Quantum Ecosystem: What it is and Why You Should Care

Dr. Carl J. Williams, Science Advisor and Consultant

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OPTICA | Formerly OSA
Advancing Optics and Photonics Worldwide

What is Quantum Information Science?

Image Source: Nations Online Project

A First Hint of Quantum Information?

"When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent *completely new opportunities* for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and *we can expect to do different things*. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc."

-- Richard P. Feynman, "*Plenty of Room at the Bottom*", December 1959

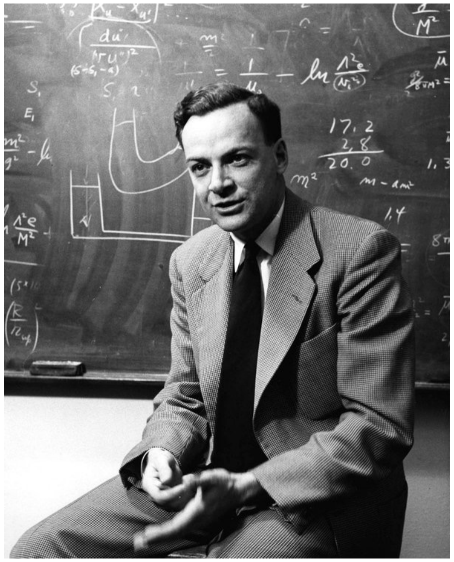
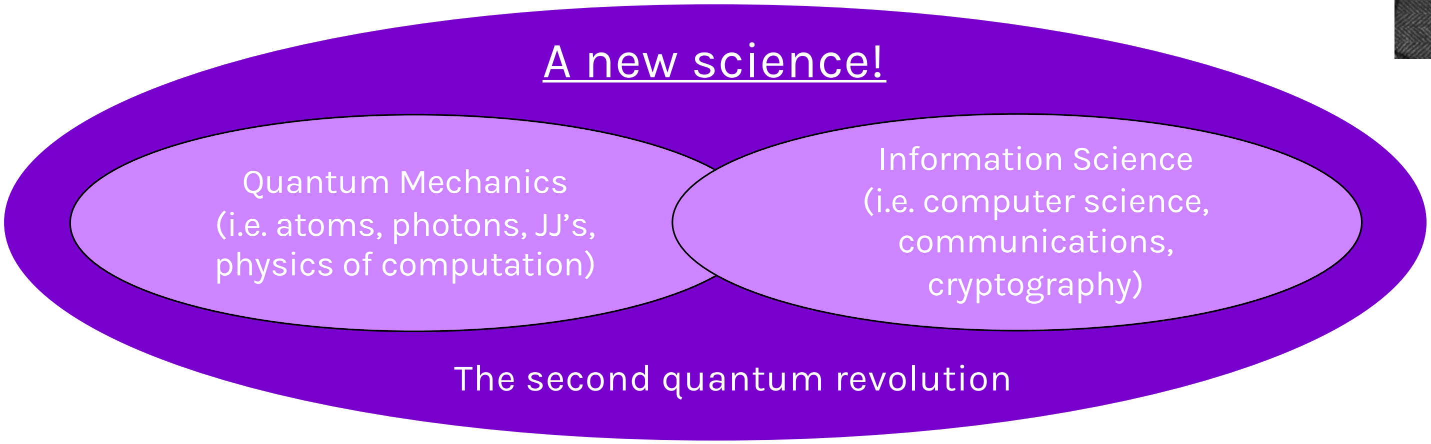


Image Source: Caltech (2018)

What is Quantum Information?

> “Quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus.”
>
> **- W. D. Phillips, 1997 Nobel Prize Winner in Physics**

A convergence of two of the 20th Century’s great revolutions



A new science!

Quantum Mechanics
(i.e. atoms, photons, JJ’s, physics of computation)

Information Science
(i.e. computer science, communications, cryptography)

The second quantum revolution

Image Source: Nobel Prize

Quantum Information Science in a Nutshell

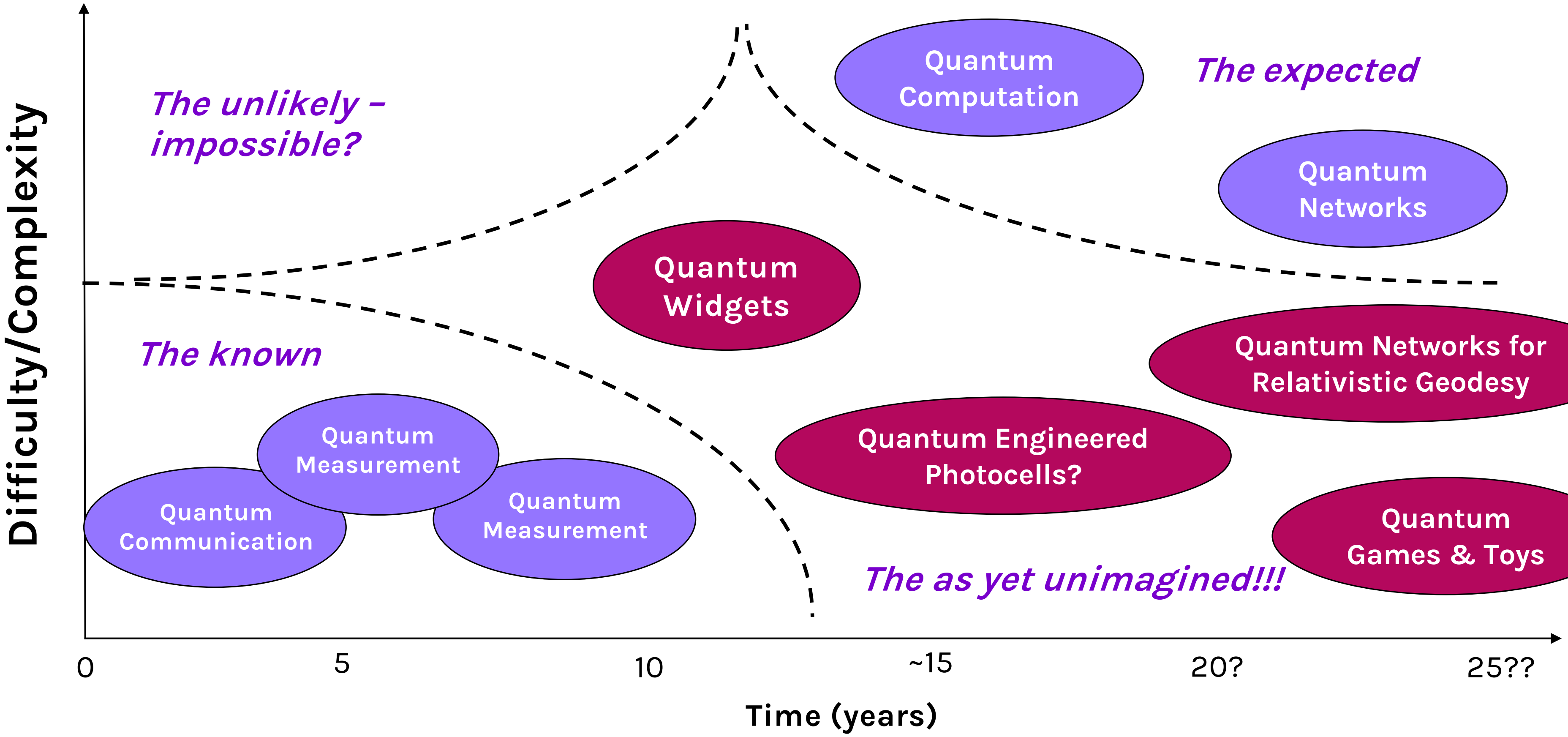
Quantum information science (QIS) exploits unique quantum properties such as *coherence, superposition, entanglement*, and *squeezing to acquire, transmit, and process* information in ways that greatly exceed existing capabilities.

QIS is a field of scientific inquiry in its own right, with applications in:

- **Sensing and metrology**: precision navigation, timekeeping, magnetic fields, etc.
- **Communication**: secure data transmission and storage, random number generation, etc.
- **Simulation**: complex materials, molecular dynamics, QCD, etc.
- **Computing**: cryptanalysis, quantum chemistry, optimization, quantum field theory, etc.

And robust intellectual connections to numerous areas of basic research.

Quantum Information & Future Technology



Difficulty/Complexity

The unlikely – impossible?

The known

Quantum Communication

Quantum Measurement

Quantum Measurement

Quantum Widgets

Quantum Computation

The expected

Quantum Networks

Quantum Networks for Relativistic Geodesy

Quantum Engineered Photocells?

Quantum Games & Toys

The as yet unimagined!!!

0

5

10

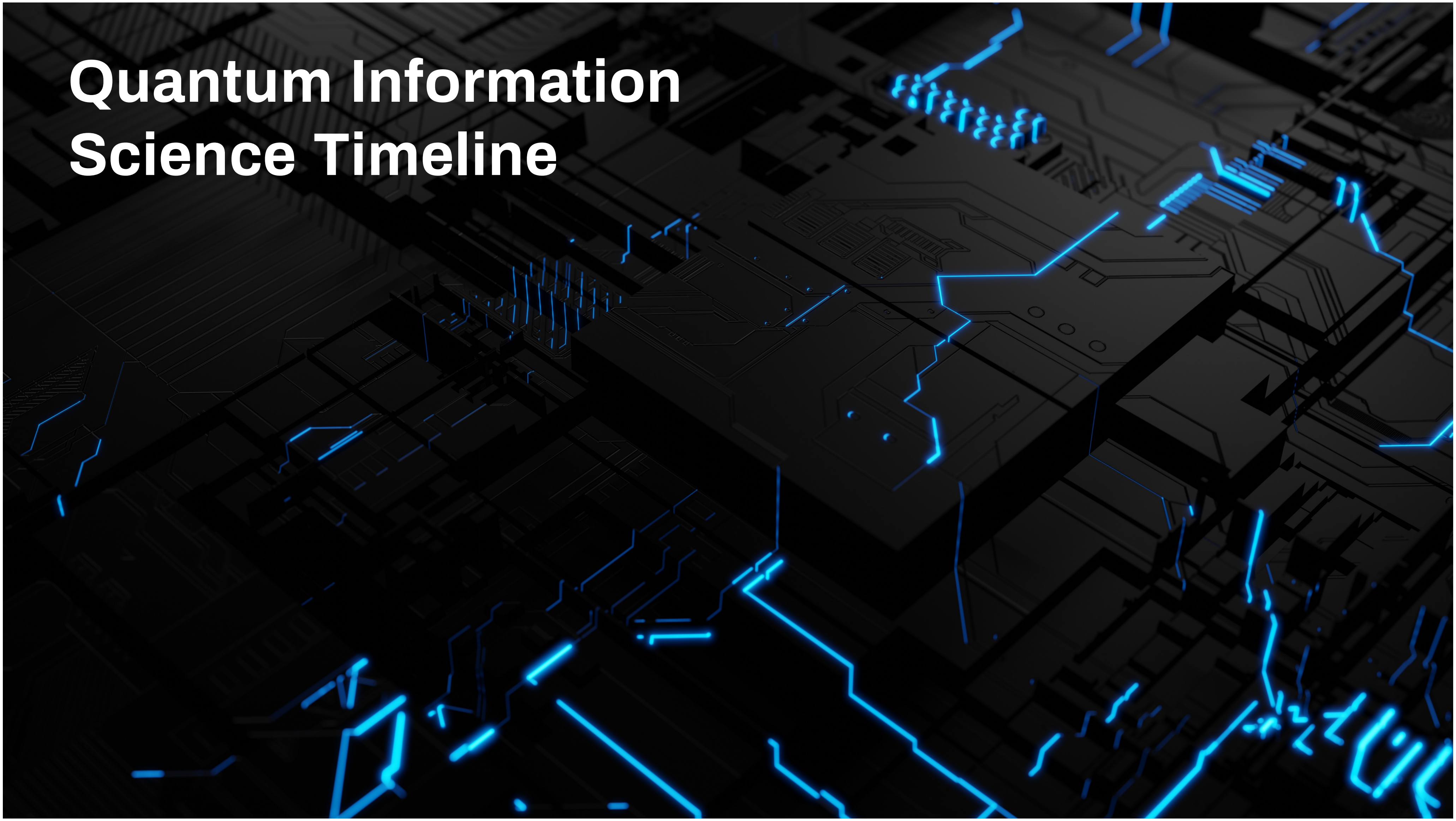
~15

20?

25??

Time (years)

Quantum Information Science Timeline



NQI Background and Coordination

2000's U.S. QIS R&D Investment & Coordination

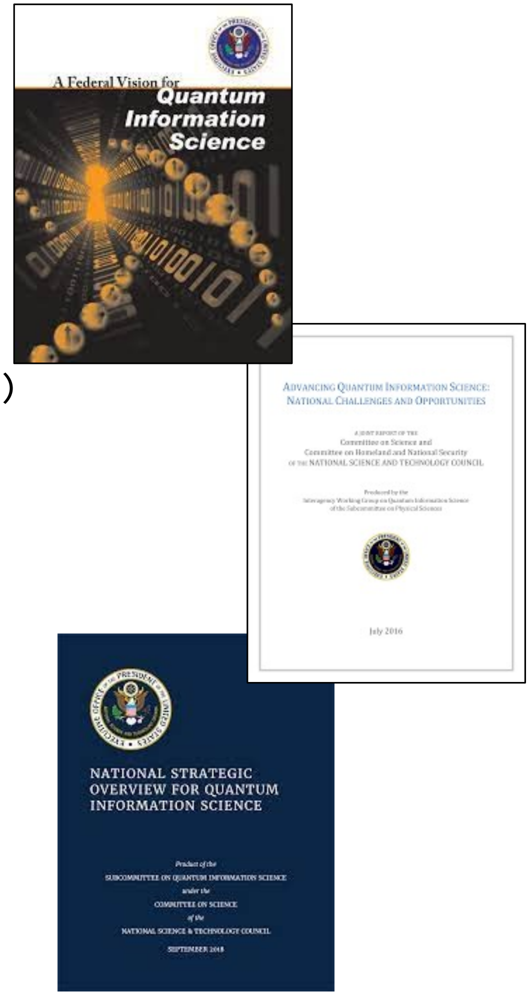
- Academic, Industry, and Government QIS efforts grow
- 2000 DARPA QUIST Program
- NIST, NSF, DOE, DOD, IC, NASA all support QIS programs and Labs
- 2009 A Federal Vision for QIS – National Science & Technology Council (NSTC)
- 2016 Advancing QIS: National Challenges and Opportunities (NSTC)

2018 National Quantum Initiative Act (Public Law 115-368)

- Oct 2017 House Science, Space, and Technology Hearing on QIS Technology
- 2018 National Strategic Overview for QIS (NSTC)
- Consortia, Centers, Coordination, Core Programs

National Defense Authorization Act (PL 115-232) & (PL 116-92)

- Defense QIS and Technology R&D Program



A Federal Vision for
Quantum
Information
Science

ADVANCING QUANTUM INFORMATION SCIENCE:
NATIONAL CHALLENGES AND OPPORTUNITIES

A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences

July 2016

NATIONAL STRATEGIC
OVERVIEW FOR QUANTUM
INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL
SEPTEMBER 2018

Source: quantum.gov; obamawhitehouse.archives.gov; nist.gov

Quantum Information as a Disruptive Technology

“Our society is being transformed by an information technology revolution … At the core of this revolution is the concept of a programmable digital computer which turned out to be the foundation for what economists call a disruptive technology, actually a whole family of technologies … Now we know that devices can be made that allow the non-intuitive quantum logic to reveal itself in practical systems … It appears that these and similar phenomena can be employed to process information in a way that transcends at least some of the built-in limitations of conventional computing. Some of the “impossible” problems are known to be solvable by a large scale quantum device … It creates a new conceptual platform for a family of potentially disruptive technologies, adding a new stage to the already staggering impact of conventional information technology”

-- John “Jack” Marburger, “A Federal Vision for Quantum Information Science,” January 2009

Image Source: Wikipedia

Advancing a New National Strategy for QIS

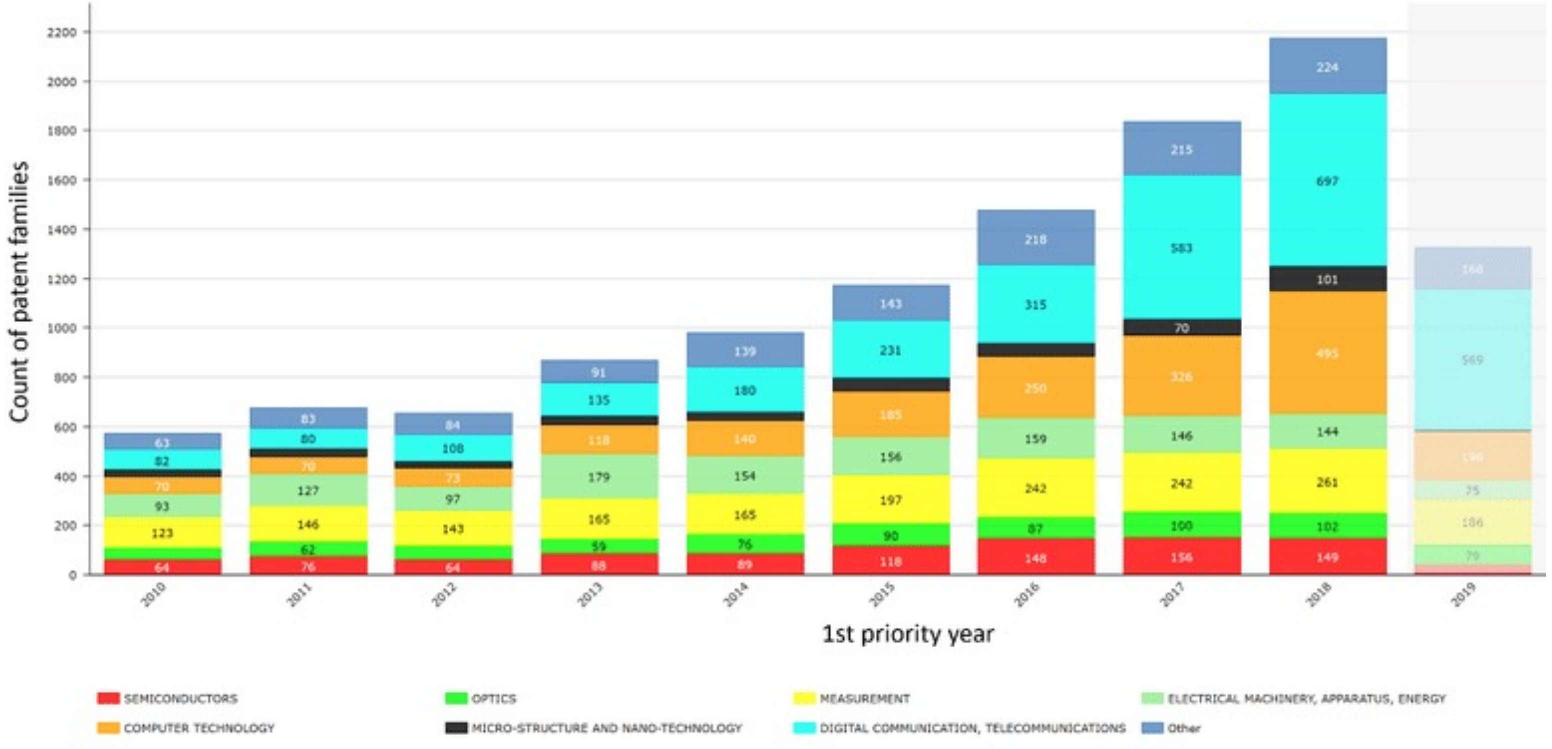
- On September 23, 2018, OSTP/NSTC released a new national strategy for QIS – consistent with the NQI Act.
- On September 24, 2018, OSTP held a *Summit on Advancing American Leadership in QIS* with about 100 participants from academy, industry, and the USG. Closing remarks were by Lamar Smith.
- NQI Act becomes law Dec. 21, 2018.
- On May 31, 2019, OSTP held an *Academic Roundtable on Innovation in Quantum Information Science*

Note: By the time of the 2016 (2^{nd}) report was published, we were already too late

Industry was moving!

Image Source: OSTP

World-Wide Patents: All of QIS



From 2009-2018 the Combined Annual Growth Rate (CAGR) for QIS patents was 18.8%.

Led by China with 5161 (mostly quantum communication) and then the U.S. with 2401 patents.

From Quantum Technologies Patents, Publications, and Investments, Michel Kurek, Sept. 2020 (Paris); Fig. 2

Source: https://www.researchgate.net/publication/350453567_Quantum_Technologies_Patents_Publications_Investissements_Landscape

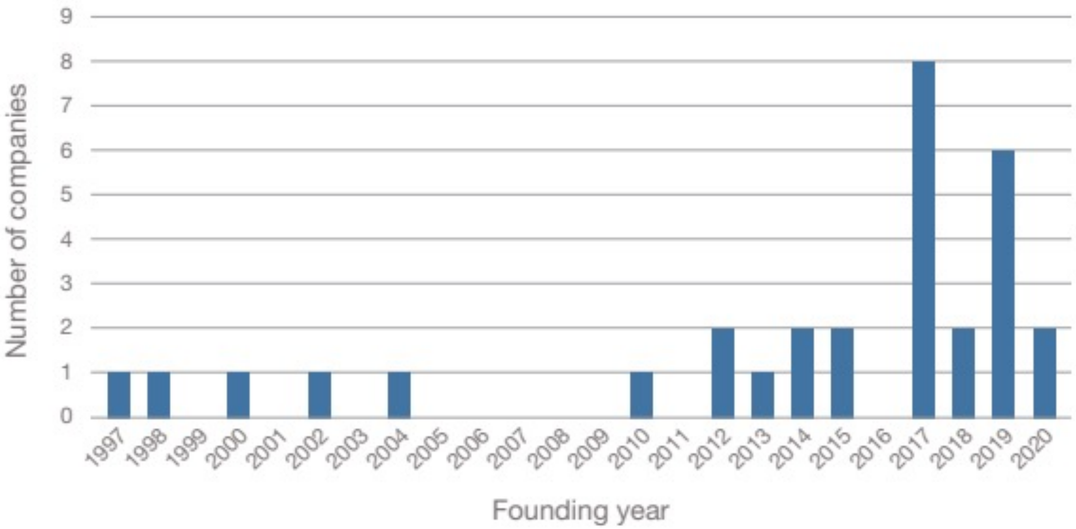
US Corporate Activity for Start-ups and QC Companies

Start of U.S. Quantum Computing: Efforts by start-ups and established companies

- ➢ IBM – mid 2000’s
- ➢ Microsoft – 2005 (2011 HW)
- ➢ Rigetti – 2013
- ➢ Google – 2013
- ➢ QCWare – 2014
- ➢ QxBranch – 2014
- ➢ IonQ – 2015
- ➢ Quantum Circuits – 2015
- ➢ Intel – 2015
- ➢ PsiQuantum -- 2016

FIGURE 3.9

Distribution of Quantum-Focused QED-C Companies by Founding Year



NOTE: One company founded before 1997 is omitted for space.

Year of establishment for 32 QED-C Quantum-Focused Start-up Companies.

Source: From “An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology” by Rand Corporation (2022).

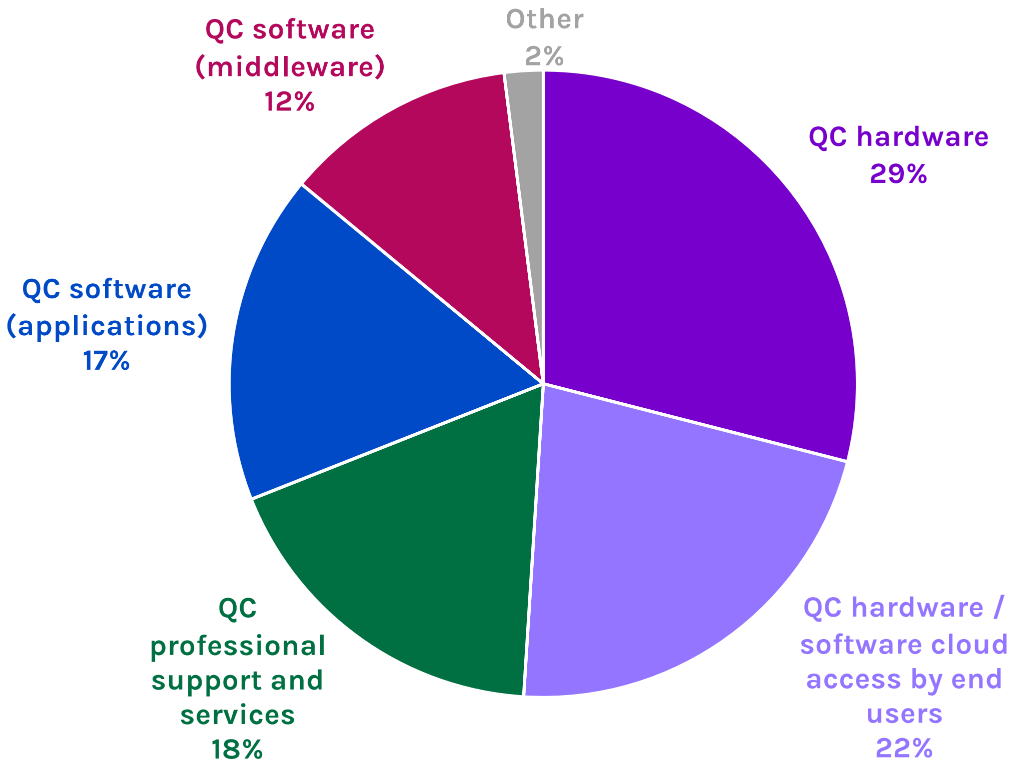
State-of-the-Art in Quantum Computing

- Numerous companies have demonstrated devices with 50-100 qubits. (U.S. leads)
- Devices are based on “noisy qubits” that are of insufficient quality to be error corrected
- Quantum error correction adds a factor of between 100-10,000 in the number of qubits needed for an error free calculation
- Multiple companies have roadmaps to scalable 1000 qubit devices by 2028.
- Technologies include superconducting qubits, atoms/ions, photons, and gated transistor like qubits.

Dilution Refrigerator for IBM QC

Image Source: IBM Q

Quantum Computing Market Size



- Global QC Market was worth about $250M in 2019
- Based on Buyer/User survey results concludes the market was approximately$320M in 2020
- Based on a Compound Aggregate Growth Rate (CAGR) of 27% it will be about $830M in 2024
- Study repeated with more data in 2021 – similar results
- Study by Hyperion Research for the Quantum Economic Development Consortium (QED-C). Study supported by NIST and Google.

Source: Optica, formerly OSA (2022)

Boston Consulting Group Analysis

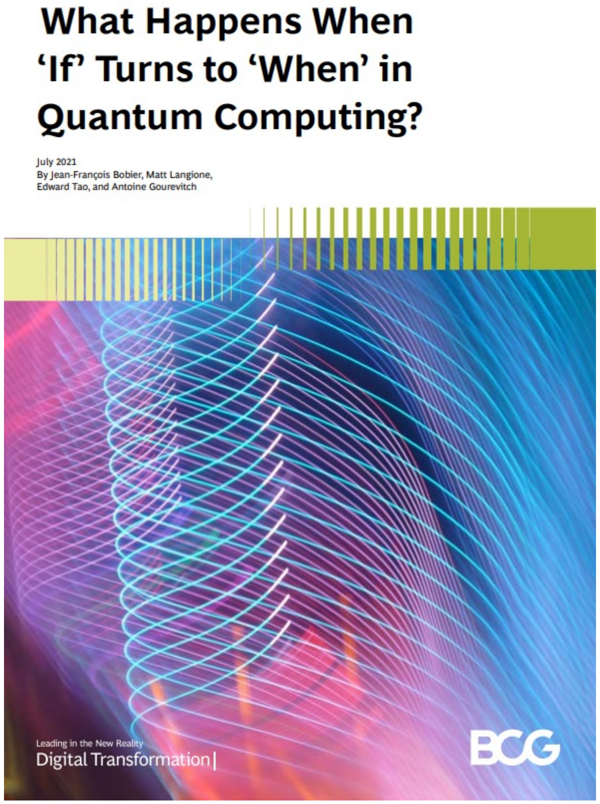
THE NEXT DECADE IN QUANTUM COMPUTING—AND HOW TO PLAY

BCG

Where Will Quantum Computers Create Value—and When?

The second of these two suggests that by 2024 quantum computing will be worth $2-5B to its end users and that in the coming decades it will surpass $450B annually.

The new report suggest the value may be $850B!



What Happens When 'If' Turns to 'When' in Quantum Computing?

July 2021
By Jean-François Bobier, Matt Langione,
Edward Tao, and Antoine Gourevitch

Leading in the New Reality
Digital Transformation |

BCG

Source: Boston Consultant Group

Where are the QC Applications Ultimately?

- Figures and Data from BCG Report – “What Happens When ‘If’ Turns to ‘When’ …”
- NISQ era (before 2030) – $5B-$10B
- Broad Quantum Advantage (after 2030) – $80B-$170B
- Full-scale fault tolerant (after 2040) – $450B-$850B

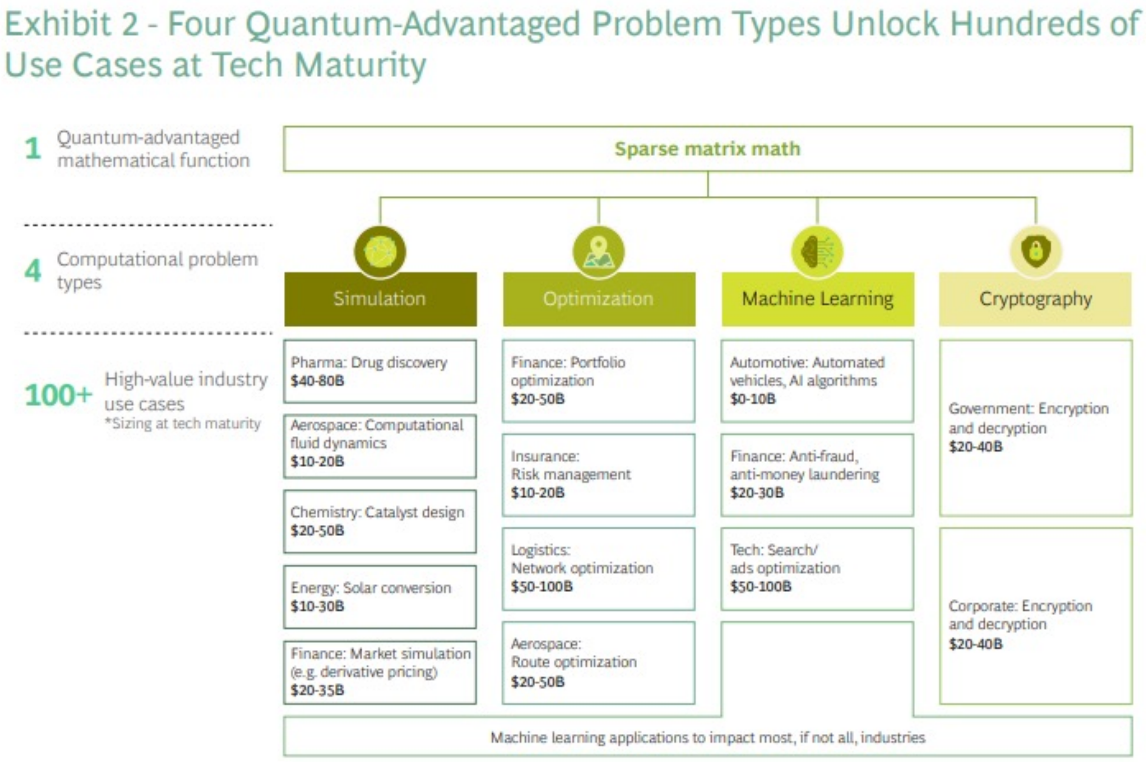


Exhibit 2 - Four Quantum-Advantaged Problem Types Unlock Hundreds of Use Cases at Tech Maturity

1 Quantum-advantaged mathematical function

Sparse matrix math

4 Computational problem types

100+ High-value industry use cases
*Sizing at tech maturity

Simulation	Optimization	Machine Learning	Cryptography
Pharma: Drug discovery $40-80B	Finance: Portfolio optimization $20-50B	Automotive: Automated vehicles, AI algorithms $0-10B	Government: Encryption and decryption $20-40B
Aerospace: Computational fluid dynamics $10-20B	Insurance: Risk management $10-20B	Finance: Anti-fraud, anti-money laundering $20-30B	Corporate: Encryption and decryption $20-40B
Chemistry: Catalyst design $20-50B	Logistics: Network optimization $50-100B	Tech: Search/ ads optimization $50-100B	
Energy: Solar conversion $10-30B	Aerospace: Route optimization $20-50B		
Finance: Market simulation (e.g. derivative pricing) $20-35B			

Machine learning applications to impact most, if not all, industries

Image Source: Boston Consulting Group

Quantum Computing Use Cases

"Some pharmaceutical players have already realized the need to join forces on the topic of QC and have started to collaborate and/or form partnerships. For example, QuPharm formed in late 2019 by major pharmaceutical players to pool ideas and expertise around QC use cases. QuPharm also collaborates with the Quantum Economic Development Consortium (QED-C), which was created in 2018 by the US government as part of the National Quantum Initiative Act and aims to enable commercial QC use-case efforts. Additionally, the Pistoia Alliance is a life sciences membership organization, which was organized to facilitate precompetitive collaboration and foster R&D innovation."

McKinsey "Pharma's digital Rx: Quantum computing in drug research and development," June 2021

This report similar to the BCG report on previous slide

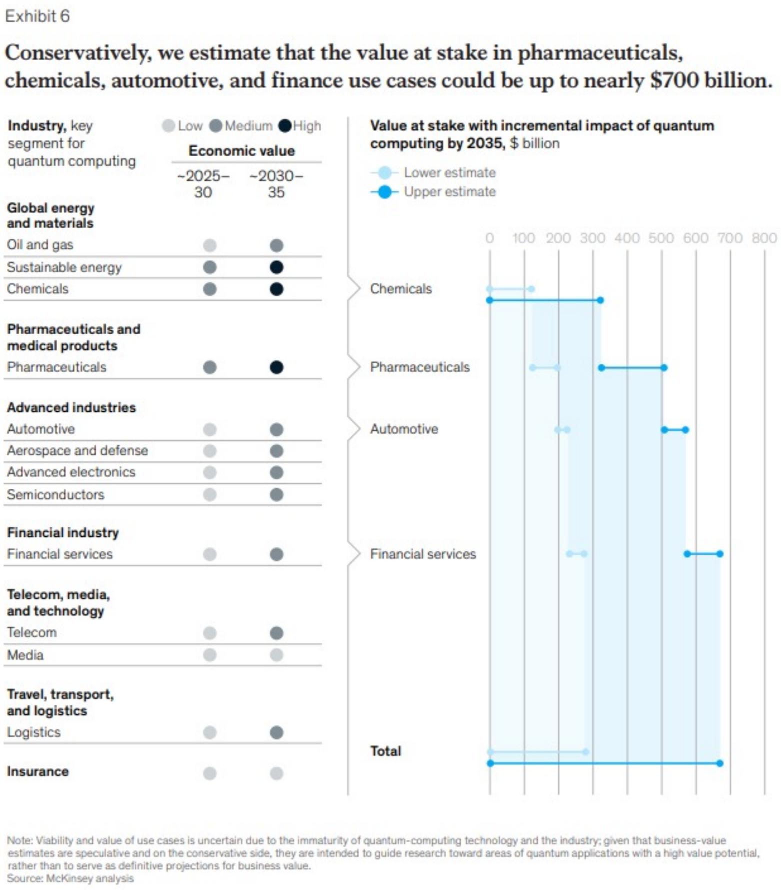


Exhibit 6

Conservatively, we estimate that the value at stake in pharmaceuticals, chemicals, automotive, and finance use cases could be up to nearly $700 billion.

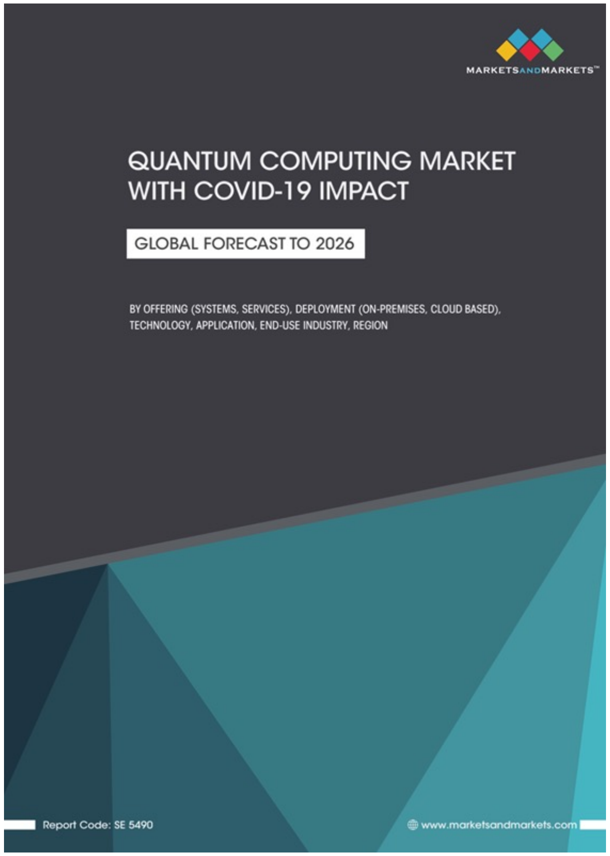
○ Low ◐ Medium ● High

Industry, key segment for quantum computing	Economic value ~2025–30	Economic value ~2030–35
Global energy and materials		
Oil and gas	○	◐
Sustainable energy	◐	●
Chemicals	◐	●
Pharmaceuticals and medical products		
Pharmaceuticals	◐	●
Advanced industries		
Automotive	○	◐
Aerospace and defense	○	◐
Advanced electronics	○	◐
Semiconductors	○	◐
Financial industry		
Financial services	○	◐
Telecom, media, and technology		
Telecom	○	◐
Media	○	○
Travel, transport, and logistics		
Logistics	○	◐
Insurance	○	○

Note: Viability and value of use cases is uncertain due to the immaturity of quantum-computing technology and the industry; given that business-value estimates are speculative and on the conservative side, they are intended to guide research toward areas of quantum applications with a high value potential, rather than to serve as definitive projections for business value.
Source: McKinsey analysis

Image Source: McKinsey Report "Quantum computing: An emerging ecosystem and industry use cases"

Markets and Market – QC Segmentation



MARKETSANDMARKETS™

QUANTUM COMPUTING MARKET
WITH COVID-19 IMPACT

GLOBAL FORECAST TO 2026

BY OFFERING (SYSTEMS, SERVICES), DEPLOYMENT (ON-PREMISES, CLOUD BASED), TECHNOLOGY, APPLICATION, END-USE INDUSTRY, REGION

Report Code: SE 5490

www.marketsandmarkets.com

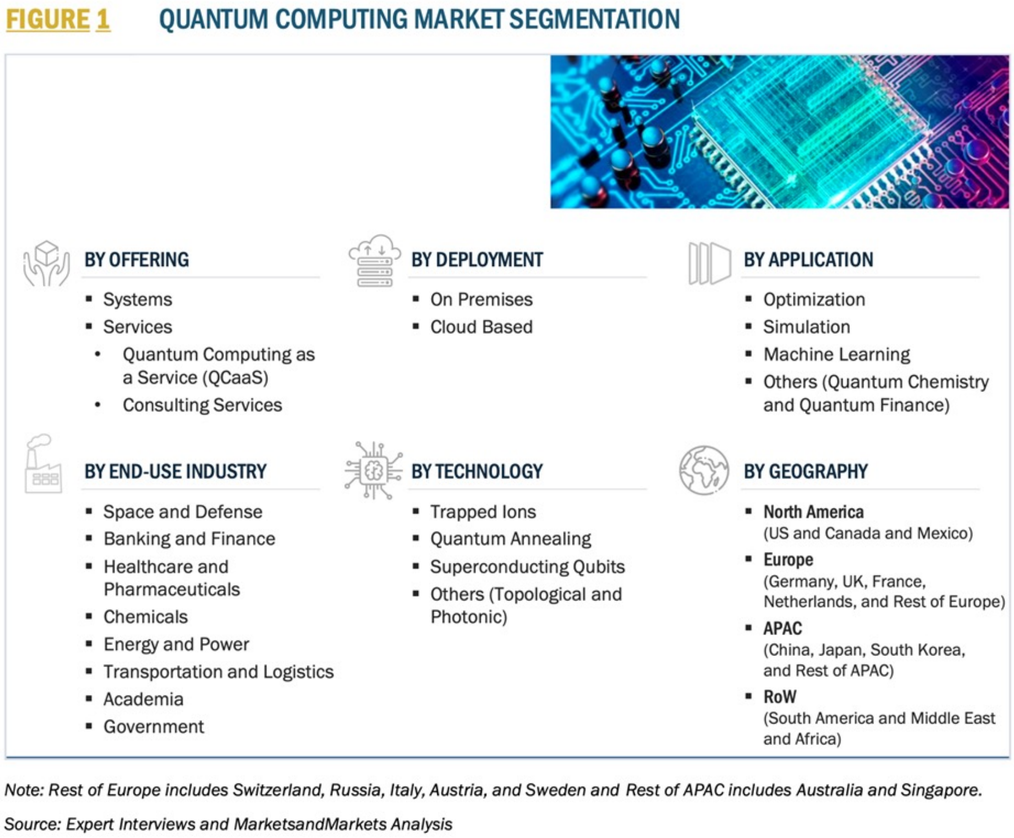


FIGURE 1 QUANTUM COMPUTING MARKET SEGMENTATION

BY OFFERING
- Systems
- Services
  - Quantum Computing as a Service (QCaaS)
  - Consulting Services

BY DEPLOYMENT
- On Premises
- Cloud Based

BY APPLICATION
- Optimization
- Simulation
- Machine Learning
- Others (Quantum Chemistry and Quantum Finance)

BY END-USE INDUSTRY
- Space and Defense
- Banking and Finance
- Healthcare and Pharmaceuticals
- Chemicals
- Energy and Power
- Transportation and Logistics
- Academia
- Government

BY TECHNOLOGY
- Trapped Ions
- Quantum Annealing
- Superconducting Qubits
- Others (Topological and Photonic)

BY GEOGRAPHY
- **North America** (US and Canada and Mexico)
- **Europe** (Germany, UK, France, Netherlands, and Rest of Europe)
- **APAC** (China, Japan, South Korea, and Rest of APAC)
- **RoW** (South America and Middle East and Africa)

Note: Rest of Europe includes Switzerland, Russia, Italy, Austria, and Sweden and Rest of APAC includes Australia and Singapore.

Source: Expert Interviews and MarketsandMarkets Analysis

Source: Markets and Markets

More Data and More Reports

- Roughly 180 “Quantum Companies” in US and 280 worldwide
- 50 Startups in US clearly directly in quantum space
- Only 15% of these have more than 50 employees
- 40% have less than 10
- For 2024 the following estimates exist:
  - Hyperion: $830M
  - BCG: $2-5B
  - Market Report: $1B (and $1.7B in 2026)

Jan 2021

MARKETSANDMARKETS™

QUANTUM COMPUTING MARKET
WITH COVID-19 IMPACT

GLOBAL FORECAST TO 2026

BY OFFERING (SYSTEMS, SERVICES), DEPLOYMENT (ON-PREMISES, CLOUD BASED), TECHNOLOGY, APPLICATION, END-USE INDUSTRY, REGION

Report Code: SE 5490

McKinsey
& Company

Quantum computing:
An emerging ecosystem and industry use cases

December 2021

Dec 2021

RAND CORPORATION

Research Report

EDWARD PARKER, DANIEL GONZALES, AJAY K. KOCHHAR, SYDNEY LITTERER, KATHRYN O'CONNOR, JON SCHMID, KELLER SCHOLL, RICHARD SILBERGLITT, JOAN CHANG, CHRISTOPHER A. EUSEBI, SCOTT W. HAROLD

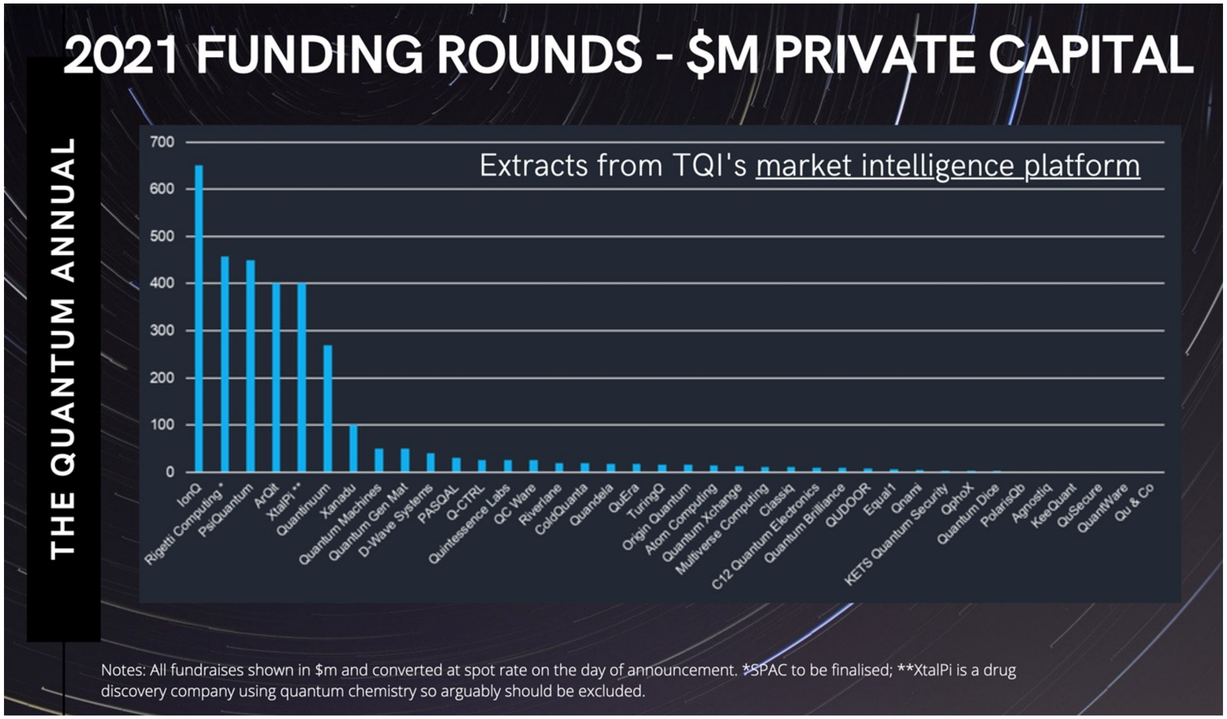
An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology

https://www.rand.org/pubs/research_reports/RRA869-1.html

Feb 2022

Image Sources: Markets and Markets; McKinsey & Company; Rand Corporation

Private Capital Investment: The Quantum Insider

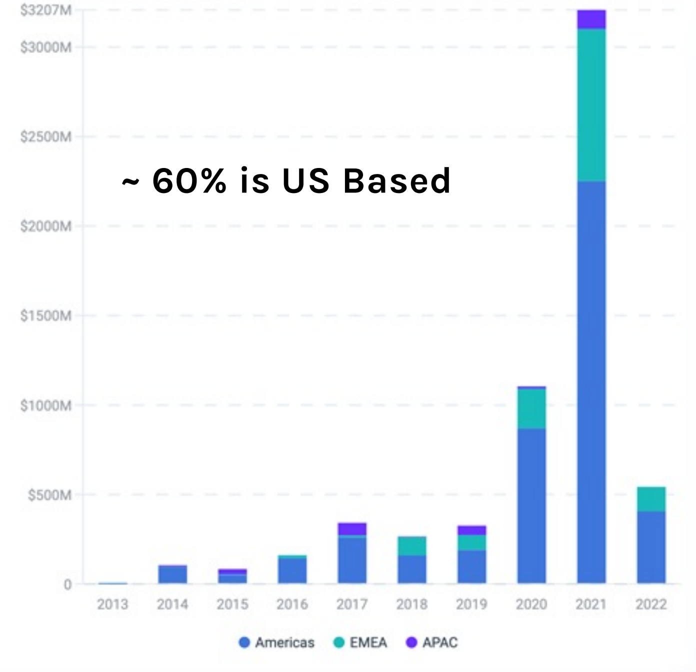


2021 FUNDING ROUNDS - $M PRIVATE CAPITAL

Extracts from TQI's market intelligence platform

Notes: All fundraises shown in $m and converted at spot rate on the day of announcement. *SPAC to be finalised; **XtalPi is a drug discovery company using quantum chemistry so arguably should be excluded.

Quantum Investment $M by Year and Region



~ 60% is US Based

Source: The Quantum Insider

Government Investments and Start-up Culture

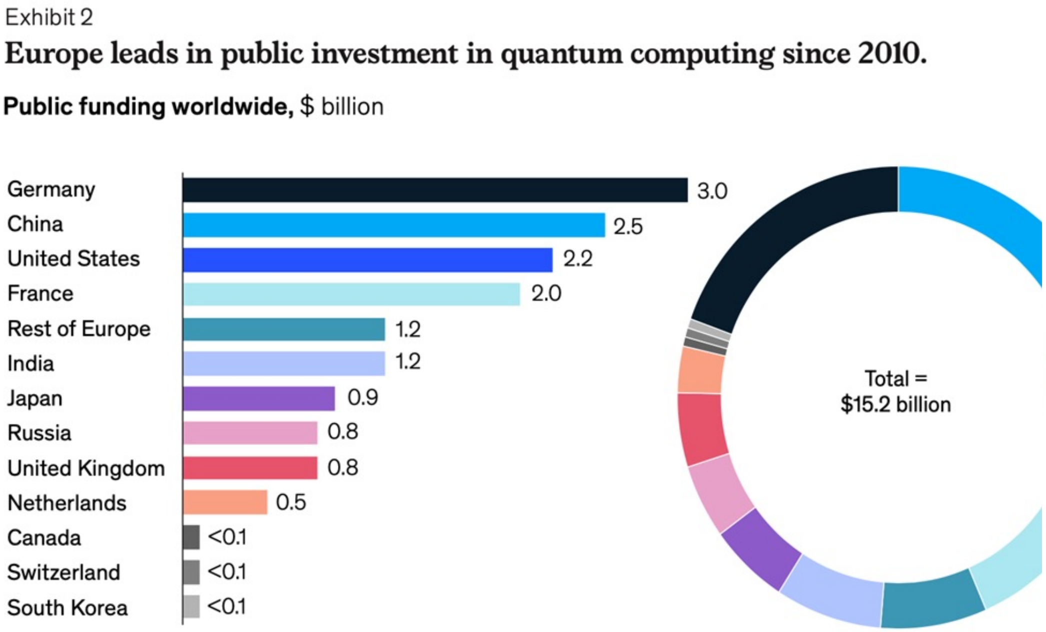


Exhibit 2

Europe leads in public investment in quantum computing since 2010.

Public funding worldwide, $ billion

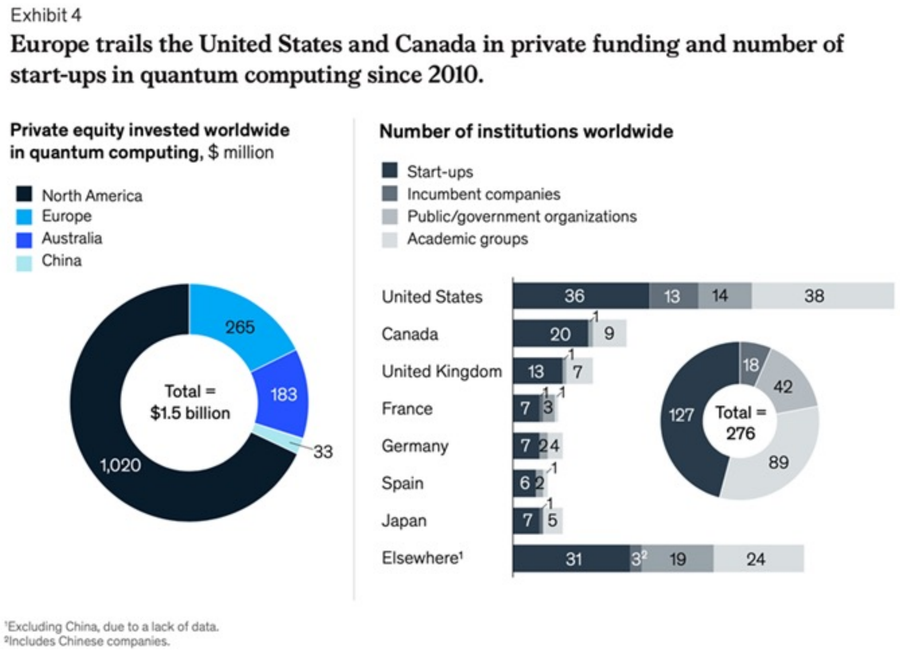


Exhibit 4

Europe trails the United States and Canada in private funding and number of start-ups in quantum computing since 2010.

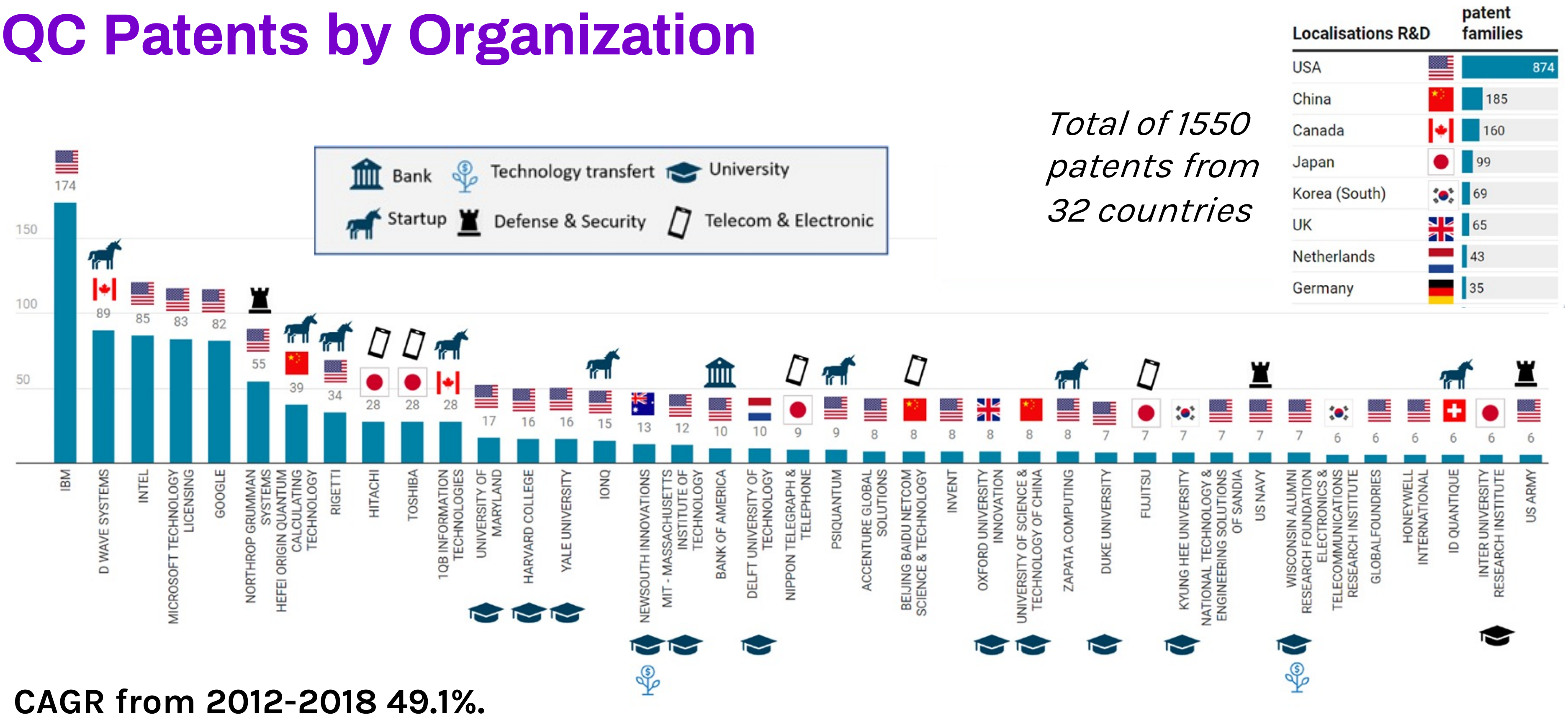
[1] Excluding China, due to a lack of data.
[2] Includes Chinese companies.

Two Exhibits from McKinsey Digital: “A quantum wake-up call for European CEOs,” December 2021

Source: McKinsey & Company

QC Patents by Organization

Total of 1550 patents from 32 countries



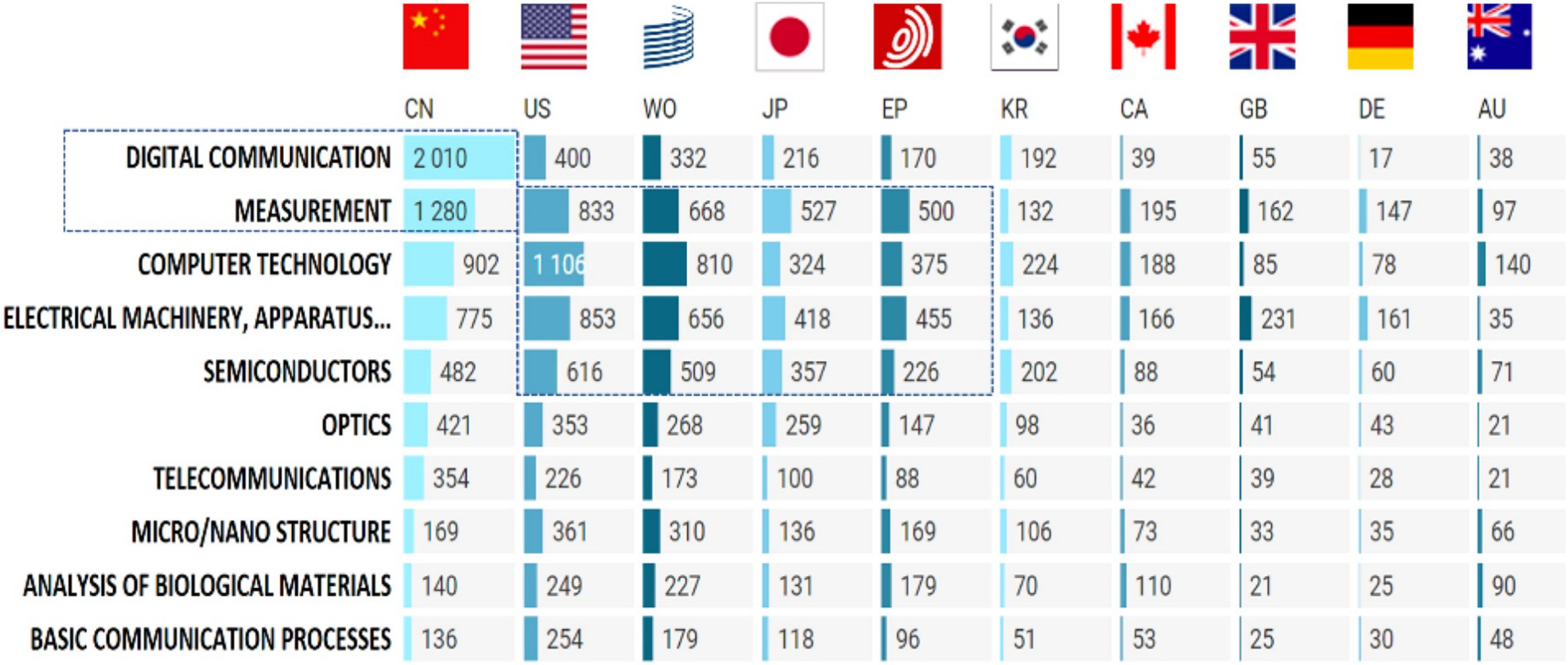
Localisations R&D	patent families
USA	874
China	185
Canada	160
Japan	99
Korea (South)	69
UK	65
Netherlands	43
Germany	35

CAGR from 2012-2018 49.1%.

Organizations with 6 or more QC patents since 2010; Kurek Fig. 15, insert- extracted from Fig. 14

Source: Kurek

Distribution of QIS Patents by Tech. Field

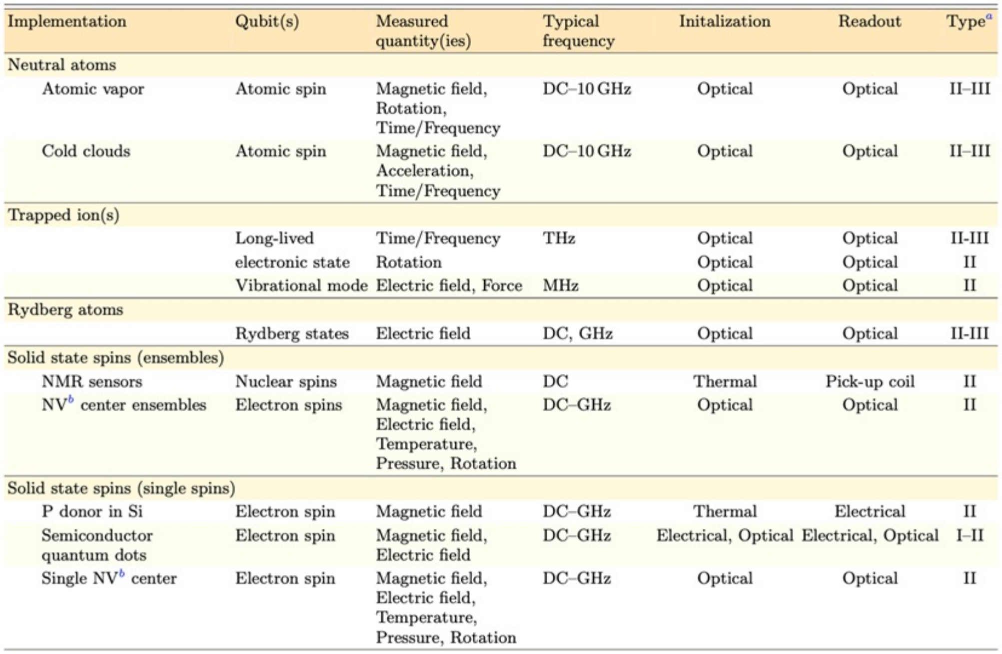


	CN	US	WO	JP	EP	KR	CA	GB	DE	AU
DIGITAL COMMUNICATION	2 010	400	332	216	170	192	39	55	17	38
MEASUREMENT	1 280	833	668	527	500	132	195	162	147	97
COMPUTER TECHNOLOGY	902	1 106	810	324	375	224	188	85	78	140
ELECTRICAL MACHINERY, APPARATUS...	775	853	656	418	455	136	166	231	161	35
SEMICONDUCTORS	482	616	509	357	226	202	88	54	60	71
OPTICS	421	353	268	259	147	98	36	41	43	21
TELECOMMUNICATIONS	354	226	173	100	88	60	42	39	28	21
MICRO/NANO STRUCTURE	169	361	310	136	169	106	73	33	35	66
ANALYSIS OF BIOLOGICAL MATERIALS	140	249	227	131	179	70	110	21	25	90
BASIC COMMUNICATION PROCESSES	136	254	179	118	96	51	53	25	30	48

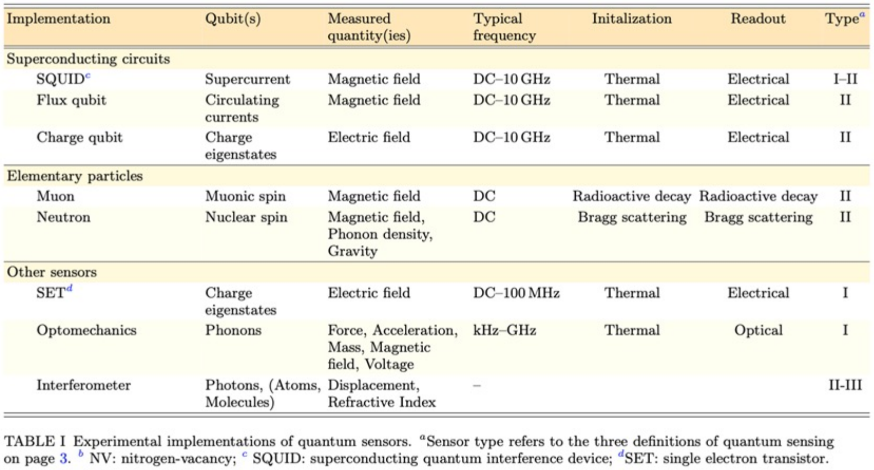
Distribution of patents by country of priority and technology field; **Kurek Fig. 5.**

Source: Kurek

Quantum Sensors



Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency	Initalization	Readout	Type[a]
Neutral atoms						
Atomic vapor	Atomic spin	Magnetic field, Rotation, Time/Frequency	DC–10 GHz	Optical	Optical	II–III
Cold clouds	Atomic spin	Magnetic field, Acceleration, Time/Frequency	DC–10 GHz	Optical	Optical	II–III
Trapped ion(s)						
	Long-lived electronic state	Time/Frequency	THz	Optical	Optical	II-III
		Rotation		Optical	Optical	II
	Vibrational mode	Electric field, Force	MHz	Optical	Optical	II
Rydberg atoms						
	Rydberg states	Electric field	DC, GHz	Optical	Optical	II-III
Solid state spins (ensembles)						
NMR sensors	Nuclear spins	Magnetic field	DC	Thermal	Pick-up coil	II
NV[b] center ensembles	Electron spins	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz	Optical	Optical	II
Solid state spins (single spins)						
P donor in Si	Electron spin	Magnetic field	DC–GHz	Thermal	Electrical	II
Semiconductor quantum dots	Electron spin	Magnetic field, Electric field	DC–GHz	Electrical, Optical	Electrical, Optical	I–II
Single NV[b] center	Electron spin	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz	Optical	Optical	II



Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency	Initalization	Readout	Type[a]
Superconducting circuits						
SQUID[c]	Supercurrent	Magnetic field	DC–10 GHz	Thermal	Electrical	I–II
Flux qubit	Circulating currents	Magnetic field	DC–10 GHz	Thermal	Electrical	II
Charge qubit	Charge eigenstates	Electric field	DC–10 GHz	Thermal	Electrical	II
Elementary particles						
Muon	Muonic spin	Magnetic field	DC	Radioactive decay	Radioactive decay	II
Neutron	Nuclear spin	Magnetic field, Phonon density, Gravity	DC	Bragg scattering	Bragg scattering	II
Other sensors						
SET[d]	Charge eigenstates	Electric field	DC–100 MHz	Thermal	Electrical	I
Optomechanics	Phonons	Force, Acceleration, Mass, Magnetic field, Voltage	kHz–GHz	Thermal	Optical	I
Interferometer	Photons, (Atoms, Molecules)	Displacement, Refractive Index	–			II-III

TABLE I Experimental implementations of quantum sensors. [a]Sensor type refers to the three definitions of quantum sensing on page 3. [b] NV: nitrogen-vacancy; [c] SQUID: superconducting quantum interference device; [d]SET: single electron transistor.

Source: C. L. Degen, F. Reinhard, and P. Cappellaro, Rev. Mod. Phys. 89, 035002, 2017

Quantum Communications and Sensors

- ➢ QC receives most of the attention, but Q. Sensors and Q. Communications efforts are more advanced.
- ➢ e.g. QKD have been on the market for more than 15 years.
- ➢ Q. Sensors could generate $5B in revenue by 2030.
- ➢ QComm. could account for $8B in revenue by 2030.

Exhibit 2

Quantum sensing has distinct advantages over alternative technologies in eight applications.

Applications for quantum sensing

Global Outlook for the Quantum Magnetometer Markets 2020-2029 - A $700 Million Market

NEWS PROVIDED BY
Research and Markets →
Sep 22, 2020, 09:30 ET

DUBLIN, Sept. 22, 2020 /PRNewswire/ -- The "Quantum Magnetometer Markets: 2020 to 2029" report has been added to **ResearchAndMarkets.com's** offering.

Source: McKinsey “Shaping the long race in quantum communication and quantum sensing,” Dec. 2021

Example of Commercialization of Quantum Sensors

MAGNI
BUSINESS & TEC
www.MagneticsMag.com
March/April 2021

Top-Tier Automotive Suppliers Tr
Become Fully Integrated e-Power

e-Traction of Netherlands Rolls A
New EV Powertrain Designs

Electric Motors from ECA Group Pov
Attack Subs for French Navy

Advanced e-Propulsion & EV Develo
Blossoms in UK with Fresh Governm

NEWS > [April 5, 2021] Variohmn Buys Magnetic Encoder & Sensor Specialist Phoenix America ▸ NEWS

HOME > NEWS > QuSpin & Mansfield Imaging Centre Advance Neuroscience with Highly Sensitive Magnetometers

QuSpin & Mansfield Imaging Centre Advance Neuroscience with Highly Sensitive Magnetometers

April 16, 2020 · Editorial Staff · News, Test and Measurement · Comments Off

QuSpin, a manufacturer of highly sensitive magnetometers that are gaining popularity among neuroscientists, reports that it has developed a three-axis variant that will bring new sensing capabilities to magnetoencephalography measurements. Meanwhile, researchers at the University of Nottingham have used the company's two-axis sensors to operate a whopping 50-channel array, shown above.

Ex. Atom Based Start-ups:

- Kernal: https://www.kernel.com
- QuSpin: https://quspin.com
- Fieldline: https://fieldlineinc.com

Ex. NV-Center Based Start-ups:

- QZabre: https://qzabre.com
- QDTI: https://qdti.com

Other companies have magnetometers with significantly larger footprints

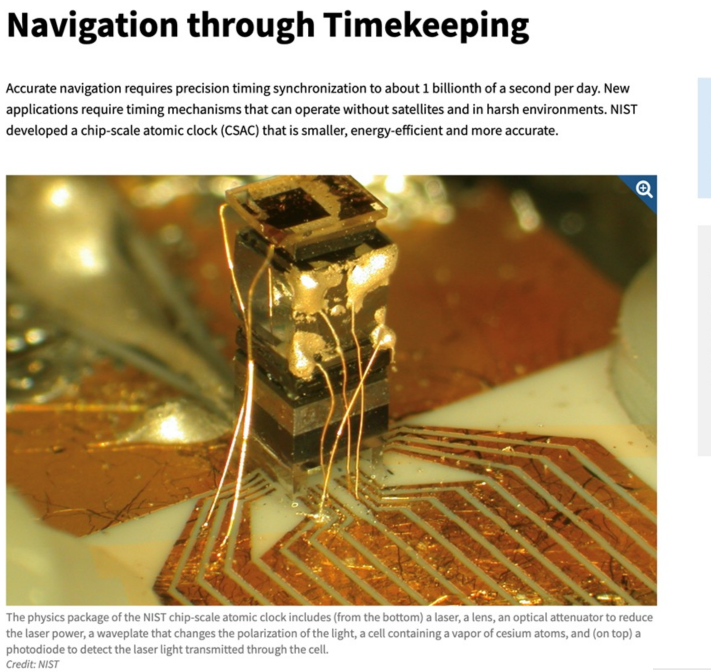
LEFT:
https://www.cercamagnetics.com

Source: Magnetics Magazine

A 2nd Magnetoencephalography System

Source: FieldLine

Chip-Scale Atomic Clock (CSAC)



Navigation through Timekeeping

Accurate navigation requires precision timing synchronization to about 1 billionth of a second per day. New applications require timing mechanisms that can operate without satellites and in harsh environments. NIST developed a chip-scale atomic clock (CSAC) that is smaller, energy-efficient and more accurate.

The physics package of the NIST chip-scale atomic clock includes (from the bottom) a laser, a lens, an optical attenuator to reduce the laser power, a waveplate that changes the polarization of the light, a cell containing a vapor of cesium atoms, and (on top) a photodiode to detect the laser light transmitted through the cell.

Credit: NIST

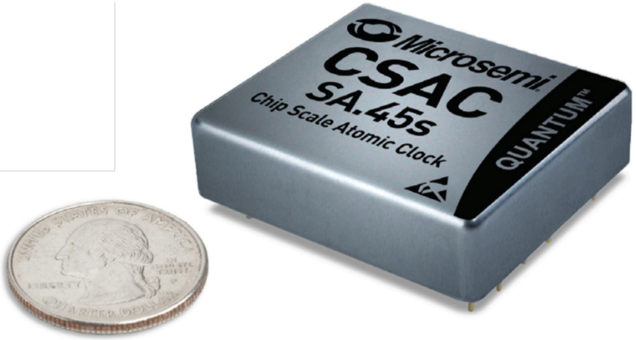
$260M

market for chip-scale atomic clocks replacing oven-controlled crystal oscillators

> "The combination of an extremely accurate and precise time source that also minimizes size, weight, and power requirements will allow us to bring the power of digital technology to more remote places around the globe, and capitalize on everything a well-defined sense of time enables."
>
> – Elizabeth Fetter, Microsemi, in *WIRED* magazine

CSAC: First demonstrated by NIST in 2003 and developed under a DARPA program

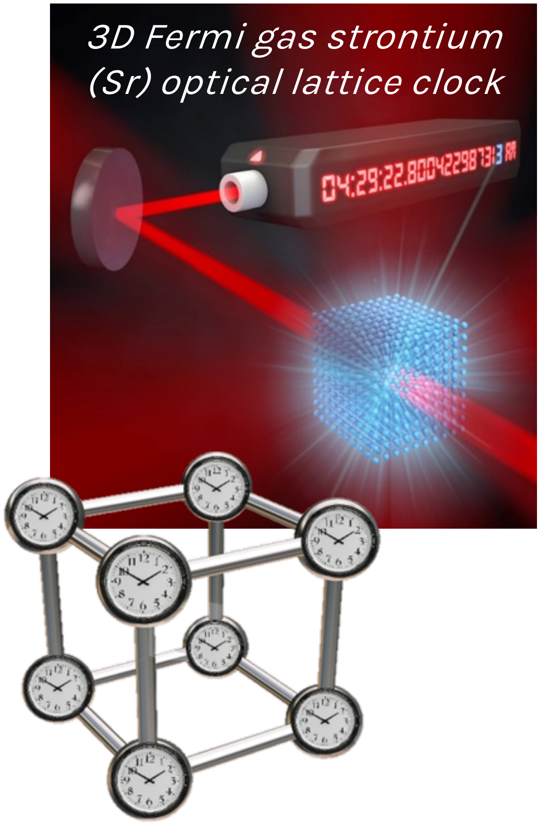
Typically used for PNT and/or Seismic surveys



First of the NIST-on-a-Chip Technologies

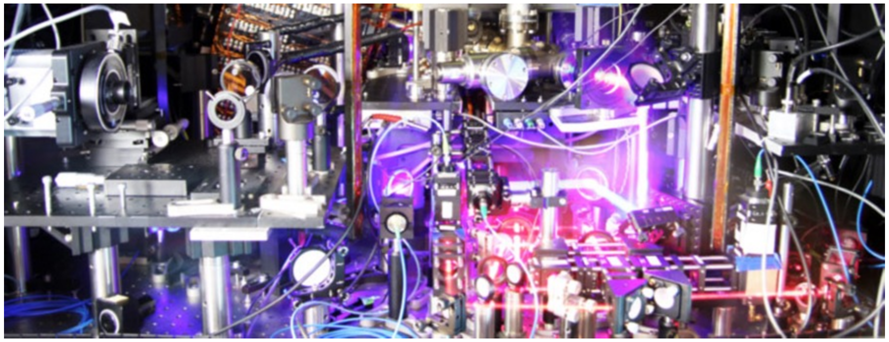
Source: NIST

Quantum Degenerate Fermi Gas Clock



3D Fermi gas strontium (Sr) optical lattice clock

- First application of a quantum degenerate gas to a “practical” measurement: A quantum-enhanced precision measurement
  - ~1 million atoms: 100 x 100 x 100 in a 3D-optical lattice
  - Pauli exclusion: Only one atom per lattice site
  - Precision 3 x 10-20 Hz-1/2, on path to 10-22 in a few years
  - Coherence time 160 seconds and improving
- Potential laboratory for fundamental physics, including quantum gravity, dark matter detection, and long-baseline astronomical observation



Source: S.L. Campbell et al., Science 358, 90 (2017); G.E. Marti et al., Phys. Rev. Lett. 120, 103201 (2018).

Gravitation Red Shift in a Lattice Optical Clock

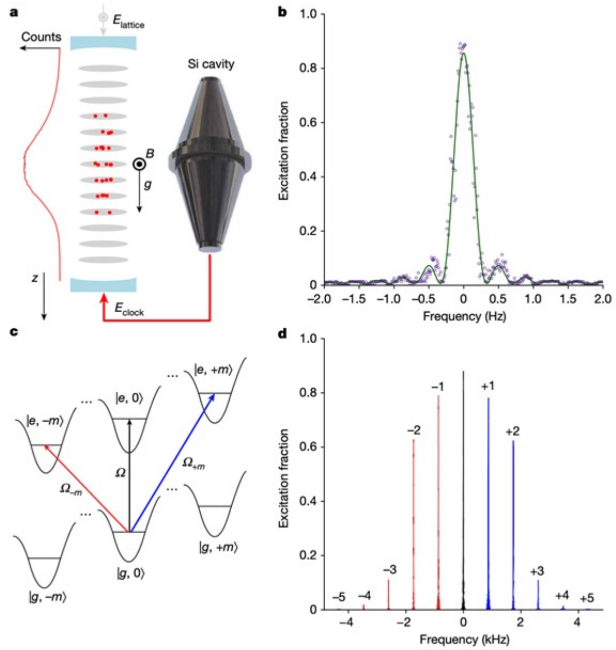


Fig. 1 | Experimental system and quantum state control. a, A millimetre-length sample of about 100,000 ^{87}Sr atoms trapped within a 1D optical lattice E_{lattice} formed in an in-vacuum cavity. The longitudinal axis of the cavity, *z*, is oriented along gravity. We probe atoms along the $^1S_0 \rightarrow {}^3P_0$ transition using a clock laser E_{clock} locked to an ultrastable crystalline silicon cavity[6,35]. **b**, Rabi spectroscopy with a 3.1 s pulse time. Open purple circles indicate data with a corresponding Rabi fit in green. **c**, Neighbouring lattice sites are detuned by the gravitational potential energy difference, creating a Wannier–Stark ladder. Clock spectroscopy probes the overlap of Wannier–Stark states between lattice sites that are *m* sites away with Rabi frequency $Ω_m$. **d**, Rabi spectroscopy probes Wannier–Stark state transitions, revealing wavefunction delocalization of up to five lattice sites. The number of lattice sites is indicated above each transition, with blue (red) denoting Wannier–Stark transitions to higher (lower) lattice sites.

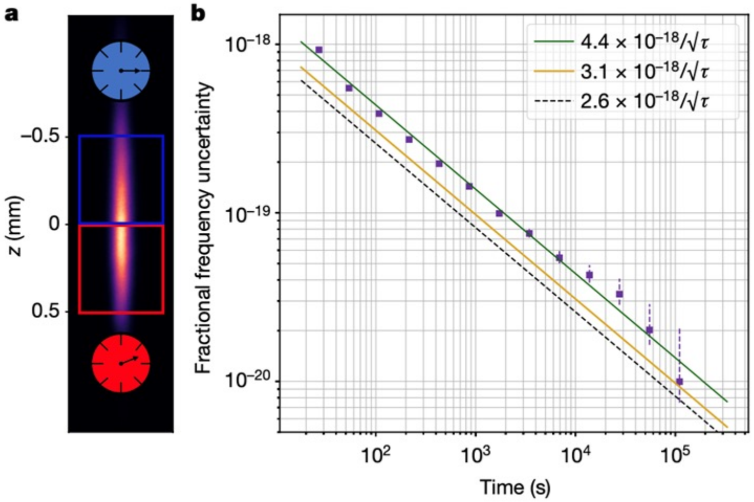
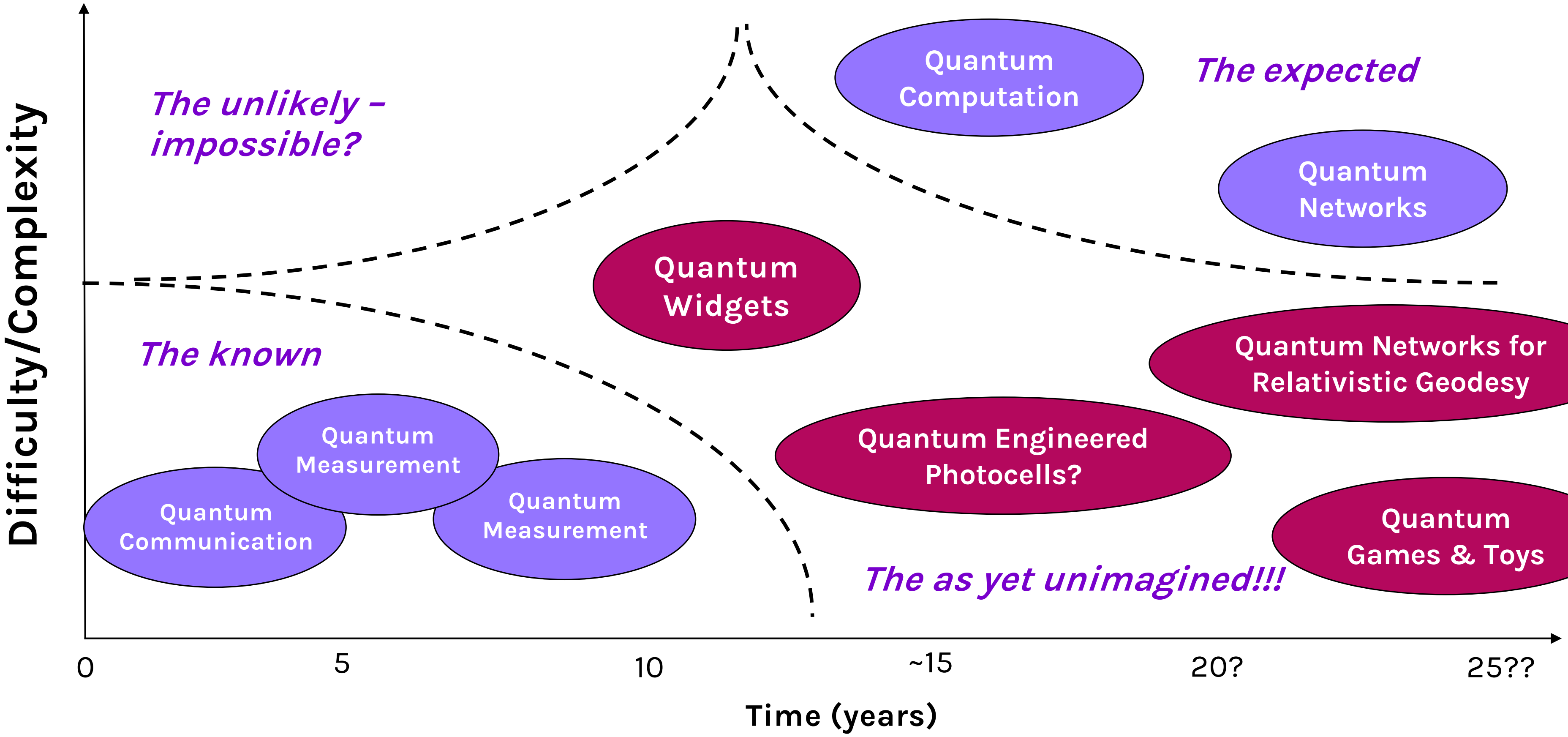


Fig. 4 | In situ synchronous clock comparison. a, The atomic cloud is separated as in Fig. 2a. The gravitational redshift leads to the higher clock (blue) ticking faster than the lower one (red). The length scale is in millimetres. **b**, Allan deviation of the frequency difference between the two regions in **a** over 92 h. Purple points show fractional frequency instability fitted by the solid green line, with the quantum projection noise limit indicated by the dashed black line. We attribute the excess instability of the measurement relative to quantum projection noise to detection noise. The expected single atomic region instability is shown in gold.

Source: T. Bothwell et al. Nature 602, 420 (2022)

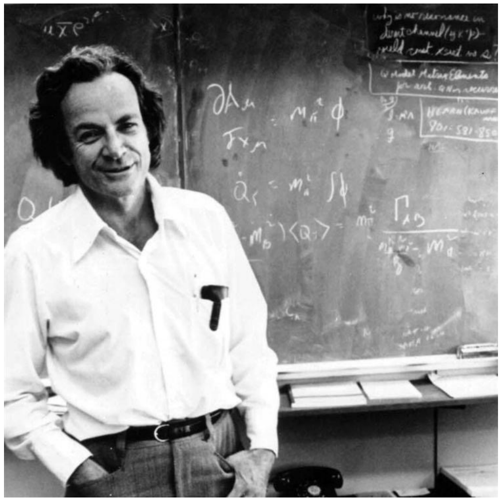
Quantum Information & Future Technology



Conclusions

We are witnessing the second quantum revolution where technology:

- Will use the weird properties of quantum mechanics
- Will exploit how nature works at the quantum level



"… and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

-- Richard P. Feynman, "*Simulating Physics with Computers*", May 1981

- **It is basically what the "laws of Physics" appropriate to everyday energy scales allow. Thus, it is a space that we can engineer improved or novel devices for future technology!**

Image Source: My Hero Project

Questions?

Image Source: Nations Online Project