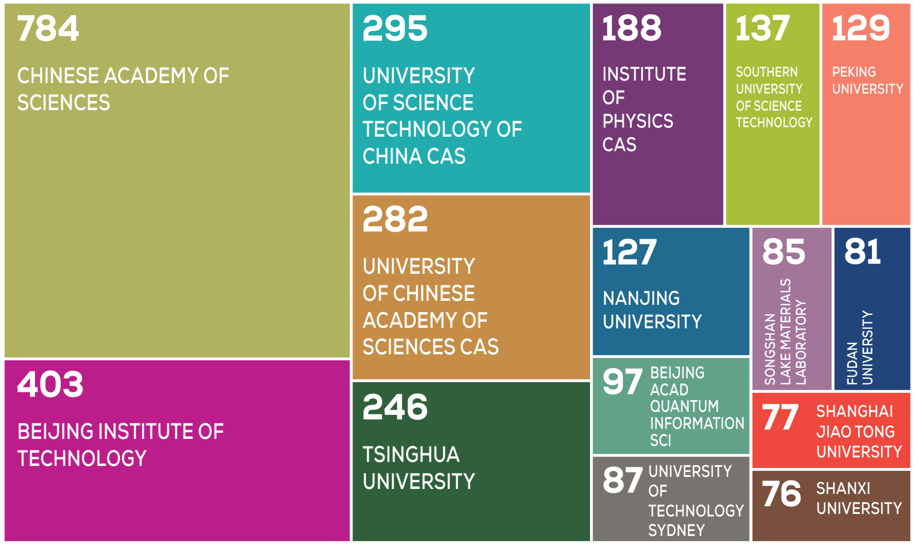
China

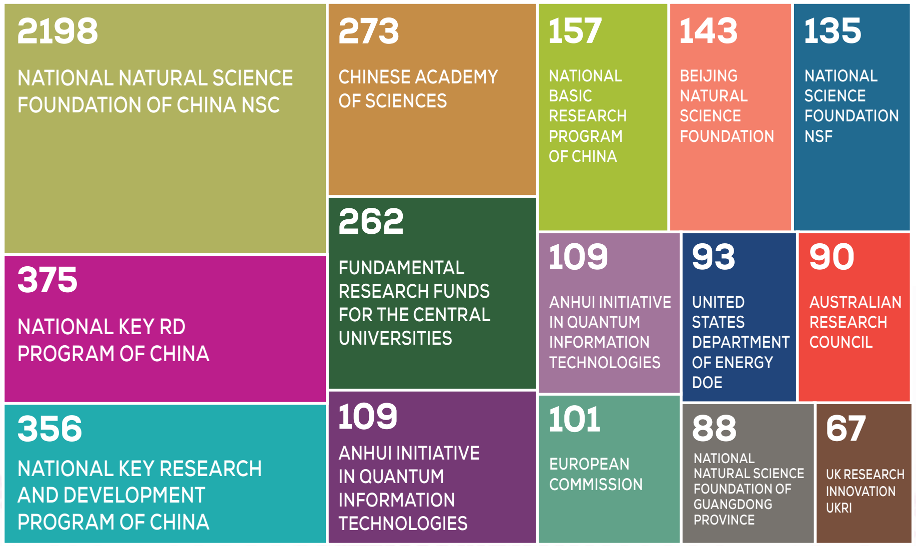
Estimates of China's investments in quantum technologies vary, but may be at least US$25B from the 1980s to 2022 [25]. Exact figures are difficult to verify, but Chinese sources report the development of a $10 billion National Laboratory for Quantum Information Sciences [26]. China has bolstered its infrastructure by developing "State Key Laboratories" at various universities to drive innovation [27]. Historically, China was known for Quantum communication (QKD over fibre, satellite), but recently has made advances in quantum computing and memories. In 2021, a team led by Pan Jianwei at the University of Science and Technology of China (USTC) in Hefei developed a programmable 62 qubit superconducting quantum processor, naming it after Zu Chongzhi 祖沖之, a 5th century Chinese mathematician and astronomer [28]. The Jiuzhang 2.0 photonic machine has been used in Gaussian boson sampling experiments, with a reported sampling rate of the order of 10^{24} faster than using brute force simulation on classical supercomputers [29].

Chinese-owned commercial organisations are also investing in quantum computing. The Baidu Institute of Quantum Computing was established in 2018, with plans to gradually integrate quantum computing into Baidu's core business [30]. The Alibaba Demo Academy has developed a Quantum Laboratory, and has recently published on a 2 qubit machine based on fluxonium, with fidelities comparable to high performing superconducting qubits [31]. Tencent have invested in a quantum computing laboratory, and have released an open source tensor network software framework [32].

Collaborations

We analysed papers published from 2018 onwards, with some or all the authors based in Chinese institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.





3041 papers from Chinese authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	232
QUANTUM INFORMATION PROCESSING	169
PHYSICAL REVIEW B	149
PHYSICAL REVIEW LETTERS	122
INTERNATIONAL JOURNAL OF THEORETICAL PHYSICS	113
ACTA PHYSICA SINICA	93
CHINESE PHYSICS B	70
PHYSICAL REVIEW RESEARCH	59
PHYSICAL REVIEW APPLIED	58
IEEE ACCESS	57

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited over 700 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Australia	9
Austria	1
Belgium	3
Brazil	2
Canada	2
China	326
Czech Republic	1
Denmark	9
Finland	1
France	2
Germany	13
Iceland	1
Ireland	2

Country	Number of citations
Italy	2
Japan	35
Mexico	2
Netherlands	13
Poland	3
Russia	1
Singapore	3
Spain	9
Switzerland	3
Thailand	1
UK	72
USA	185
Grand Total	**701**

The lead author's institutional country for these fifty papers is shown below.

Country	Number of papers
Australia	1
China	28
Germany	1
Japan	3
Netherlands	1
Spain	1
UK	10
USA	5
Grand Total	**50**

India

India is estimated to have invested $1B in quantum technologies in recent years [33]. The Indian Government announced a National Mission on Quantum Technologies & Applications (NM-QTA) in 2020, with a total budget outlay of Rs 8000 Crore ($1.2B) for a period of five years to be implemented by the Department of Science & Technology (DST). It focuses on

- Quantum communication
- Quantum simulation
- Quantum computation
- Quantum sensing and metrology

There are 21 quantum hubs in the country, with a further four Quantum research parks across India.

Quantum Centres

QuIC Lab

Quantum Information and Computing (QuIC) Lab at the Raman Research Institute is one of the first Indian labs to manufacture and establish the use of heralded and entangled photon sources for quantum technology applications. They have recently demonstrated entanglement based secure quantum communications through an atmospheric free space channel between a stationary source and a moving receiver – the first such demonstration in India [34].

Indian Institute of Science

IISc launched its Quantum Technology Initiative (IQTI) in September 2020. Its short term aims include:

- Reliable and high-fidelity elementary quantum components.
- 8-qubit quantum processor with superconducting transmon technology.
- Software simulators to verify and validate noisy quantum devices.
- Quantum-inspired algorithms that can be executed on existing computers and devices.
- Peripheral devices (electronics and nanotechnology) to interact with quantum components, incorporating efficient hybridization techniques.
- Novel materials and architectures (e.g. layered devices).
- On-field trials, reliability testing, packaging etc. of viable peripheral and quantum-enhanced components.
- Infrastructure development for large scale semiconductor and device processing needed for quantum.
- Introduction of MTech and PhD programs specialising in Quantum Technology.

Longer term (4-6 year) aims include:

- Improve the accuracy of all the short-term targets.
- Multi-qubit quantum processors based on transmons, optical and other platforms.
- Campus-wide quantum-secured communication network.
- High precision sensors, measurement devices and transducers.
- Hardware simulation of few-body quantum systems.
- Creation of new devices by integrating elementary components.
- Quantum illumination and imaging (LiDAR) at lab scale.

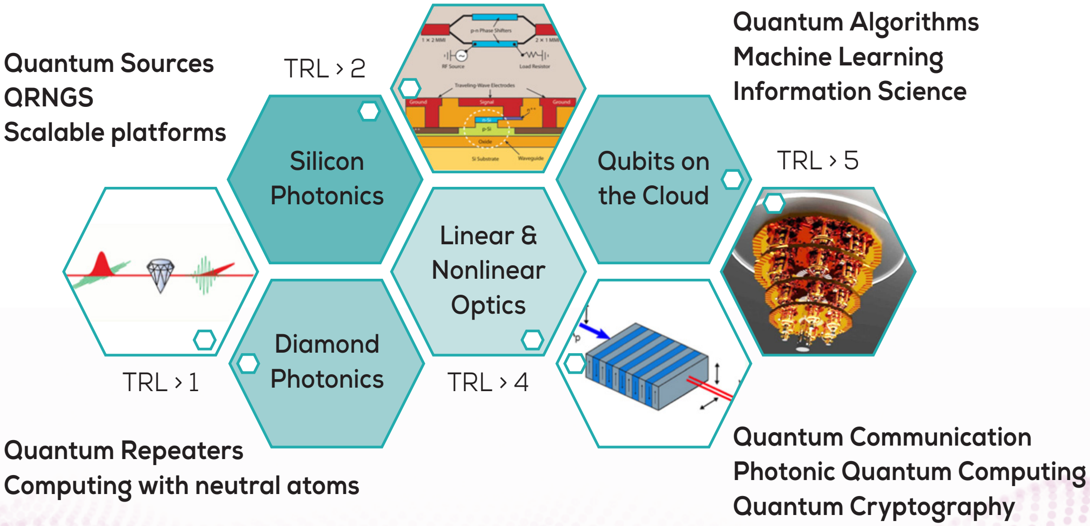
Tata Institute of Fundamental Research (TIFR)

The Quantum Measurement and Control Laboratory (QuMaC) at TIFR primarily investigates quantum phenomena in superconducting circuits. They have research programmes in Quantum Error Correction, quantum simulations, novel qubit designs, quantum limited parametric amplifiers, weak quantum measurements, and nanomechanical systems in the quantum regime.

Indian Institute of Science and Education Research

The I-HUB Quantum Technology Foundation is hosted by IISER Pune and is one of the 25 technology hubs funded by the Department of Science and Technology under the National Mission for Interdisciplinary Cyber-Physical Systems. I-HUB aims to harness quantum phenomena for developing advanced computing systems, as well as for more immediate applications in precision sensors, navigation devices for global positioning systems, geological mapping, atomic clocks, encrypted communications, and novel materials. Beyond technology development, I-HUB facilitates technology translation, incubation and human resource development. I-HUB operates in a hub-and-spoke model to bring together expertise from across India.

Indian Institute of Technology Madras



Technology platforms being investigate at CQuICC

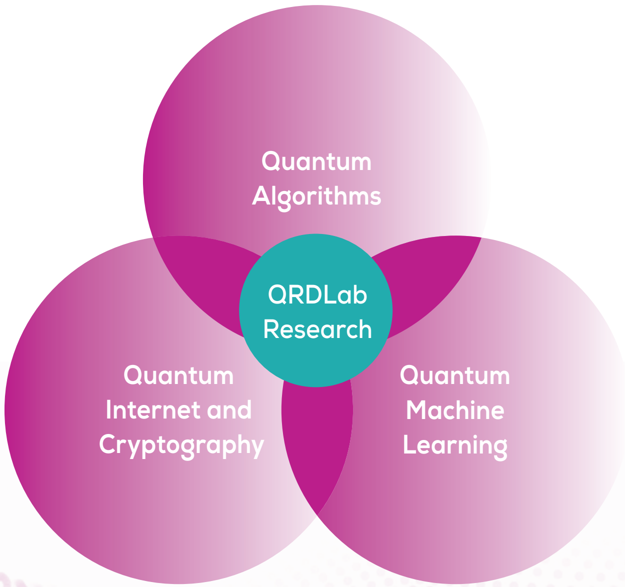
IIT Madras' Centre for Quantum Information, Communication and Computing has an objective of developing facets of various applications of quantum technologies in secure quantum communications, including quantum key delivery, quantum random number generation, quantum sensing and metrology, and quantum computing.

It is conducting research in:

- Quantum Key Distribution
- Quantum Sensors
- Quantum Computing
- Post Quantum Cryptography
- Quantum Error Correction
- Quantum Communication
- Quantum Algorithms

QRDLab

QRDLab is an Industry-first initiative originated in Kolkata, India to promote quantum research, education and consulting in multiple areas of Quantum Computing. Its objective is to pursue high end research in several areas of quantum-inspired software to simulate real-life problems. QRDLab aims to collaborate with independent researchers and academic institutions to accelerate quantum research. The effort includes translating nascent research ideas and advancing the quantum computing technology stack in India.

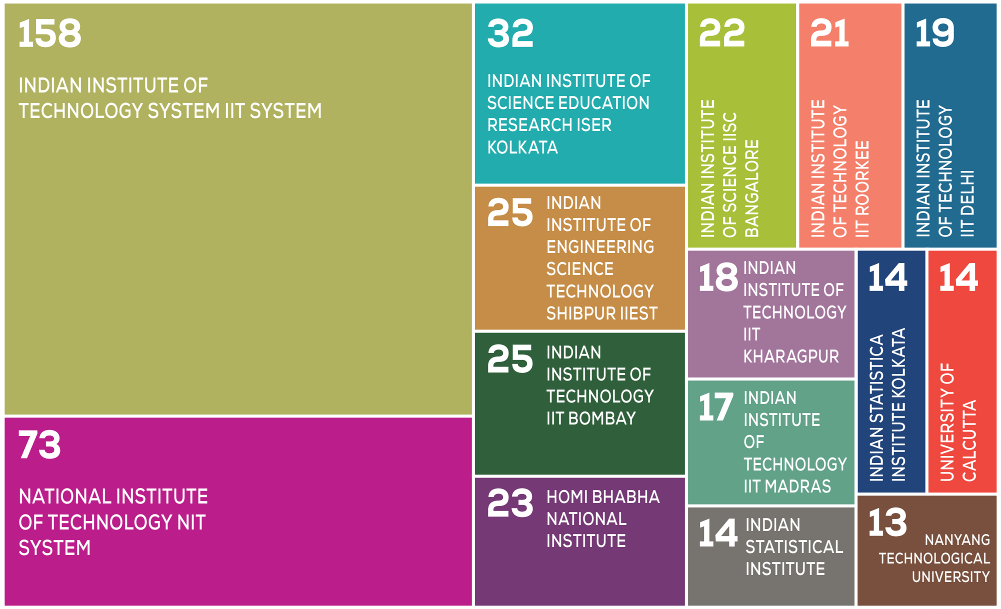


Collaborations

India and Finland have signed a digital partnership that will focus on collaboration in developing future ICT (Information and Communications Technology) and mobile technologies, including research and development in 6G, and the use of digital tools to transform education. The idea of jointly developing a quantum computer with the use of AI and 5G technology is seen as an important area of collaboration for both countries [35]. Additionally, Indian firm QpiAI has signed a memorandum of understanding with Finnish firm QuantrolOx to jointly develop India's first 25-qubit quantum computing testbed and offerings for the European and Indian markets [36].

The Ministry of Electronics and Information Technology (MeitY) in India has established a Quantum Computing Applications Lab, in collaboration with Amazon Web Services (AWS), to accelerate quantum computing-led research and development and enable new scientific discoveries. This is MeitY's first initiative in the country to provide scientific, academic, and developer communities with access to a quantum computing development environment in the cloud. This is also the first quantum computing applications lab on AWS Cloud to support a government's science and technology mission at a country level [37].

We analysed papers published from 2018 onwards, with some or all the authors based in Indian institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.



630 papers from Indian authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
QUANTUM INFORMATION PROCESSING	61
PHYSICAL REVIEW A	32
INTERNATIONAL JOURNAL OF THEORETICAL PHYSICS	14
IEEE ACCESS	10
SCIENTIFIC REPORTS	10
INTERNATIONAL JOURNAL OF QUANTUM INFORMATION	8
NEW JOURNAL OF PHYSICS	8
JOURNAL OF CIRCUITS SYSTEMS AND COMPUTERS	7
PHYSICAL REVIEW B	6
PHYSICAL REVIEW RESEARCH	6

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 282 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Australia	4
Austria	1
Brazil	2
Canada	7
Chile	1
China	5
Denmark	2
France	7
Germany	4
Hungary	2
India	145
Iran	2
Italy	8
Japan	5
Korea	1

Country	Number of citations
Netherlands	2
Norway	1
Pakistan	3
Saudi Arabia	8
Singapore	2
South Africa	6
Spain	8
Sweden	2
Switzerland	3
Thailand	2
Turkey	1
UK	11
USA	35
Vietnam	2
Grand total	**282**

The lead author's institutional country for these fifty papers is shown below.

Country	Number of papers
Australia	1
Canada	1
Hungary	1
India	38
Italy	1
Pakistan	1
South Africa	1
Turkey	1
USA	3
Vietnam	1
Japan	1
Grand total	**50**

Japan

In 2020, the government of Japan published its Quantum Technology and Innovation Strategy [38], identifying key priority areas, including gate-based quantum computing, and establishing quantum technology hubs, whose focus was on basic research, demonstrators and skills development [39]. This was followed in April 2022 by an additional strategy, the Vision of Quantum Future Society, which expanded on the initiatives for social innovation through quantum technology, such as creating opportunities for industrial growth and a carbon-neutral society [38]. Japan ranks seventh among the top 10 nations producing quantum scholarly outputs for the quality and impact of its quantum science [5].

Japan has a number of national programs supporting QIT research, most notably the MEXT (Ministry of Education, Culture, Sports, Science and Technology) Q-LEAP initiative – an R&D program running from 2018-2027 aiming to achieve leaps in economical and societal goals by taking advantage of quantum technology. It covers three technological areas: next generation lasers, quantum metrology and sensing, and QIT (encompassing both gate-based quantum computing and quantum simulation) [40].

The QIT area is composed of two flagship projects and six basic research projects, as shown in the tables below.

Flagship Projects

Project Name	Project Leader	Institute
Research and Development of Superconducting Quantum Computers	NAKAMURA Yasunobu	Center for Emergent Matter Science, RIKEN
Development of quantum software by intelligent quantum system design and its applications	FUJII Keisuke	Center for Quantum Information and Quantum Biology (QIQB), Osaka Univ.

Basic Foundation Research

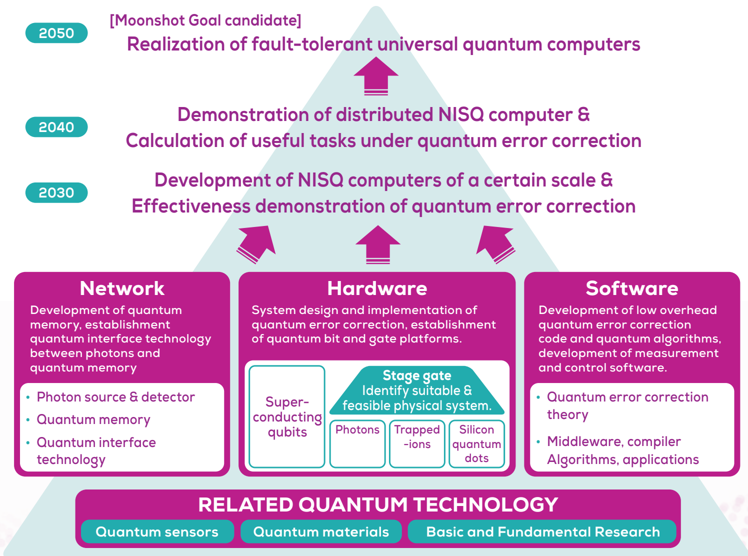
Project Name	Project Leader	Institute
Development of cold atom-based quantum simulators by optical control with precisions on the attosecond temporal and nanometre spatial scales and their applications to quantum computing	OHMORI Kenji	Institute for Molecular Science, National Institutes of Natural Sciences
Multi-degree-of-freedom complex quantum simulator using cooled ions	TOYODA Kenji	Institute for Open and Transdisciplinary Research Initiatives, Osaka University
Architecture and applications for small to large scale quantum computation	NEMOTO Kae	Principles of Informatics Research Division, National Institute of Informatics
Development of quantum software applications by fast classical simulator of quantum computers	FUJII Keisuke	Graduate School of Engineering Science, Osaka University
Large scale integration of silicon qubits to realise quantum computer	MORI Takahiro	Nanoelectronics Research Institute, National Institute of Advanced Industrial Science and Technology
Quantum software	YAMAMOTO Naoki	Faculty of Science and Technology, Keio University

MEXT, through the Japan Science and Technology Agency, also funds several Strategic Basic Research Programs which have QIT-related projects, such as CREST and PRESTO. These have projects in "Creation of an innovative quantum technology platform based on the advanced control of quantum states" and "Technological Foundation of Advanced Quantum Computing and Information Processing" respectively [41]. The latter involves multiple workstreams across different institutions, and those in FY21 are shown below.

Institution	Name
NTT Corporation	Optimization and verification of distributed quantum operations for multipartite secure quantum communication protocols
The University of Tokyo	Quantum simulation of many-body wave functions in condensed-matter problems
RIKEN	Development of classical and quantum computation methods for field theories with sign problems
Osaka University	Development of a multi-level interface program connecting first-principles methods with quantum algorithms
RIKEN	Exponential speedup in quantum computing based on quantum many-body theory
Kyoto University	Development of quantum algorithms for early universe
Nihon University	Development of quantum state reconstruction method and quantum entanglement detection for artificial quantum systems
The University of Tokyo	Establishing Quantum Parallel Computing Infrastructure
Shibaura Institute of Technology	Development of Imaginary Time Quantum Toolbox

Perhaps Japan's most ambitious effort in QIT is as part of its Moonshot Research and Development Program, which promotes 9 challenging projects with the aim of resolving difficult societal issues [42].

Moonshot Goal 6 is the realisation of a fault-tolerant universal quantum computer that will revolutionise the economy, industry, and security by 2050. This has various milestones, as shown in the figure below.



There are multiple streams of R&D projects making up this Moonshot Goal, as shown in the table below.

Institution	Title & Description
The University of Tokyo	**Research and Development of Theory and Software for Fault-tolerant Quantum Computers** This project aims to construct a co-design model encompassing qubit design, fault-tolerant architecture, and compilers and programming languages for efficient computation through collaborations of researchers in quantum information, architecture, and specific physical systems, thereby endeavouring to realise a large-scale quantum computer by the year 2050.
Yokohama National University	**Development of Quantum Interfaces for Building Quantum Computer Networks** This project aims to develop a quantum interface in which quantum memory is combined with an optomechanical crystal, to connect the superconducting qubit and the communication photon, towards realization of a large-scale superconducting quantum computer by 2050.
Okinawa Institute of Science and Technology Graduate University	**Fault-tolerant Quantum Computing with Photonically Interconnected Ion Traps** This project aims to develop ion trap devices that facilitate building large-scale systems beyond the limitations posed by conventional approaches. The new approach is based on a novel idea of photonically interconnecting multiple ion traps.
The University of Tokyo	**Development of Large-scale Fault-tolerant Universal Optical Quantum Computers** This project aims at the realisation of large-scale fault-tolerant universal quantum computers based on a "quantum look-up table" by 2050, which works at room temperature.
Hitachi, Ltd.	**Large-scale Silicon Quantum Computer** This project aims to achieve large-scale integration of silicon qubits by utilizing silicon semiconductor integrated circuit technology.
Center for Quantum Information and Quantum Biology, Osaka University	**Quantum Cyberspace with Networked Quantum Computer** This project aims to develop elemental technologies for networking quantum computers with photons, atoms, semiconductors and so on, aiming to network small and medium quantum computers.
NEC Corporation	**Development of Integration Technologies for Superconducting Quantum Circuits** This project aims to develop hardware technologies required for scaling up the circuit of superconducting qubits to accelerate R&D of superconducting quantum computers.
Waseda University	**Large-scale quantum hardware based on nanofiber cavity QED** This project aims to develop novel quantum-computing hardware based on nanofiber cavity QED. Aim to develop large-scale distributed quantum-computing hardware and to realise a fault-tolerant universal quantum computer and a quantum internet.

Institution	Title & Description
Institute for Molecular Science, National Institutes of Natural Sciences	**Large-scale and high-coherence fault-tolerant quantum computer with dynamical atom arrays** We will implement a "dynamical qubit array" in which many cold-atom qubits are assembled with optical tweezers, and each of them is moved arbitrarily and at high speed to perform gate operations as well as error detections and corrections. Furthermore, under close industry-academia collaborations, all components will be integrated and packaged to achieve unprecedentedly high stability and usability. Aims to realise a fault-tolerant quantum computer that will revolutionise the economy, industry, and security by 2050.
Kyoto Institute of Technology	**Development of a Scalable, Highly Integrated Quantum Error Correction System** To realise an error-tolerant general-purpose quantum computer, this project addresses the technical issues of algorithms and scalable backends for classical hardware for error correction, scalable quantum-to-classical input/output frontends, semiconductor chips for backend/frontend, and cryogenic operation of optical integrated circuits for high bandwidth and low power quantum-classical input/output. Aims to implement a quantum computer with 1,000,000 physical qubits by 2050.
RIKEN Center for Quantum Computing	**Development of scalable Silicon quantum computer technology** This project aims to develop scalable technologies for Silicon quantum computers. We will use sparse integration and medium-distance quantum coupling to implement a unit structure of qubits and scale up the qubit system by increasing the number of the unit structures. Based on this method we will develop fundamental technologies appropriate to implement large-scale quantum computers by 2030 and expand the technologies in cooperation with the semiconductor industry to implement universal quantum computers by 2050.
Keio University	**Scalable and Robust Integrated Quantum Communication System** In this project, we will build a testbed for a general-purpose quantum communication network, which is a key technology for distributed large-scale quantum computers and integrate hardware and software to demonstrate the principles and technologies of communication architectures and protocols with a view to actual operation. The results of this project will lead not only to distributed large-scale quantum computers but also to the quantum Internet, and will contribute to the realization of a world in which quantum information can be freely generated, distributed, and processed.

Separately to the above, in September 2021 the Quantum Strategic Industry Alliance for Revolution (Q-STAR) was established, an industrial group (founding members shown below) to promote quantum technologies and explore new applications, collaborating with industry, government and academia [43].

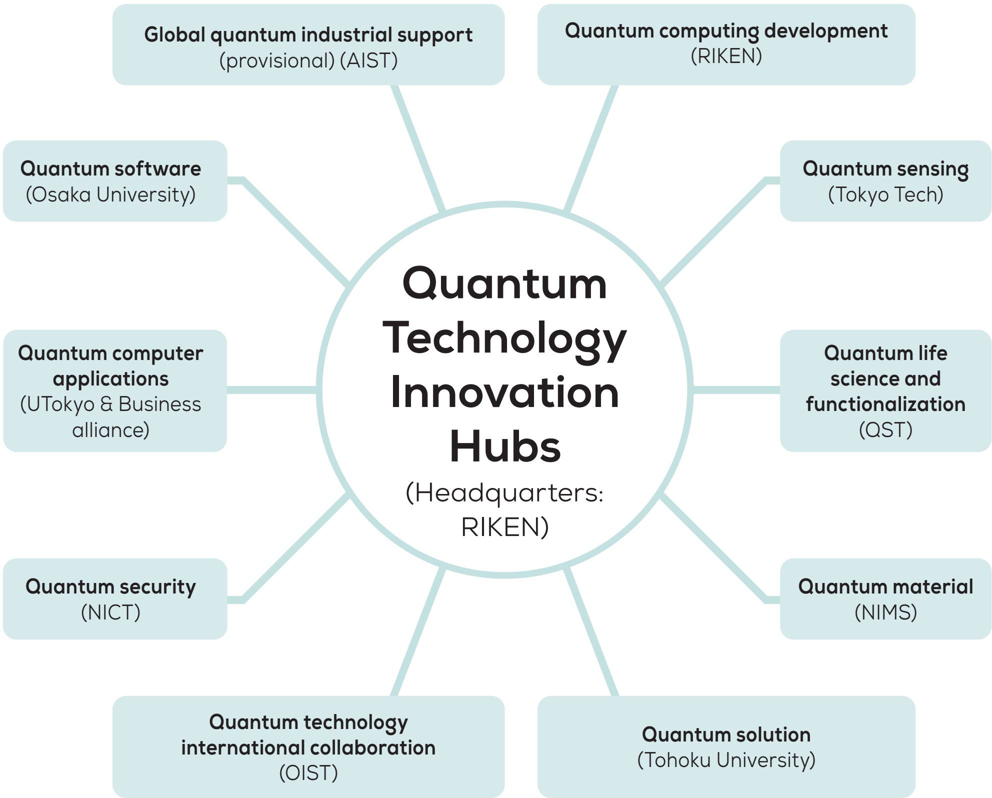
Founding members of Q-STAR	
• ITOCHU Techno-Solutions Corporation (CTC)	• Toppan Inc.
• SBS Holdings, Inc.	• Toyota Motor Corporation
• Canon Inc.	• NEC Corporation
• JSR Corporation	• Nippon Telegraph and Telephone Corporation
• Sumitomo Corporation	• Hitachi, Ltd.
• SOMPO Holdings, Inc.	• Fujitsu Limited
• Dai-ichi Life Insurance Company, Ltd.	• Mizuho Financial Group, Inc.
• Dai Nippon Printing Co., Ltd.	• Mitsui Sumitomo Insurance Company, Ltd.
• Daiwa Securities Group Inc.	• Sumitomo Mitsui Financial Group, Inc.
• Chodai Co., Ltd.	• Mitsui & Co., Ltd.
• Tokio Marine Holdings, Inc.	• Mitsubishi Chemical Corporation
• Toshiba Corporation	• Mitsubishi Electric Corporation

Quantum Centres

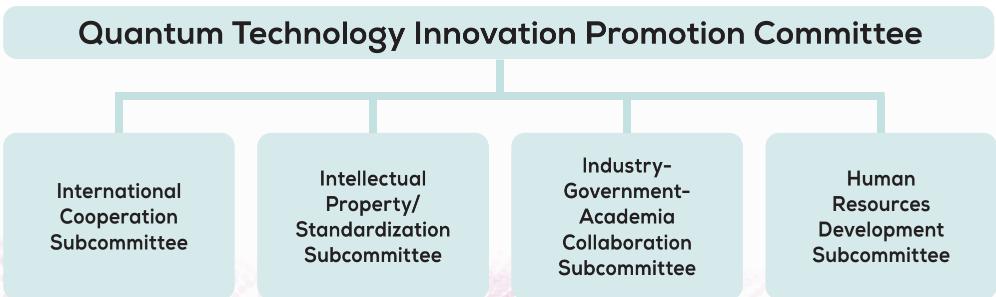
Japan's 2020 Quantum Technology and Innovation Strategy established eight new centres to facilitate collaboration and accelerate research. These are shown in the table below, and notably include the *Quantum Computer Development Hub*, the *Quantum Computing Applications Hub and the Quantum Software Research Hub.*

Hub Lead Site	Organisation	Department
Quantum computer development hub	RIKEN	RIKEN Center for Quantum Computing
Quantum life science hub	QST	Quantum Life Science Research Hub
Quantum secure network hub	NICT	NICT Quantum ICT Collaboration Center
Quantum devices development hub	AIST	Department of Electronics and Manufacturing
Quantum materials hub	NIMS	Corporate Strategy Office
Quantum computing application hub	University of Tokyo and business alliance	University Corporate Collaboration Department, Corporate Partnership Group (Quantum Innovation Initiative Consortium Office)
Quantum software research hub	Osaka University	Center for Quantum Information and Quantum Biology (QIQB)
Quantum sensors hub	Tokyo Institute of Technology	Quantum navigation unit Institute of Innovative Research Q-LEAP Department of Electrical and Electronic Engineering

As part of Japan's ambition to have 10m quantum computing users by 2030, [44] further Hubs were established in 2022, leading to ten Hubs in total, as shown in the figure below.



The Hubs are managed under the Quantum Innovation Hubs (QIH) umbrella, headquartered at RIKEN. QIH has various subcommittees dedicated to activities such as standardisation, which are shown in the figure below.



The RIKEN Center for Quantum Computing has strengths in superconducting and semiconductor based QIT. In 2022, researchers demonstrated error correction in a three-qubit silicon-based quantum computing system [45]. A full list of the RIKEN research teams is shown in the figure below.

RIKEN Center for Quantum Computing

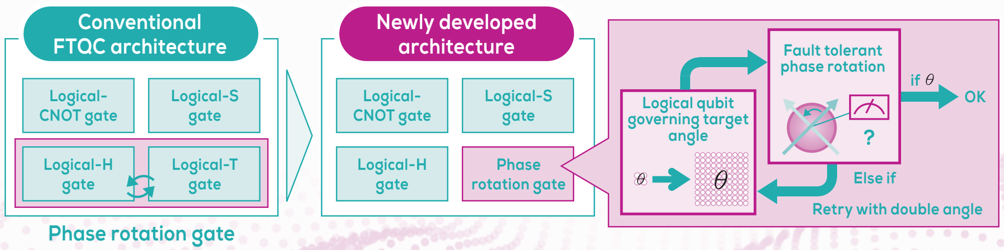
- Superconducting Quantum Electronics Research Team Superconducting
- Quantum Simulation Research Team
- Superconducting Quantum Electronics Joint Research Unit
- Superconducting Quantum Computing System Research Unit
- Hybrid Quantum Circuits Research Team
- Optical Quantum Computing Research Team
- Quantum Many-Body Dynamics Research Team
- Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team
- Semiconductor Quantum Information Device Research Team
- Semiconductor Quantum Information Device Theory Research Team
- Quantum Computing Theory Research Team
- Quantum Information Physics Theory Research Team
- Quantum Computational Science Research Team
- Quantum Computer Architecture Research Team
- Analytical Quantum Complexity RIKEN Hakubi Research Team
- Mathematical Quantum Information RIKEN Hakubi Research Team
- RIKEN RQC-FUJITSU Collaboration Center
- Office of the Center Director

Collaborations

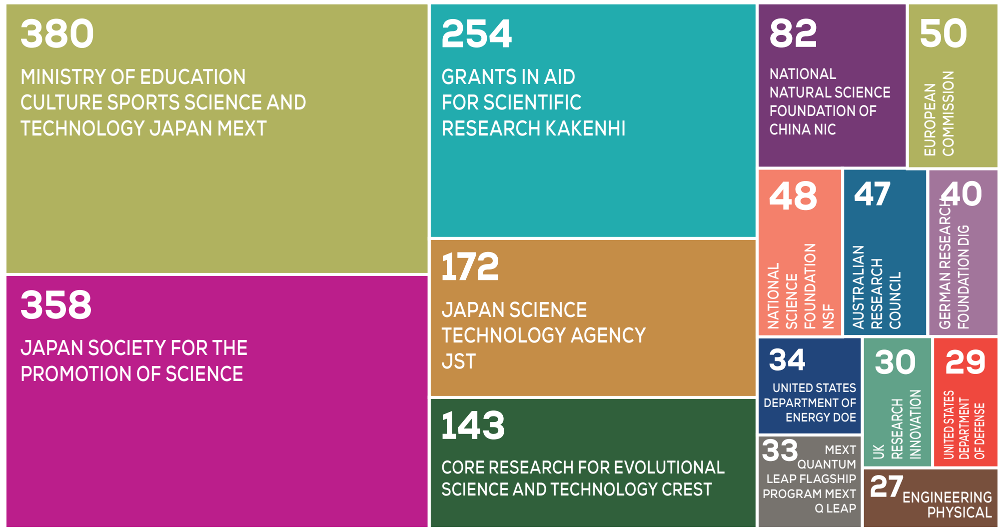
In December 2019, the governments of Japan and the United States of America signed the Tokyo Statement on Quantum Cooperation, focussing on quantum information science and technology. This set out the two countries' ambition to facilitate research collaboration, support the next generation of scientists and engineers in the field (including potential personnel exchanges), and work together in workshops, seminars and conferences [46]. The statement also refers to leveraging regular multilateral opportunities, and that same month Kyoto hosted the first EU-USA-Japan International Symposium on Quantum Technology, involving both researchers and policy makers [47]. Recently, in October 2022, Japan hosted a Quantum-Photonics-Nano Innovation Mission from the Netherlands, with a basic joint ambition to work towards bilateral partnership [48].

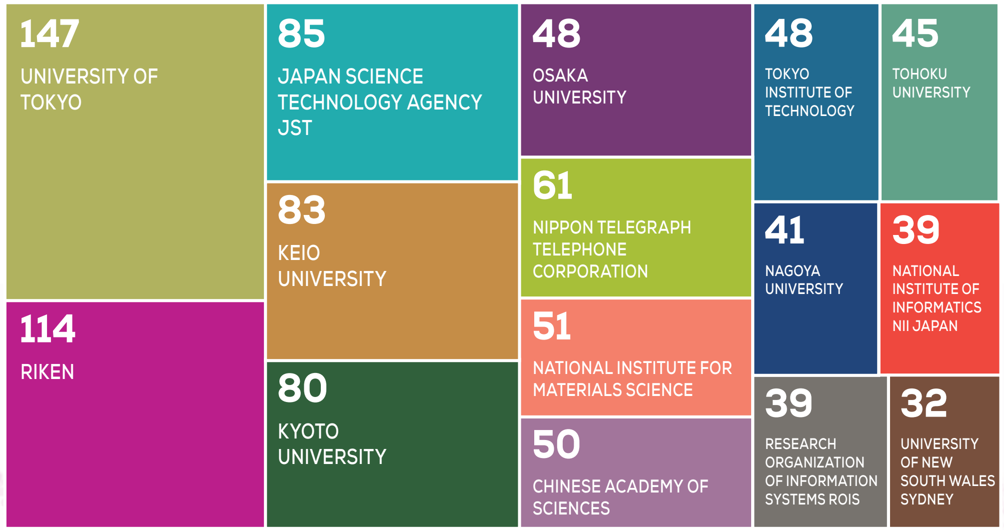
Japan also has a track record in fostering collaboration between academia and industry. In 2018, Keio University's Yagami Campus became an IBM Q Hub, at the time the only facility in Asia enabled to use IBM Q's cloud computing system [49]. This was followed in 2019 with IBM and the University of Tokyo announcing the Japan – IBM Quantum Partnership, focused on three areas: the development of quantum applications with industry, quantum computing system technology development, and advancing the state of quantum science and education [50]. In 2021, the University of Tokyo received the second IBM Quantum System One assembled outside the U.S. [51].

In April 2021, RIKEN and Fujitsu announced the establishment of the RIKEN RQC-FUJITSU Collaboration Center, jointly conducting research and development on the practical application of superconducting quantum computers, with a target to deliver a 1,000-qubit system for March 2027 [52]. Fujitsu also partnered with Osaka University's Center for Quantum Information and Quantum Biology, and in March 2023 announced the development of a new analogue rotation quantum computing architecture, as shown in the figure below.



We analysed papers published from 2018 onwards, with some or all the authors based in Japanese institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. Japan's MEXT (including the Japan Science and Technology Agency) is the dominant funder, with the United States also featured prominently through the Departments of Energy and Defense. There is also collaboration with China, the EU and the UK. The affiliations of the authors are also shown.





812 papers from Japanese authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	65
PHYSICAL REVIEW RESEARCH	39
PHYSICAL REVIEW LETTERS	33
PHYSICAL REVIEW B	32
NATURE COMMUNICATIONS	24
SCIENTIFIC REPORTS	21
PHYSICAL REVIEW APPLIED	20
NPJ QUANTUM INFORMATION	17
QUANTUM INFORMATION PROCESSING	17
INTERNATIONAL JOURNAL OF THEORETICAL PHYSICS	15
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN	15

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 628 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question, with notable activity with both the US and China.

Country	Number of citations
Argentina	1
Australia	55
Austria	1
Azerbaijan	5
Belgium	2
Brazil	2
Canada	5
China	130
Czech Republic	1
Denmark	1
Finland	9
France	3
Germany	9
Hungary	1
Iceland	1
India	3

Country	Number of citations
Ireland	1
Italy	7
Japan	140
Mexico	3
Netherlands	1
Poland	3
Russia	14
Singapore	2
Spain	5
Sweden	3
Switzerland	11
Thailand	1
UK	28
USA	180
Grand total	**628**

The lead author's institutional country for these fifty papers is shown below.

Country	Number of papers
Australia	4
Canada	1
China	7
Finland	1
Italy	1
Japan	23
Russia	1
Switzerland	1
UK	3
USA	8
Grand total	**50**

Russia

Russia has historically had a strong physics community, with several Nobel prizes won in Quantum Science. International sanctions introduced following Russia's invasion of Ukraine in 2022 have no doubt had an impact on scientific collaborations, and building a clear picture of the state of quantum technologies research in Russia since this time is not straightforward.

In 2017, Russia announced its Digital Economy Programme, which included several digital technologies, including quantum technologies [53]. In 2019, the Rosatom State Corporation launched a competition for proposals for quantum computing, with quantum communications being overseen by Russian Railways, and quantum sensing and metrology being overseen by the Rostec State Corporation. The quantum computing competition led to an announcement of an approximately €330M funding round, with around €187M coming from government, and the remainder coming from industry.

The main goal of the Russian Quantum Technologies Roadmap is to create a full stack of quantum computing moving from laboratory prototypes to cloud-accessible noisy intermediate-scale quantum (NISQ) devices. There is a particular focus on superconducting quantum technologies, neutral atoms, trapped ions, and photonics; polaritonics and impurity atoms are also seen as potentially interesting technologies. In the software and applications domain, there is work in quantum error correction codes, quantum error suppression methods, quantum and quantum-inspired algorithms, building large-scale systems for emulating quantum devices, and creating cloud platforms for access to quantum computing systems [54].

Quantum Centres

Russian Quantum Centre / Leading Research Centre

The RQC was founded in 2010 as a non-profit science and technology centre. Over the next ten years, it created 15 research laboratories, generated 8 spinoffs aimed at commercialization of the RQC's developments, and published more than 900 publications in scientific journals, including Nature and Science. Focus areas have been superconductors, ion traps, neutral atoms, photonic chips, algorithms and emulation. The RQC also identified magnons, polaritons and impurity atoms as promising platforms.

In 2020, the RQC launched the Leading Research Centre, aiming to build a trapped ion system.

National Quantum Laboratory

In November 2020, Rosatom announced that it had established a new National Quantum Laboratory [55]. At the launch, seven organisations had joined the NQL, JV Kvant (a Rosatom company), NRU HSE, MISIS, MIPT (NRU), P. N. Lebedev Physical Institute of RAS, the Russian Quantum Center and the Skolkovo Foundation.

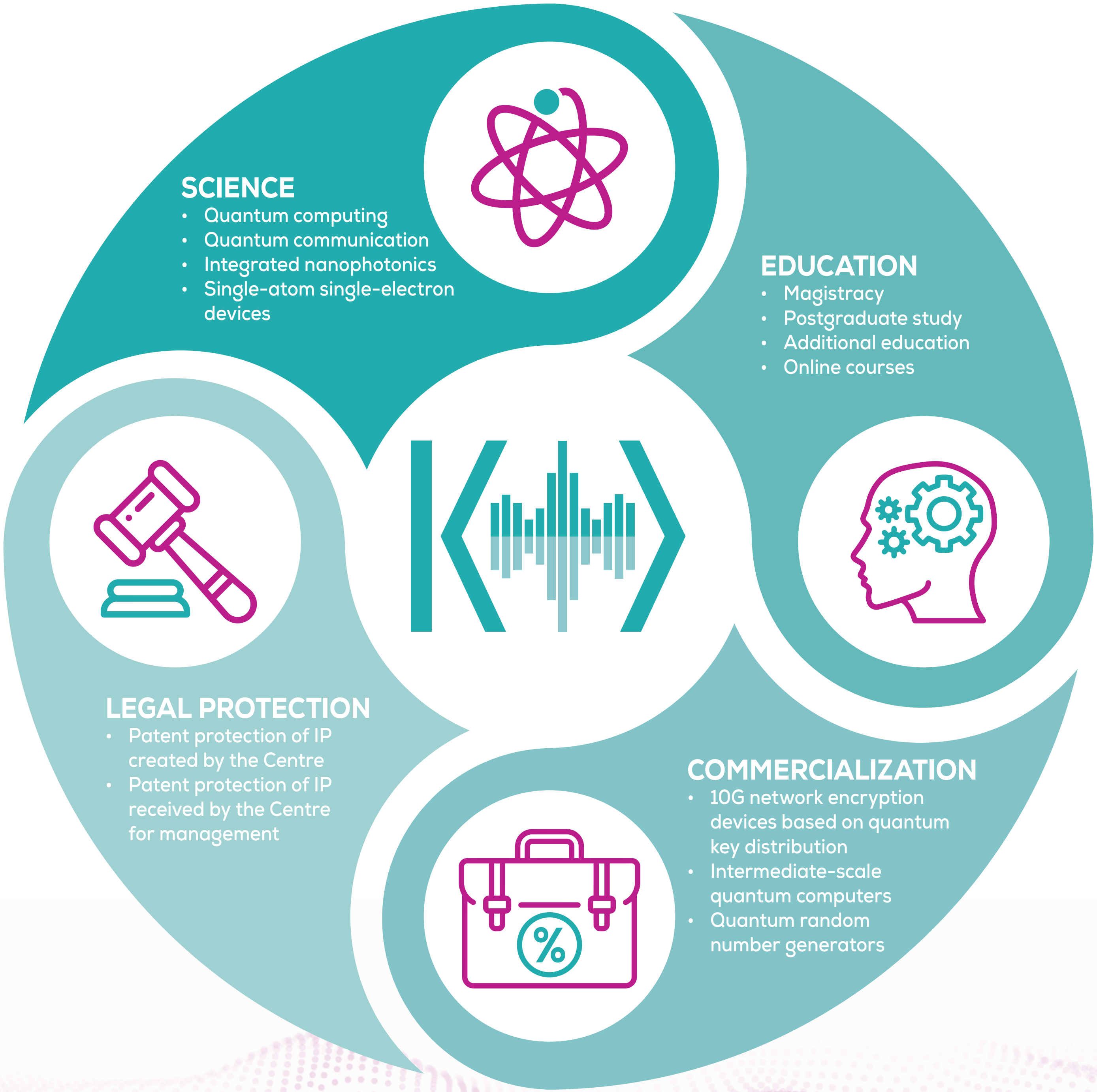
Skoltech Laboratory for Quantum Information Processing

Founded in 2017, Skoltech's resident theory team, which is known as the Deep Quantum Laboratory, specialises in the theory and experimental implementation of quantum enhanced algorithms for machine learning, quantum enhanced optimization and quantum enhanced simulation of electronic structure. The lab has developed a professional education program covering modern quantum technology, as well as an MSc in quantum information processing held at the Skolkovo Institute of Science and Technology [56].

MSU Quantum Technology Centre

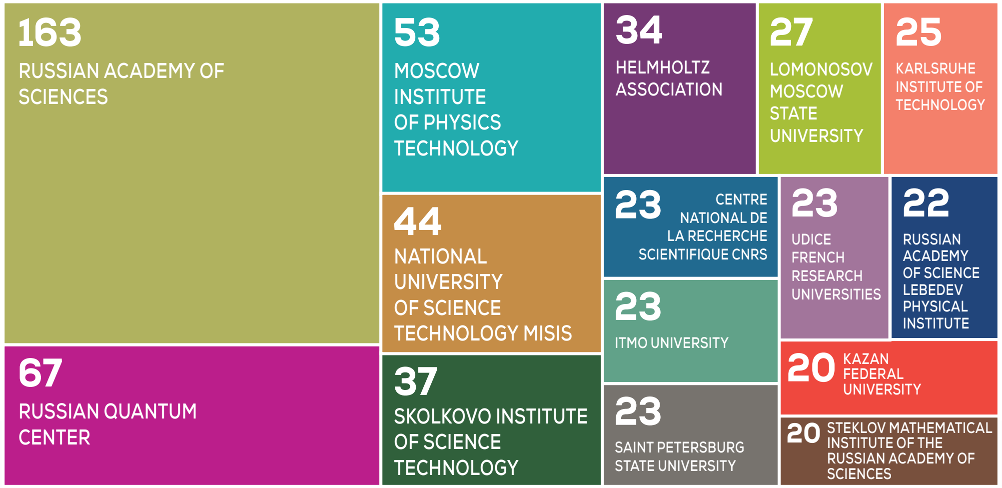
The Quantum Technology Centre was established at the Faculty of Physics, Lomonosov MSU, in 2018 under the National Technological Initiative. The Centre's activity aims to progress quantum technologies, develop related educational programs, and connect with industrial partners for further commercialization of quantum technology products.

The centre leads research programs in fibreoptic and atmospheric quantum cryptography, cold atom physics, quantum optics, nanophotonics, nonlinear optics, and cryoelectronics. The centre is involved in major projects developing quantum cryptographic systems designed for urban fibreoptic networks, atmospheric quantum communication equipment, and optical quantum processors [57].



Collaborations

We analysed papers published from 2018 onwards, with some or all the authors based in Russian institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.



These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 632 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Australia	21
Austria	28
Azerbaijan	5
Belgium	2
Brazil	2
Canada	6
China	24
Croatia	1
Czech Republic	4
Finland	9
France	24
Germany	131
Greece	1
Hungary	1
Iceland	1

Country	Number of citations
Italy	20
Japan	6
Korea	6
Mexico	2
Netherlands	11
Norway	1
Poland	3
Russia	94
Spain	15
Sweden	5
Switzerland	19
Thailand	1
UK	21
USA	168
Grand total	**632**

The lead author's institutional country for these fifty papers is shown below.

Journal	Number of papers
Australia	1
Austria	3
China	3
Finland	2
France	1
Germany	10
Italy	2
Korea	2
Netherlands	1
Russia	17
Switzerland	1
UK	2
USA	5
Grand total	**50**

Singapore

Singapore has invested in quantum technologies, and has a national Quantum Engineering Programme (QEP) which provides research grants for work in quantum tech, and works to develop the ecosystem [58]. QEP has been supported since 2018 by the Singapore National Research Foundation (NRF). It is hosted at the National University of Singapore (NUS), and supports projects led from any of Singapore's institutes of higher learning and research. The National Research Foundation is investing a total of $121.6 million in the Quantum Engineering Programme in two phases: $25 million for QEP1.0 (2018-2023) and $96.6 million for QEP2.0 (2020-2025).

QEP has deliverables in the following three areas:

- Engagement of industry and user-agencies, with cash and in-kind contributions to projects.
- Talent development through training of research scientists and engineers, some of whom will be deployed in industry and user-agencies, and of PhD students co-funded with industry.
- Collecting evidence of intellectual property and industrial outcomes, measured in spin-offs, prototypes, collaborations and membership of a quantum technology consortium.

The most recent round of funding has supported work in quantum communication and security, quantum computing and processors, quantum sensors and enabling technologies. As examples of the type of projects funded specifically in quantum computing, the 2021 call funded projects shown in the table.

Institutions Involved	Project
National University of Singapore (NUS)	A scalable, programmable atom-array platform for quantum simulation of dynamical and material physics
NUS Institute of Microelectronics (IME, A*STAR)	Advanced Quantum Processor Platform
Singapore University of Technology and Design (SUTD) Centre for Quantum Technologies (CQT) NUS Institute of High Performance Computing (IHPC, A*STAR)	Advancing cavity QED: materials and algorithms
Institute of Materials Research and Engineering (IMRE, A*STAR) Nanyang Technological University (NTU)	Atomic Engineering of Donor-based Spin Qubits in Silicon
NUS CQT NTU SUTD	Computer science approaches to quantum computing for finance
IHPC, A*STAR NUS	Quantum computing for accelerated design of auxetic mechano-luminescence materials
NTU Singapore Management University (SMU) CQT NUS	Quantum-Enhanced Modelling of Financial Time-Series Data for Rare Event Forecasting
NUS	Quantum processor with trapped ions
NUS IHPC, A*STAR CQT NUS SMU	Resource efficient quantum algorithms and applications for chemistry, route optimization and finance
NUS IME, A*STAR	Towards a scalable quantum machine learning solution using trapped ions
NUS IHPC, A*STAR	VCSEL-based quantum annealer

Quantum Centres

Centre for Quantum Technologies (CQT)

The Centre for Quantum Technologies (CQT) is a Research Centre of Excellence (RCE) bringing together physicists, computer scientists and engineers to undertake basic research on quantum physics and to build devices based on quantum phenomena, including computing, communications, and sensing.

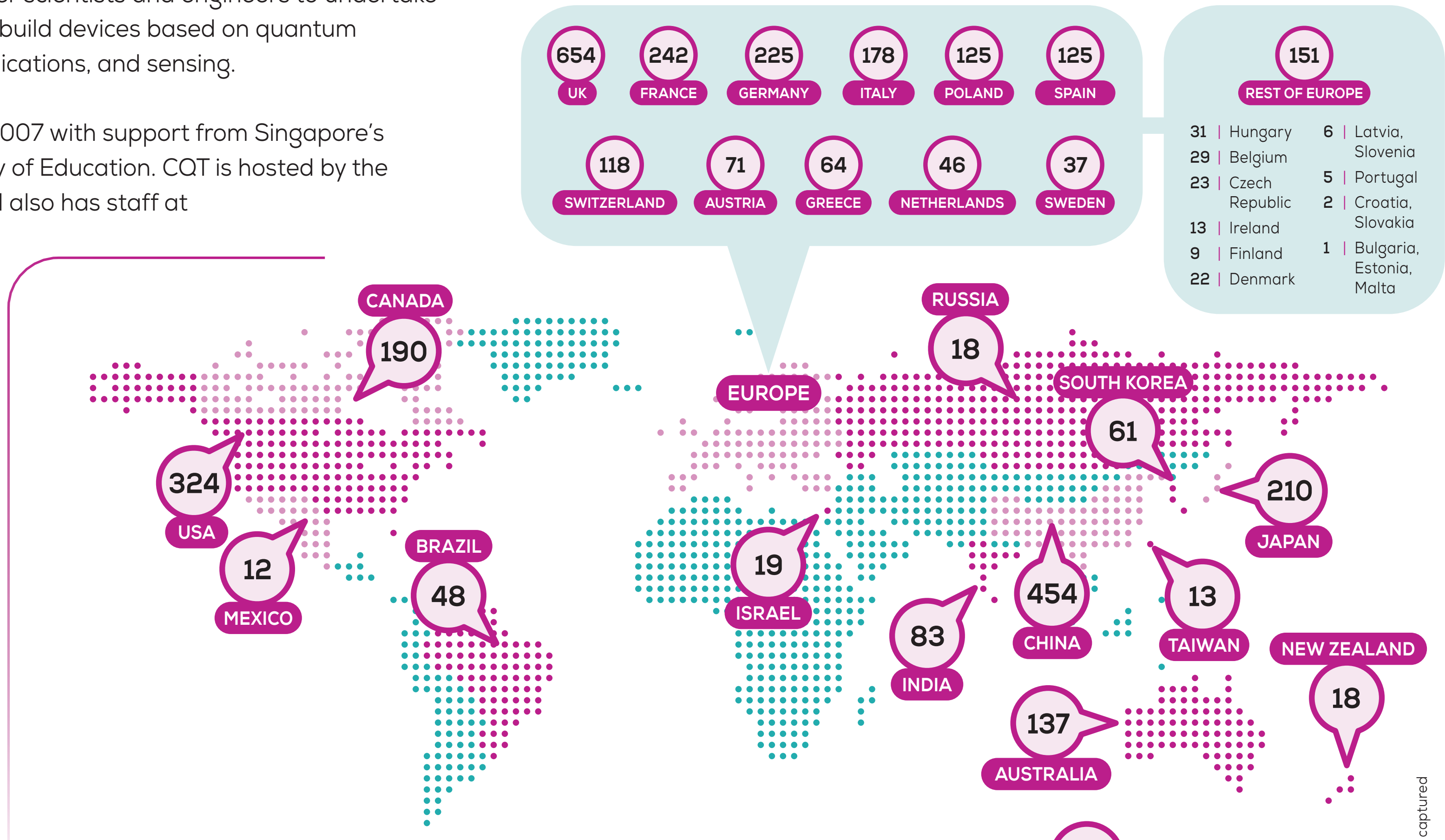
The Centre was established in December 2007 with support from Singapore's National Research Foundation and Ministry of Education. CQT is hosted by the National University of Singapore (NUS) and also has staff at Nanyang Technological University (NTU).

Research includes:

- Ion traps
- Superconducting qubits
- Cold atom systems
- Ultracold quantum gases
- Quantum measurement
- Topological physics
- Quantum simulation With optical lattices
- Boson sampling
- Noisy-intermediate scale Quantum computers
- Quantum chemistry
- Quantum error correction
- Quantum photonics
- Algorithms

International collaboration is strong, as shown in the diagram [59].

CQT has wide networks of collaborators at both the individual and institutional level. The world map shows counts of co-authorships by country across all publications including CQT researchers.



86 REST OF WORLD

16 | United Arab Emirates
8 | South Africa, Turkey
7 | Iceland
6 | Chile, Qatar
5 | Argentina, Norway
4 | Armenia, Serbia
3 | Iran, Malaysia, Saudi Arabia
2 | Colombia
1 | Belarus, Botswana, Egypt, Indonesia, Nigeria, Uruguay

Source: Clarivate Web of Science. Data captured for publications 2008-2021.

In 2021, CQT through NUS was part of agreements with institutions including:

- UMI MajuLab agreement with the Nanyang Technological University, the French National Centre for Scientific Research (CNRS), the Université Côte d'Azur and the Sorbonne University, France
- Partner Organisation Agreement with the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) at the University of New South Wales, Australia
- Memorandum of Understanding with each of TCG Centres for Research and Education in Science and Technology, India; University of Catania, Italy; Graduate School of Information Science and Graduate, School of Mathematics, Nagoya University, Japan; University of Otago, New Zealand; National Institute of Metrology, Thailand; and the University of Applied Sciences Northwestern Switzerland

National Quantum Computing Hub

The Centre for Quantum Technologies, A*STAR's Institute of High Performance Computing (IHPC), and the Singapore National Supercomputing Centre have recently launched a National Quantum Computing Hub [60].

Researchers at CQT and IHPC will develop quantum computing hardware and middleware. They will also explore applications with industry collaborators in fields such as finance, supply chain, and chemistry. NSCC will host a quantum computing facility and provide the supercomputing power needed to develop and train the algorithms that could eventually be used on quantum computers. The Hub will also build international collaborations and train new talent.

National Quantum Fabless Foundry

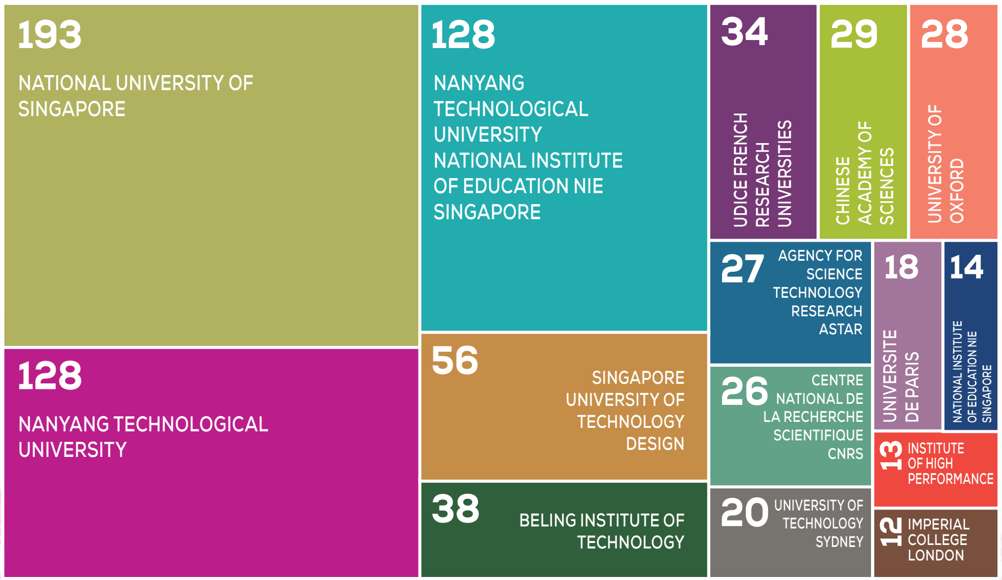
The National Quantum Fabless Foundry (NQFF) is a national platform in Singapore to build capabilities in designing, fabricating, and characterising micro- and nano- devices that are essential for quantum technologies [61].

It is hosted at the Institute of Material Research and Engineering (IMRE), and works closely with the Institute of Micro Electronics (IME). In IMRE, NQFF has state-of-the-art design and characterisation facilities. The foundry has developed fabrication processes in:

- Superconducting qubits
- Integrated ion traps
- Photonic integrated circuits
- Site-specific donor on silicon

Collaborations

We analysed papers published from 2018 onwards, with some or all the authors based in Singaporean institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.



326 papers from Singaporean authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	37
PHYSICAL REVIEW B	25
PHYSICAL REVIEW LETTERS	22
IEEE TRANSACTIONS ON INFORMATION THEORY	12
NPJ QUANTUM INFORMATION	10
NATURE COMMUNICATIONS	9
NEW JOURNAL OF PHYSICS	9
PHYSICAL REVIEW RESEARCH	9
TOWARDS A SCALABLE QUANTUM COMPUTING PLATFORM IN THEULTRASTRONG COUPLING REGIME	8
PRX QUANTUM	7

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 380 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

Country	Number of citations
Australia	17
Canada	11
China	107
Czech Republic	1
Denmark	3
Finland	12
France	6
Germany	2
Hungary	1
India	1
Ireland	1
Israel	3
Italy	19
Japan	13
Malaysia	1
Netherlands	1
Singapore	78
South Africa	2
Spain	9
Sweden	2
Switzerland	3
Thailand	3
UK	49
USA	35
Grand total	**380**

The lead author's institutional country for these fifty papers is shown below.

Country	Number of papers
Australia	2
China	17
Finland	1
Israel	1
Italy	2
Japan	2
Singapore	15
Spain	2
Switzerland	1
UK	6
USA	1
Grand total	**50**

South Korea

In February 2019, the Republic of Korea's Ministry of Science and ICT (MSIT) announced it would invest $40 million in quantum computing over the next five years. The investment of KRW 44.5 billion ($39.7 million) was to develop the core technology of quantum computing and to expand the domestic research base. There was also an additional investment of KRW 13.4 billion ($11.9 million) in next-generation ICT technology including ultra high-performance computing, system software, software engineering, information and intelligence systems, and human-computer Interaction. This was followed up with a KRW 49 billion ($37.6 million) allocation to quantum technology R&D in April 2021 [62].

In June 2022, the Minister of Science, Technology and Information and Communication Lee Jong-ho held a reporting session on the establishment of a 50-qubit quantum computer and the development of quantum internet at the Korea Research Institute of Standards and Science (KRISS) in Daejeon, with KRW 49 billion and KRW 45.6 billion invested respectively to 2026. The Institute aims to build a 20-qubit quantum computer by the end of 2024, with demonstrations of cloud services, and a 50-qubit quantum computer by the end of 2026, with the intent to provide quantum computing services to domestic researchers [63]. Director of the Institute, Lee Jong-ho, noted "It is difficult for domestic conditions alone, so we need to seek expert advice from overseas and, if necessary, send domestic researchers abroad for training," [63].

In its policy plan for 2023, the Government set quantum technology as one of the future technologies the Republic of Korea should nurture [64], and in May of 2023 a national quantum technology development roadmap was announced. In partnership with the country's major conglomerates, South Korea expects to spend 3.5 trillion won ($2.6 billion) on quantum science and technology development by 2035. In the same period, it aims to bolster its share in the global quantum technology market to 7.3% from 1.8% over the same period, increase research talent in the field to 2,000 from 300, and increase the number of quantum startups from 9 to 100. The public and private collaboration is led by Korea's Ministry of Science and ICT, alongside Samsung Electronics, Hyundai Motor, SK Telecom and LG Electronics [65]. One initial measure was the announcement of a new quantum technology graduate school, led by the Korea Advanced Institute of Science and Technology, receiving 24.2 billion won over the next nine years, aiming to produce 180 doctoral students. LG, Samsung and others will run internship programs with the graduate school [66].

Quantum Centres

KRISS

KRISS is home to a Quantum Technology Institute, which carries out a broad range of R&D projects for next-generation quantum computing, quantum communications, and quantum sensors. The Institute is subdivided into several teams: Quantum Spin, Hybrid Quantum Systems, Quantum Optics, Quantum Magnetic Imaging, Fab Infra, Ultracold Atom Quantum Research and Single-electron Quantum Devices. There is a focus on measuring and controlling quantized physical entities such as photons, atoms, electrons, and phonons, as well as the generation and control of quantum mechanical effects [67]. KRISS has a number of MoUs with international counterparts – see the Collaborations section. In May 2021, in collaboration with the Quantum Information Group at the Korea Institute for Advanced Study and the Electronics and Telecommunications Research Institute, KRISS demonstrated a highly accurate quantum state estimation, a requirement for reliable QIT [68].

Busan

The Busan Metropolitan Government aims to build a quantum computing ecosystem. In July 2022 it signed an MoU with IBM, with IBM providing technology and manpower whilst Busan city supports administration. The government also signed an agreement with the development investment company Hines, planning to build a quantum complex [69]. It formally launched Busan's Quantum Initiative in 2023, with the complex's completion scheduled for 2027 [70].

Others

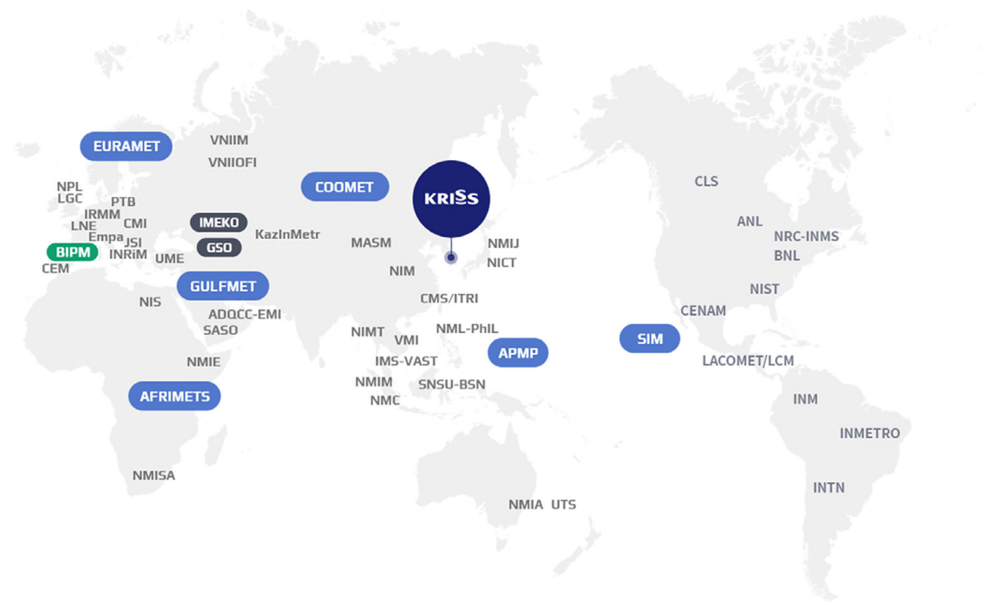
The Q Center is an independent organisation at Sungkyunkwan University focused on quantum information science. It signed a three-year quantum alliance partnership with IonQ in 2021, to make IonQ's trapped-ion based quantum computers available for research and teaching [71].

Seoul National University has a Quantum Information and Quantum Computing Lab, with a focus on trapped-ion technology as well as development of quantum algorithms and quantum information theory [72]. A list of trapped-ion groups across South Korea is shown in the table below.

Institution	Group	City
Pohang University of Science and Technology	Quantum Computing and Quantum Network	Pohang
Ewha Womans University	Trapped Ion Quantum Computing Lab	Seoul
Seoul National University	Nano/Micro system & controls Lab	Seoul
Seoul National University	Quantum Information and Quantum Computing Lab	Seoul
Sungkyunkwan University	Quantum Engineering with Trapped Ions	Suwon

Yonsei University signed an agreement with IBM in 2022 to establish the Yonsei-IBM Quantum Computing Center, with the university seeking to promote quantum industry and research, develop software and train future quantum talent [73].

KRISS has several partnerships and MoUs in place with metrology and other institutes worldwide, as shown in the figure below.



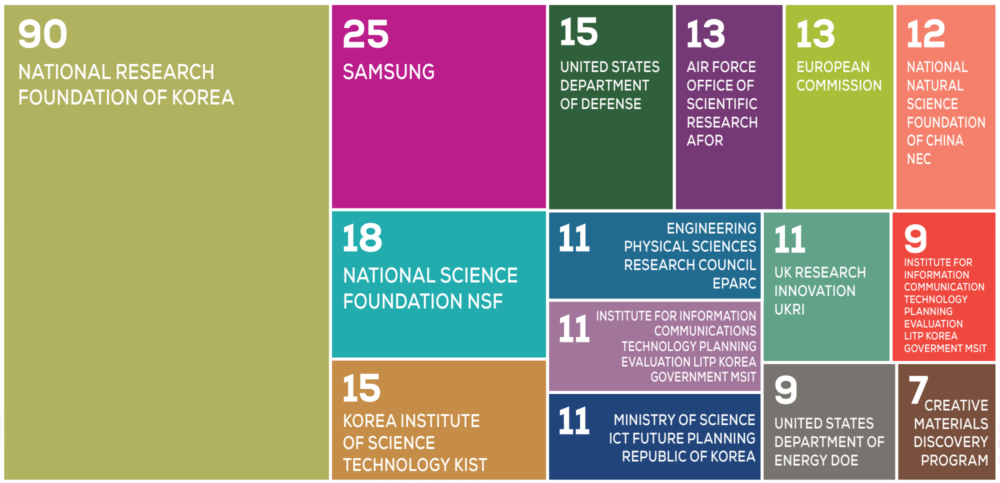
Collaborations

South Korea signed an agreement with the USA in 2023 to cooperate on quantum information science and technology. The countries plan to facilitate interactions between government, academia and industry to understand QIT research and identify opportunities for cooperation. They also intend to promote joint research, including personnel exchanges [74].

In January 2023 President Yoon Suk Yeol visited the Swiss Federal Institute of Technology, speaking with quantum technology experts [75]. A Swiss-Korean forum on “Preparing for the Age of Quantum” was held in Seoul in May 2023 [76].

Australia and South Korea signed an MoU on Cyber and Critical Technology Cooperation, which listed quantum computing as a critical technology. The MoU sought to enhance information sharing and drive shared economic prosperity [77].

We analysed papers published from 2018 onwards, with some or all the authors based in South Korean institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. The affiliations of the authors are also shown.



300 papers from South Korean authors were published in this period. The most common journals these papers were published in are shown below.

Journal	Number of papers
INTERNATIONAL JOURNAL OF THEORETICAL PHYSICS	17
SCIENTIFIC REPORTS	15
PHYSICAL REVIEW A	13
IEEE ACCESS	12
QUANTUM INFORMATION PROCESSING	11
APPLIED SCIENCES-BASEL	9
PHYSICAL REVIEW B	7
PHYSICAL REVIEW LETTERS	7
ACS PHOTONICS	6
NANO LETTERS	6

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 380 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

The lead author's institutional country for these fifty papers is shown below.

Country	Number of citations
Australia	1
Austria	2
Brazil	4
Canada	1
Chile	1
China	13
Denmark	1
Egypt	6
France	14
Germany	26
India	1
Japan	10
Korea	133
Mexico	2
Netherlands	4
Poland	1
Russia	5
Saudi Arabia	1
Singapore	1
Spain	9
Switzerland	15
Taiwan	2
Thailand	1
UK	34
USA	68
Vietnam	1
Grand Total	**357**

Country	Number of papers
Brazil	1
China	2
Egypt	2
France	2
Germany	3
Japan	1
Korea	24
Netherlands	1
Spain	1
Switzerland	1
UK	4
USA	8
Grand total	**50**

United States

The United States of America is considered a leader in QIT, ranking number one in terms of quantum computing related patents issued between 2010 and 2020, as well as private equity deal activity since 2016 [78], [79]. Nevertheless, it is only relatively recently that there has been a push towards a co-ordinated national quantum strategy. The National Science Foundation (NSF) announced "10 Big Ideas" in 2016 for driving important aspects of NSF's long-term research agenda, which included "Quantum Leap" [80] and in 2018 announced a $15m grant for creating a practical quantum computer [81].

In September 2018, the Subcommittee on Quantum Information Science published its National Strategic Overview for Quantum Information Science (QIS), and in December of that year the National Quantum Initiative (NQI) Act was passed by Congress [82]. This allocated $1.1bn [83] to a dedicated national program, coordinated by a newly-established National Quantum Coordination Office (NQCO), over a five-year period to 2023. The act called for both the NSF and Department of Energy (DOE) to carry out research on quantum information science. The NSF was also expected to award grants to establish multidisciplinary quantum research and education centres, whilst the DOE was expected to establish and operate its own centres – these are covered in detail in the next section of the report. The National Institute of Standards and Technology was called to "convene a consortium to identify the future measurement, standards, cybersecurity, and other needs to support the development of a quantum information science and technology industry," [82].

The NQI program has ramped up significantly, with agencies reporting actual budget expenditures for QIS R&D of $449 million in Fiscal Year 2019, $672million in FY 2020, and $855 million in FY 2021, followed by $918 million of enacted budget authority for QIS R&D in FY 2022, and a requested budget authority of $844 million for QIS R&D in FY 2023 [84].

A National Quantum Initiative Advisory Committee was established in August 2020 [85], with further enhancements in May 2022 [86], and in October of that year the NQCO and the White House published a Quantum Frontiers report [87] which listed eight core issues considered priority areas:

- Expanding Opportunities for Quantum Technologies to Benefit Society
- Building the Discipline of Quantum Engineering
- Targeting Materials Science for Quantum Technologies
- Exploring Quantum Mechanics through Quantum Simulations
- Harnessing Quantum Information Technology for Precision Measurements
- Generating and Distributing Quantum Entanglement for New Applications
- Characterizing and Mitigating Quantum Errors
- Understanding the Universe through Quantum Information

The USA ranks second among the top 10 nations producing quantum scholarly outputs for the quality and impact of its quantum science [5].

Quantum Centres

NSF

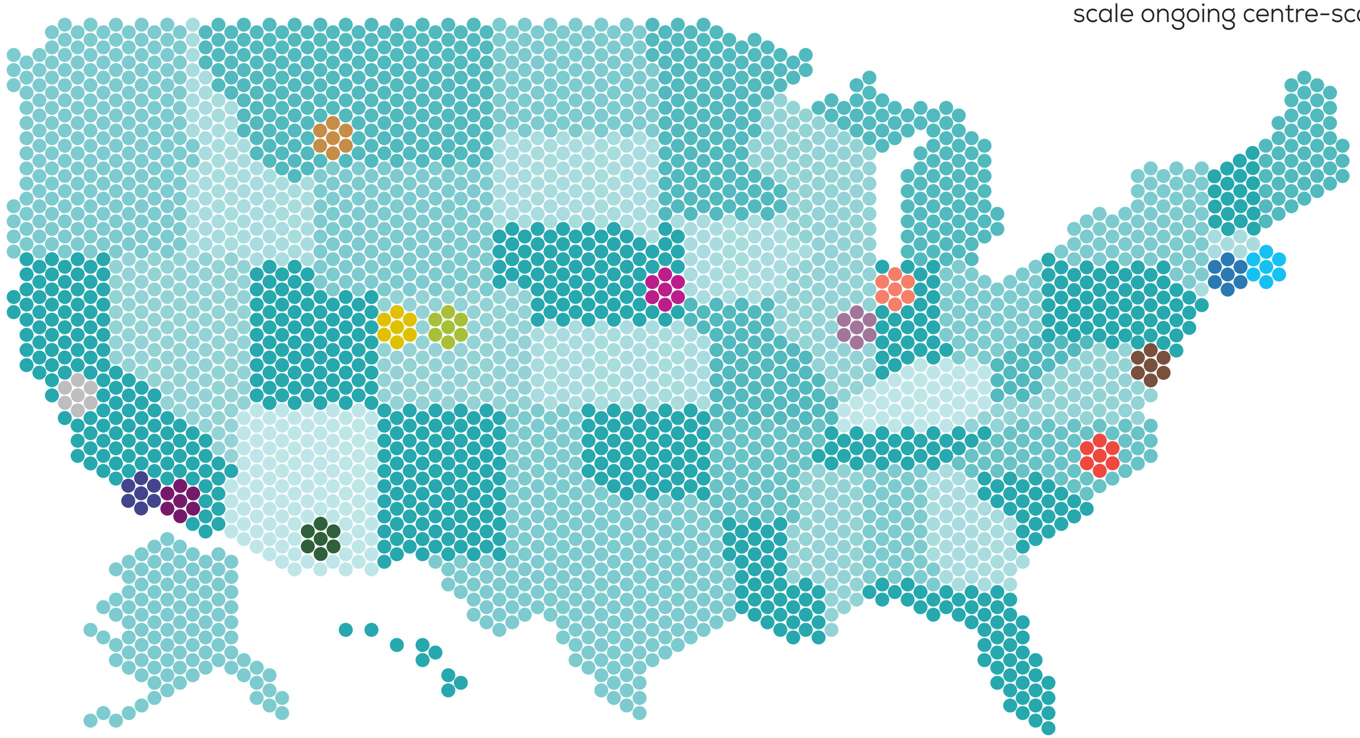
In July 2020 the NSF announced awards for 3 quantum technology centres, as shown in the figure below, initially running from September 2020 to August 2025.

Name	Award $m	Description
NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States.	**25**	This institute, led by the University of Colorado, will design, build, and employ quantum sensing technology for a wide variety of applications in precision measurement.
NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks.	**25**	This institute, led by the University of Illinois, Urbana-Champaign, will build interconnected networks of small-scale quantum processors and test their functionality for practical applications.
NSF Quantum Leap Challenge Institute for Present and Future Quantum Computing.	**25**	This institute, led by the University of California, Berkeley, plans to learn from these to design advanced, large-scale quantum computers, develop efficient algorithms for current and future quantum computing platforms, and ultimately demonstrate that quantum computers outperform even the best conceivable classical computers.

In September 2021 the NSF announced two further awards for Quantum Leap Challenge Institutes in biological sensing and quantum simulation, with each awarded $25m. The NSF Quantum Leap Challenge Institute for Robust Quantum Simulation, led by the University of Maryland, College Park, will develop quantum systems and the methods and tools for large-scale quantum simulators that will allow for quantum computation [88].

The NSF also provided $1.8m of funding to a UCLA centre to develop chemical qubits for quantum computing [89], as well as establishing the Quantum Computing & Information Science - Faculty Fellows (QCIS-FF) to encourage hiring of tenure-track and tenured faculty in quantum computing and quantum communication [90].

Numerous other investments have been made in QIT, and a map showing the full scale ongoing centre-scale NSF investments is shown in the figure below.



NSF Engineering Research Center for Quantum Networks (CQN) (Award-1941583)
University of Arizona

Brigham Young University
University of Massachusetts Amherst
Howard University
Massachusetts Institute of Technology
Northern Arizona University
Stanford University
University of Chicago
Harvard University
University of Oregon Eugene
Yale University

RII Track-1: Emergent Quantum Materials and Technologies (EQUATE) (Award-2044049)
University of Nebraska

Creighton University Nebraska Indian Community College University of Nebraska at Omaha
Creighton University Nebraska Indian Community College University of Nebraska at Omaha

QLCI-CI: NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States (Award -2016244)
University of Colorado at Boulder

Harvard University
Massachusetts Institute of Technology
Stanford University
University of Delaware
University of New Mexico
University of Oregon Eugene

QLCI-CI: NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks (Award -2016136)
University of Illinois at Urbana-Champaign

University of Chicago
University of Wisconsin-Madison

QLCI-CI: NSF Quantum Leap Challenge Institute for Present and Future Quantum Computing (Award-2016245)
University of California-Berkeley

California Institute of Technology
Massachusetts Institute of Technology
University of California-Los Angeles
University of California-Santa Barbara
University of Texas at Austin
University of Washington

QLCI-CI: NSF Quantum Leap Challenge Institute for Quantum Sensing in Biophysics and Bioengineering (Award -2121044)
University of Chicago

Chicago State University
Harvard University
University of Illinois at Chicago

QLCI-CI: NSF Quantum Leap Challenge Institute for Robust Quantum Simulation (Award -2120757)
University of Maryland, College Park

Duke University
North Carolina State University
Princeton University
Yale University

Center for Integrated Quantum Materials (Award -1231319)
Harvard University

Bunker Hill Community College
Gallaudet University
The Learning Center for the Deaf
Massachusetts Institute of Technology
Prince Georges Community College
Museum of Science
Wellesley College
Howard University
Mount Holyoke College

The Institute for Quantum Information and Matter: Advancing the Entanglement Frontier (Award -1733907)
California Institute of Technology

JILA PFC: Measurement, Manipulation, and Meaning at the Quantum Frontier (Award -1734006)
University of Colorado at Boulder

Center for Ultracold Atoms (Award -1734011)
Massachusetts Institute of Technology

Harvard University

PFCQC: STAQ: Software-Tailored Architecture for Quantum co-design (Award-1818914)
Duke University

Massachusetts Institute of Technology
North Carolina State University
University of Maryland, College Park
Tufts University
University of Chicago
University of New Mexico
University of California-Berkeley

Enabling Quantum Leap: Q-AMASE-i: Quantum Foundry at UCSB (Award-1906325)
University of California-Santa Barbara

Boston University
University of California-San Diego
University of Pittsburgh

Enabling Quantum Leap: Q-AMASE-i: MonArk Quantum Foundry: Rapidly Incubating Translational Advances in QISE with a 2D-Quantum Materials Pipeline (2D-QMaP) (Award -1906383)
Montana State University

University of Arkansas

DOE

In January 2020, the DOE announced up to $625 million over the next five years to establish two to five multidisciplinary Quantum Information Science Research Centres in support of the NQI. These 5 centres are detailed in the figure below.

C²QA Co-design Center for Quantum Advantage

Website:
bnl.gov/quantumcenter

Lead laboratory:
Brookhaven National Laboratory

The Co-design Center for Quantum Advantage (C2QA) aims to overcome the limitations of today's noisy intermediate scale quantum (NISQ) computer systems to achieve quantum advantage for scientific computations in high-energy, nuclear, chemical, and condensed matter physics. Its technology focus is superconducting microwave circuits and modules for quantum computation and hybrid superconducting/optical devices for quantum communication. The integrated five-year aspirational goal of C2QA is to deliver a factor of 10 improvement in software optimization, underlying materials and device properties, and quantum error correction, and to ensure these improvements combine to provide a factor of 1,000 improvement in appropriate metrics for computation and communication.

Q-NEXT Next Generation Quantum Science and Engineering

Website:
q-next.org

Lead laboratory:
Argonne National Laboratory

Q-NEXT brings together leading experts from national laboratories, academia and the private sector to develop the science and technology to control and distribute quantum information. The center develops technologies to enable: secure communication over long distances using quantum repeaters; quantum sensors to achieve unprecedented sensitivities; and processing and test beds for quantum simulators and future full-stack universal quantum computers. Q-NEXT will also create two national foundries for quantum materials, establish a first-ever National Quantum Devices Database for the standardization of next-generation quantum devices, and train the next-generation quantum workforce through innovative programs with industry, academia, and government.

QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

Website:
quantumsystemsaccelerator.org

Lead laboratory:
Lawrence Berkeley National Laboratory

The Quantum Systems Accelerator (QSA) will catalyze national leadership in quantum information science to co-design the algorithms, quantum devices, and engineering solutions needed to deliver certified quantum advantage in scientific applications. Led by Lawrence Berkeley National Laboratory with lead partner Sandia National Laboratories, the QSA brings together dozens of scientists who are pioneers of many of today's quantum capabilities from 15 institutions. The team pairs advanced quantum prototypes - based on neutral atoms, trapped ions, and superconducting circuits - with algorithms specifically designed for imperfect hardware to demonstrate optimal applications for each platform in scientific computing, materials science, and fundamental physics.

QUANTUM SCIENCE CENTER

Website:
qscience.org

Lead laboratory:
Oak Ridge National Laboratory

The Quantum Science Center (OSC) performs cutting edge research at national laboratories, universities, and industry partners to overcome key roadblocks in quantum state resilience, controllability, and ultimately the scalability of quantum technologies. QSC researchers are designing materials that enable topological quantum computing; implementing new quan- tum sensors to characterize topological states and detect dark matter; and designing quan- tum algorithms and simulations to provide a greater understanding of quantum materials, chemistry, and quantum field theories. These innovations will enable the QSC, headquar- tered at ORNL, to accelerate information processing, explore the previously unmeasurable, and better predict quantum performance across technologies.

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Website:
sqms.fnal.gov

Lead laboratory:
Fermi National Accelerator Laboratory

The Superconducting Quantum Materials and Systems Center (SQMS) brings together part- ners from national laboratories, academia, and industry to make revolutionary advances in quantum information science, including the building and deployment of the first quantum computer at Fermilab. A key SQMS goal is to extend the 'coherence time' of quantum states - the lifetime of a qubit or a quantum sensor. Building on a world-record coherence time, demonstrated at Fermilab in superconducting devices, and drawing on world-class expertise in materials science, condensed matter physics, particle physics, and computational science, SQMS will deliver new national QIS platforms for scientific discovery.

The DOE has announced various other awards in support of the NQI, including $25m in August 2021 for the establishment of a quantum internet testbed [91].

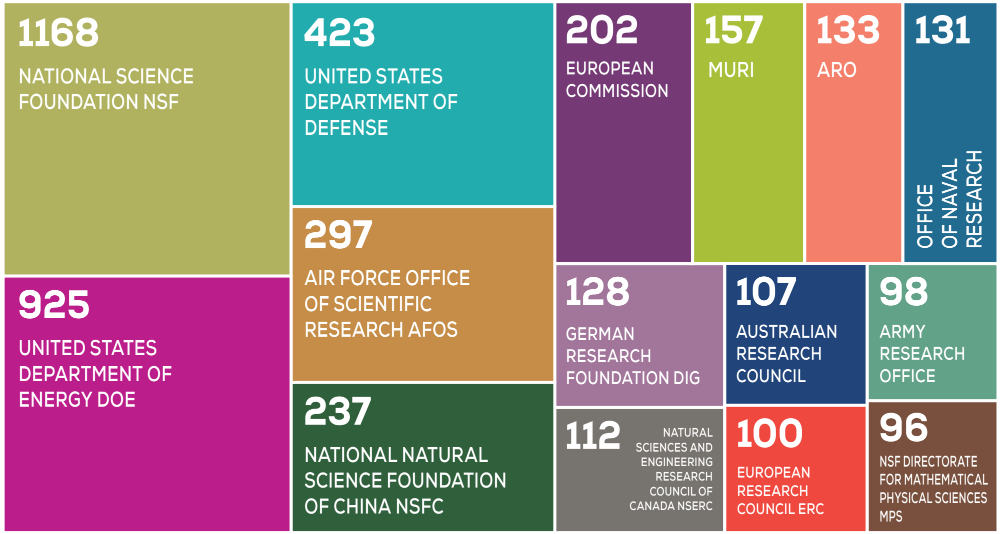
There are also regional initiatives, such as the Washington Metropolitan Quantum Network Research Consortium (DC-QNet) which seeks to create, demonstrate and operate a quantum network as a regional testbed [92].

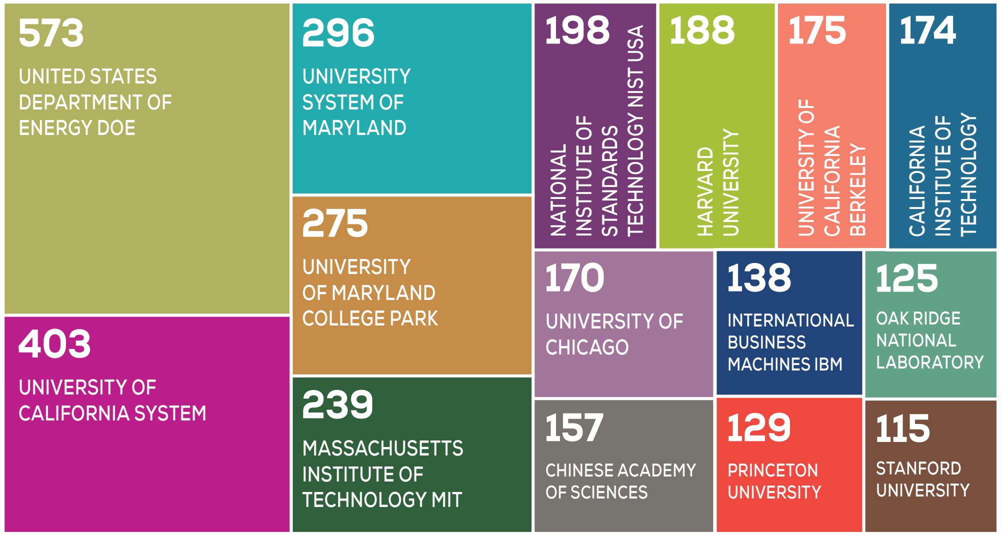
Collaborations

The 2018 NQI Act called for the evaluation of "opportunities for international cooperation with strategic allies on research and development in quantum information science and technology," and the USA has been particularly active on this front. In December 2019, the Tokyo Statement on Quantum Cooperation was signed by the USA and Japan, encouraging increased engagement in Quantum Information Science and Technology (QIST) through international conferences and events, cooperative efforts to prepare the next generation of QIST scientists and engineers and the sharing of research [93]. This was followed by two further statements in November 2021. The USA and UK, on the four-year anniversary of the inaugural USA-UK Science and Technology Agreement, issued a joint statement of intent to further cooperation on QIST, which included an enhanced partnership between the NSF and UK Research and Innovation [94]. A joint statement was also issued by the USA and Australia, strengthening their ability to exchange quantum knowledge and skills, creating more opportunities to promote research and development, and encouraging greater market access for quantum businesses in both nations [95]. Three further cooperation in QIST statements were issued in 2022, with Finland and Sweden both in April, and Denmark in June [96], [97], [98]. In May 2022, The White House Office of Science and Technology Policy (OSTP) and the U.S. Department of State hosted a roundtable on Pursuing Quantum Information Together. This included representatives from Australia, Canada, Denmark, Finland, France, Germany, Japan, the Netherlands, Sweden, Switzerland and the UK [99].

There has also been activity with South Korea. In 2021 The U.S. Air Force Research Laboratory's Air Force Office of Scientific Research, the National Research Foundation of Korea, and South Korea's Institute of Information & Communications Technology Planning & Evaluation announced joint three-year research grants in quantum information science and technologies [100]. In 2022 the U.S. Department of Defense named quantum computing as a key technology for a U.S.-South Korea Technology Collaboration [101]. A wider agreement between the USA and South Korea was announced in 2023.

We analysed papers published from 2018 onwards, with some or all the authors based in USA institutions. A visualisation of the top ten funding organisations for these bodies of work is shown below. As well as the NSF and DOE, the military funds a large proportion of QIT research. The affiliations of the authors are also shown.





The most common journals USA QIT papers were published in are shown below.

Journal	Number of papers
PHYSICAL REVIEW A	296
PHYSICAL REVIEW LETTERS	210
PHYSICAL REVIEW B	172
PHYSICAL REVIEW RESEARCH	127
QUANTUM SCIENCE AND TECHNOLOGY	96
PRX QUANTUM	95
QUANTUM	89
NPJ QUANTUM INFORMATION	84
PHYSICAL REVIEW X	78
NATURE COMMUNICATIONS	76

These papers were then ranked in terms of number of citations, and the top fifty selected. These fifty papers were cited 600 times between them. These citations can provide an indication of activity, as well as crosslinks and collaborations between the countries in question.

The lead author's institutional country for these fifty papers is shown below.

Country	Number of citations
Australia	5
Belgium	2
Brazil	2
Canada	3
China	31
Czech Republic	3
Denmark	10
Finland	6
France	5
Germany	9
Iceland	1
Ireland	1
Israel	11
Italy	4
Japan	13

Country	Number of citations
Malaysia	1
Mexico	2
Netherlands	30
Poland	3
Portugal	2
Russia	1
Singapore	1
South Africa	1
Spain	11
Sweden	1
Switzerland	11
Thailand	1
UK	14
USA	415
Grand Total	**600**

Country	Number of papers
China	2
Denmark	1
Finland	1
Israel	2
Japan	2
Netherlands	3
Spain	2
Switzerland	1
UK	1
USA	35
Grand total	**50**

Closing remarks

The two parts of this report on the international state of quantum information technologies research demonstrate the commitment of many nations to a quantum-enabled economy of the future, and the robust science base that is needed to underpin this. There is still much research work to be done before we reach quantum advantage in a way that can be usefully applied to industry, but the strong levels of governmental support in many nations is evident and continuing to grow. A significant number of the nations covered in this report have now published national quantum strategies. Whilst this report has not focussed on commercial activity, it is clear that industry engagement and activity to bring technology out of the lab is key, with many nations focussing on wider ecosystem development.

It is encouraging to see the amount of cross-border collaboration, evidenced by the wide range of international collaborators in quantum computing research publications. While many nations have a stated sovereign need to develop their own hardware, there is clearly a high level of networking in the academic communities across borders. Many nations are now implementing bilaterals and MOUs with trusted partners to strengthen their relationships in QIT and wider quantum technology.

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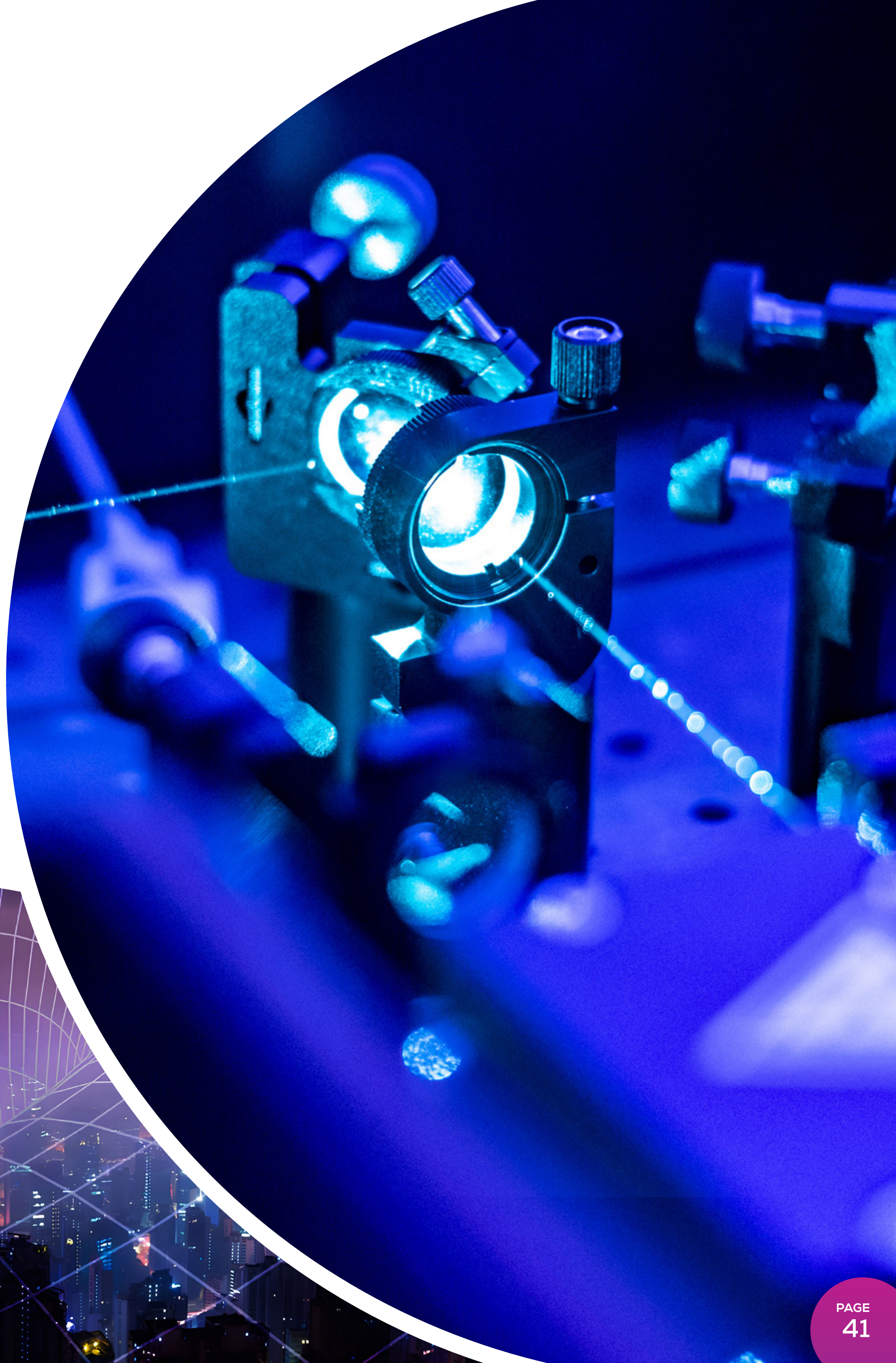

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