Quantum Information Science
What is it?
What is it good for?
How can we make progress faster?

Celia Merzbacher, PhD
QED-C Associate Director

Background

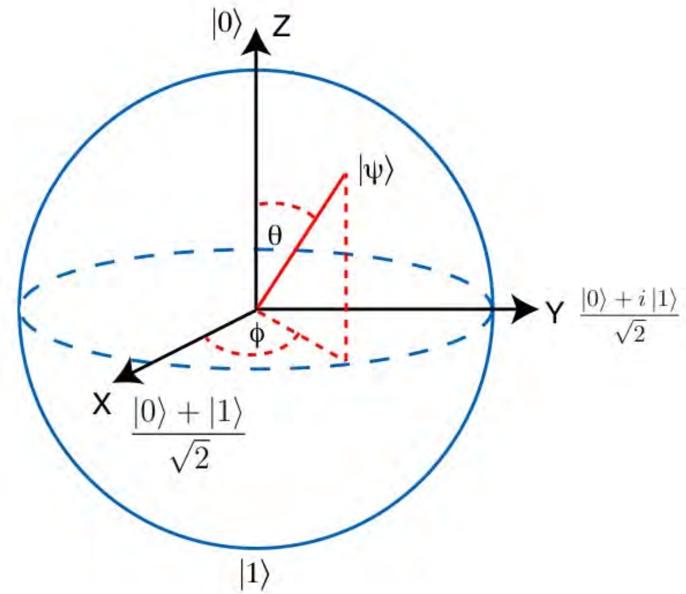
What differentiates quantum?

- Quantized states
- Uncertainty
- Superposition
- Entanglement

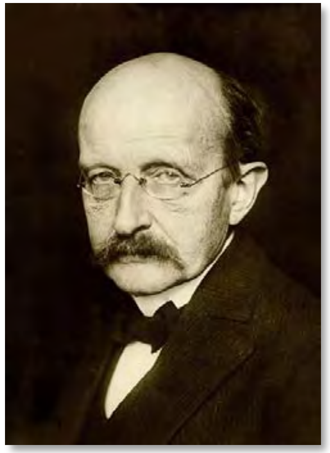
● 0

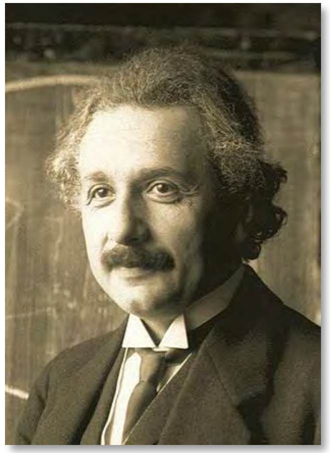
● 1

Classical "bit"

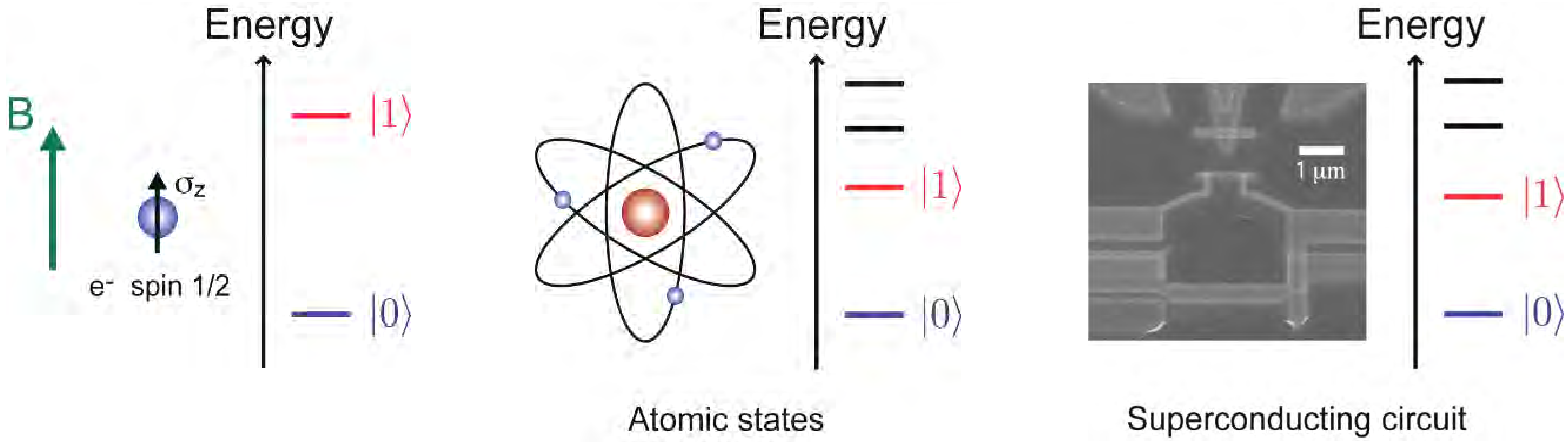


Quantum "bit"



Examples of qubits

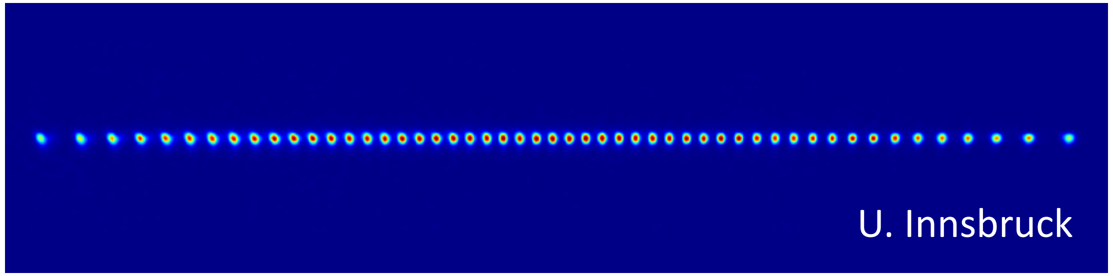


quantum effects require $k_B T$ << E_{01}

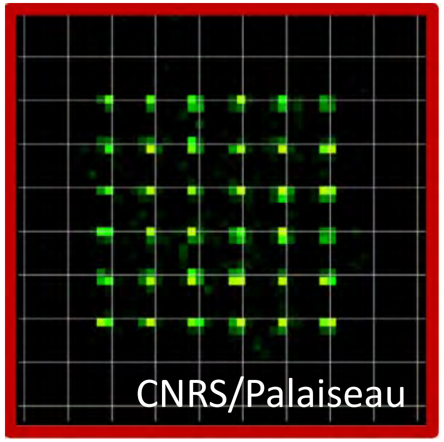
$\Rightarrow$ **go cryogenic or use laser cooling**

Credit: Daniel Slichter, NIST

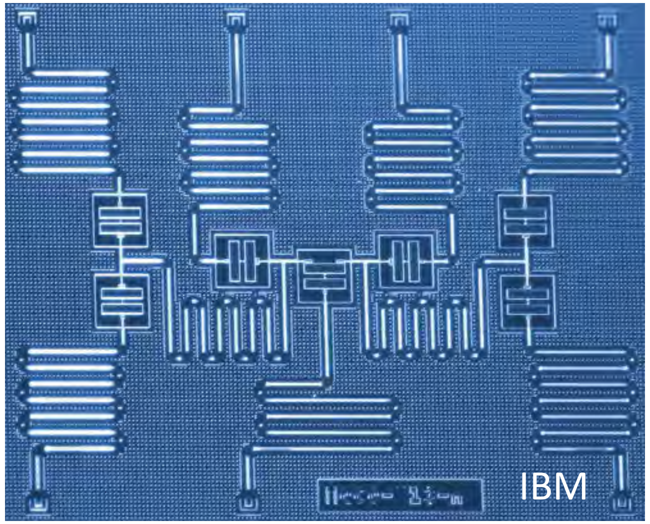
Candidates for practical qubits



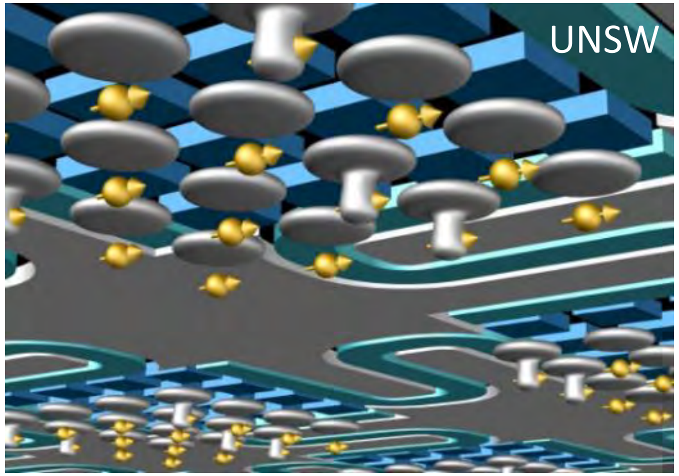
trapped ions



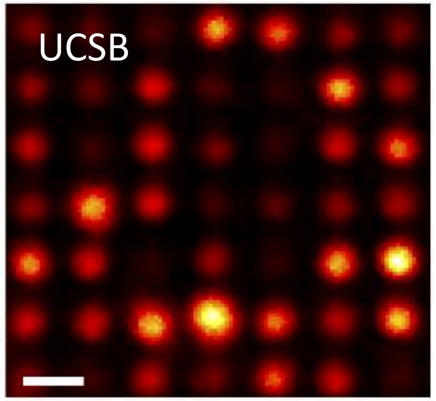
neutral atoms



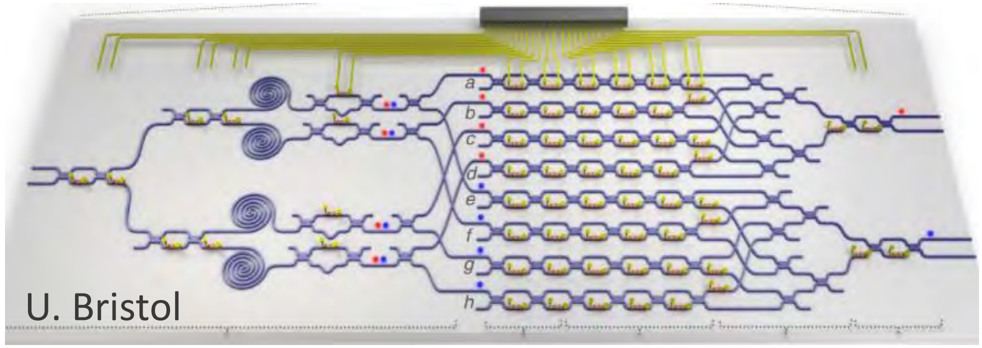
superconducting qubits



Si qubits



NV centers



photonics

Credit: Daniel Slichter, NIST

DiVincenzo's criteria for a quantum computer

- ✓ A scalable physical system with well characterized qubit
- ✓ Ability to initialize the state of the qubits to a simple fiducial state
- ✓ Long relevant decoherence times
- ✓ A "universal" set of quantum gates
- ✓ A qubit-specific measurement capability

What about software?

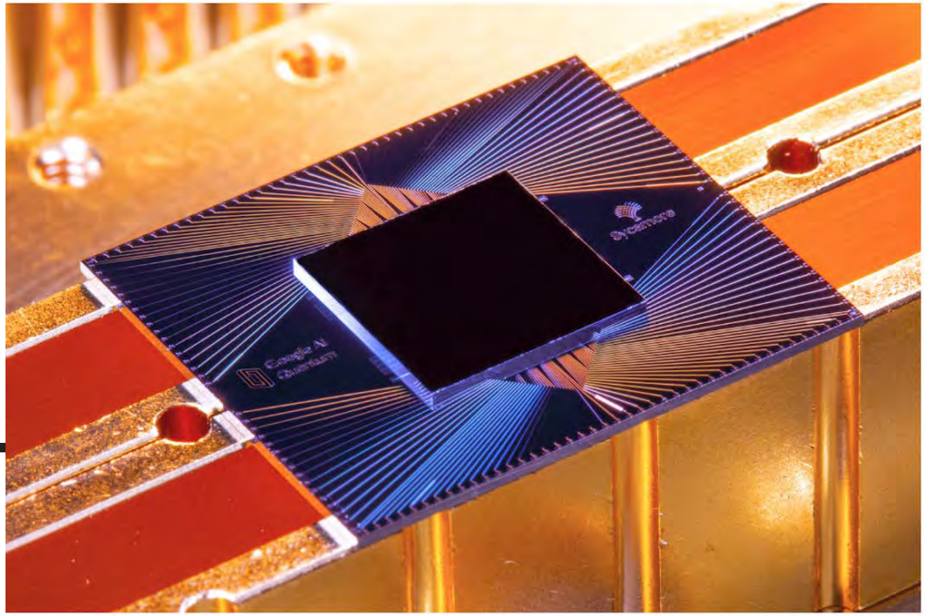
- Basic steps of running a quantum computer:
  - Qubits are prepared in a particular state
  - Qubits undergo a sequence of quantum logic gates
  - A quantum measurement extracts the output
- Current quantum computers are “noisy” and error prone
  - Need error correction
- Hybrid quantum/classical computation will be essential
- Companies are developing software that is technology agnostic and can take advantage of NISQ* systems that will be available relatively soon

*Noisy Intermediate Scale Quantum

What might quantum computers enable?

- Simulation and optimization of materials and chemical processes
- Acceleration – e.g. faster search algorithms
- Machine learning
- Need for new encryption

Status of Quantum Computing

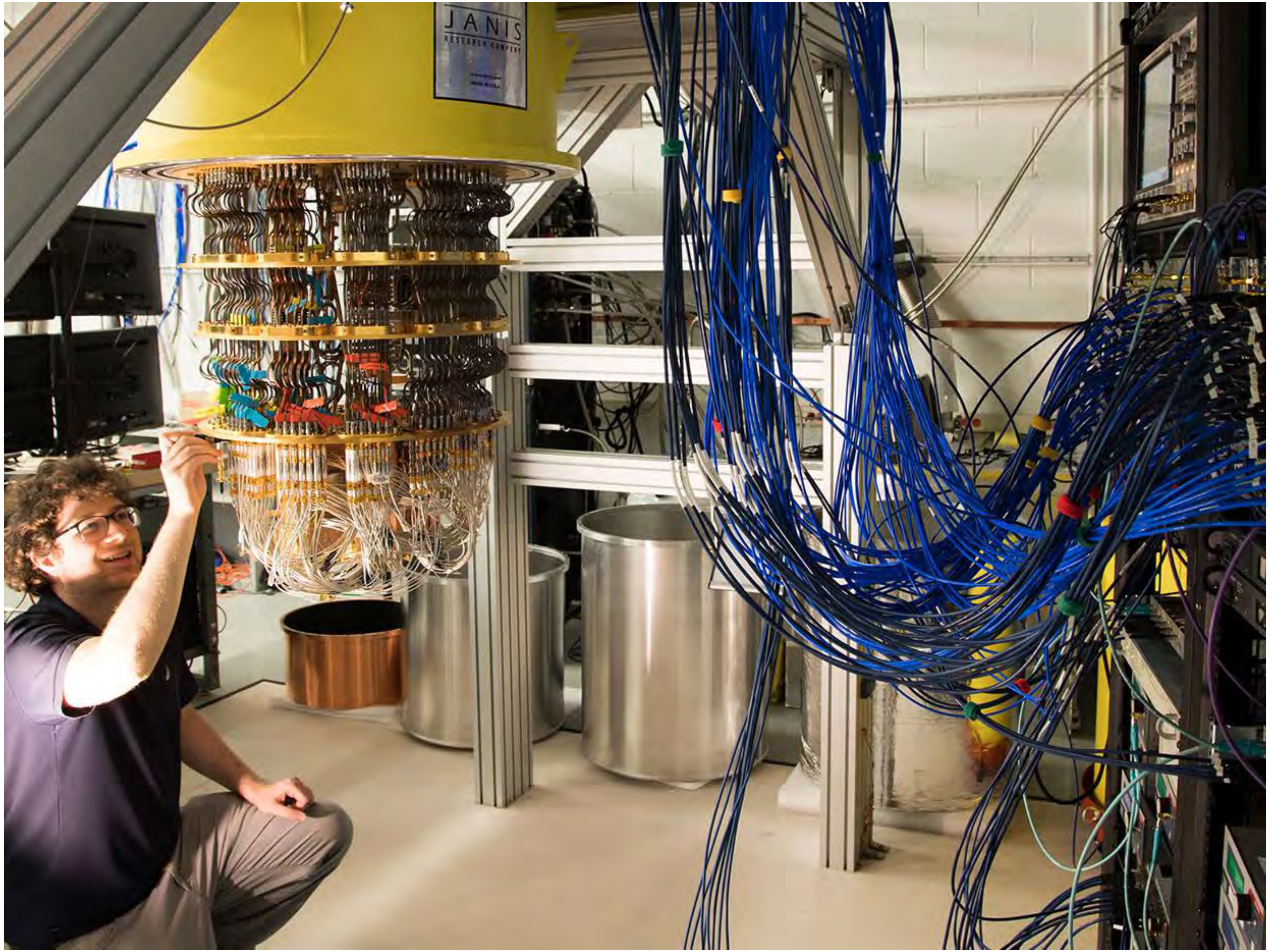


nature

NEWS · 23 OCTOBER 2019

Hello quantum world! Google publishes landmark quantum supremacy claim

The company says that its quantum computer is the first to perform a calculation that would be practically impossible for a classical machine.



https://spectrum.ieee.org/tech-talk/semiconductors/design/google-team-builds-circuit-to-solve-one-of-quantum-computings-biggest-problems

Status of Quantum Computing

TechCrunch

IBM will soon launch a 53-qubit quantum computer

Frederic Lardinois @fredericl / 8:00 am EDT • September 18, 2019

Comment

ZDNet

November 4, 2019

Microsoft's Azure Quantum employs Honeywell quantum hardware

Honeywell is bringing its "trapped ion" quantum computing hardware to Microsoft's Azure cloud computing service, part of an evolution from the age of quantum "co-processors" to an ultimate era of quantum supremacy.

SCIENTIFIC AMERICAN

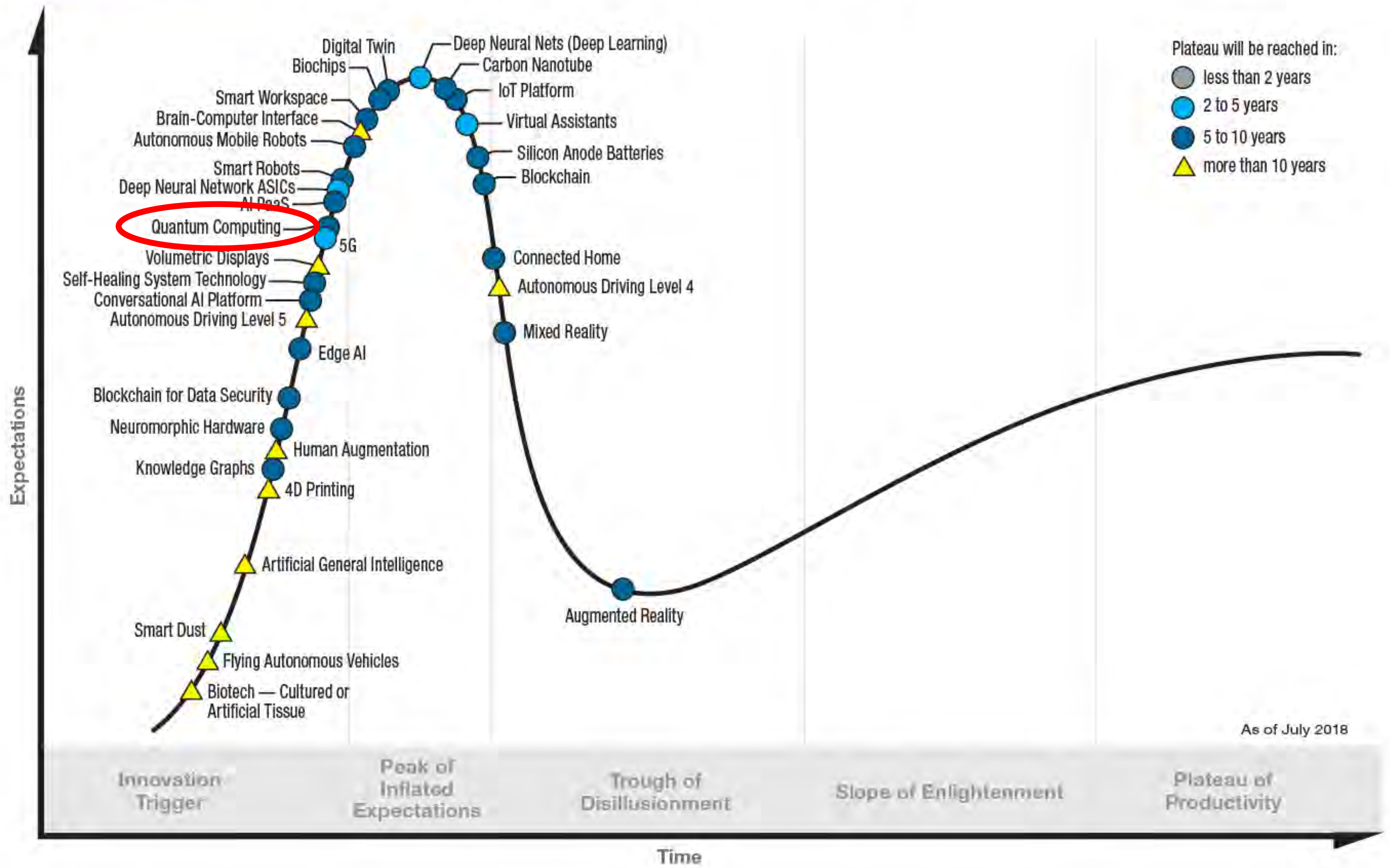
November 6, 2019

PHYSICS

Quantum Computer Made from Photons Achieves a New Record

The limited system made a notable advancement on the road to beating classical machines

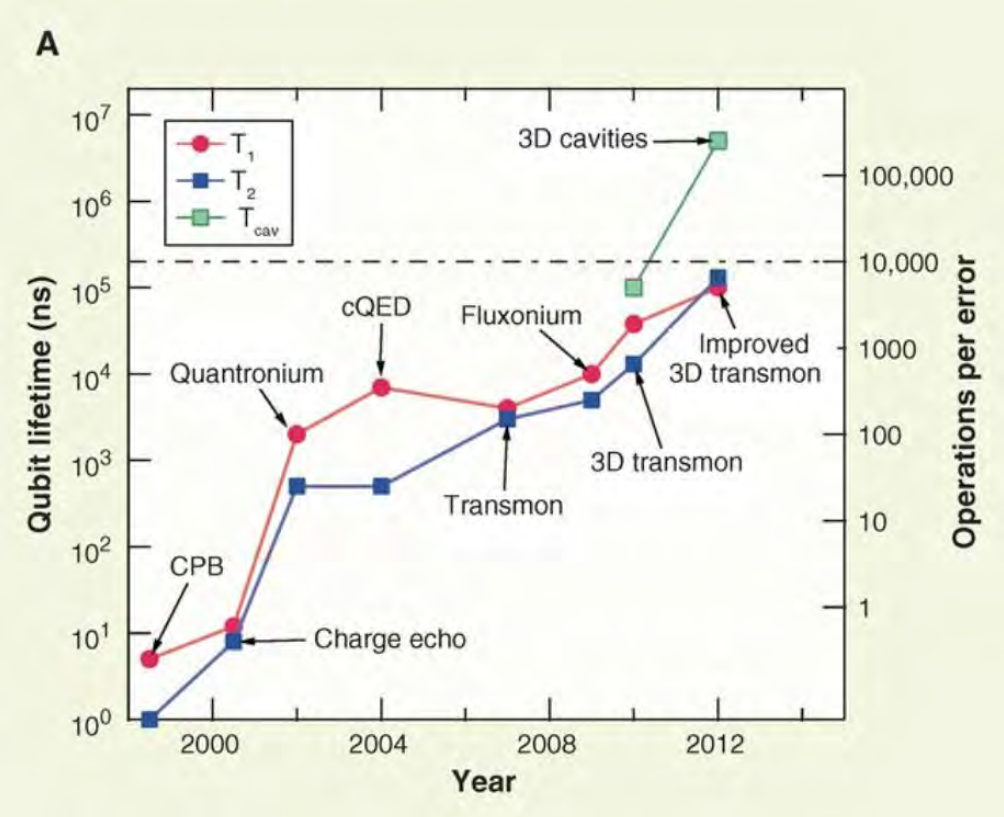
Gartner Hype Cycle for Emerging Technologies, 2018



Source: Gartner.com/smarterwithgartner

Quantum computing faces hurdles

- Coherence times
- Fidelity
- I/O
- Enabling technologies
  - Lasers
  - Cryogenics
  - Control electronics
  - Photonics
  - Software

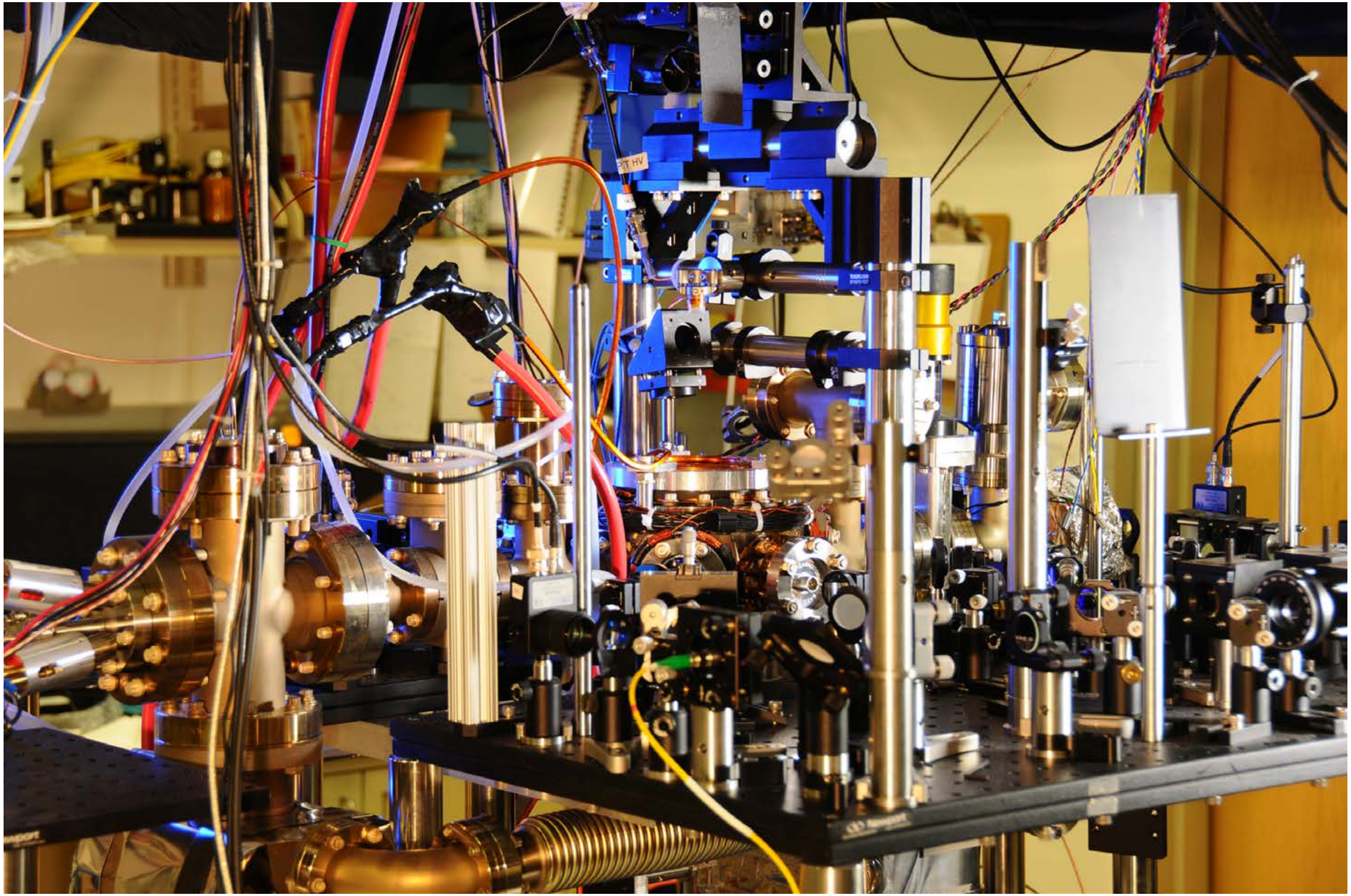


Devoret and Schoelkopf, Science (2013)

"It's difficult to make predictions, especially about the future."

Quantum-based sensors

- Based on exquisite sensitivity of quantum state to environment
- Many types of sensors possible
  - Clocks
  - Magnetic field
  - Electric field
  - Gravity
  - Temperature
- Absolute; do not require calibration



https://www.nist.gov/news-events/news/2013/08/nist-ytterbium-atomic-clocks-set-record-stability

Fieldable quantum sensors are available

Source: Microsemi

Source: Twinleaf

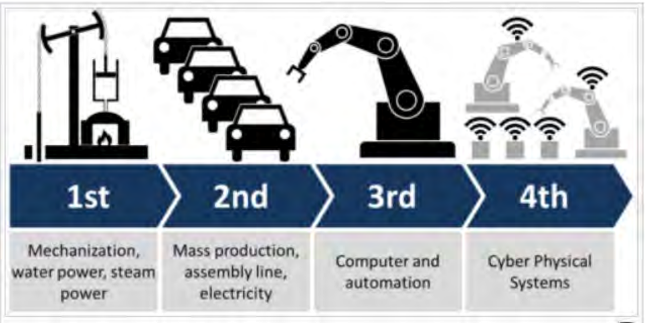
Source: AOSense

NIST-on-a-Chip (NOAC)

1. A suite of quantum-based measurement devices
2. …that are self-calibrating, fit-to-function, manufacturable
3. …that take measurement services out of the lab and directly to the end user

NOAC at the Convergence of Industry Trends

NIST



Industry 4.0

Where products communicate with their users and the machinery of their own production through a digital choreography

QIS lets us beat classical limits of sensing and enables always-accurate measurement devices

Quantum 2.0 Revolution

NIST on a Chip

The redefinition of the SI enables new possibilities for traceable, chip-scale standards

Advances in nanofabrication and integrated photonics enable scaling

Nano-manufacturing

Technology Readiness

Basic Research → Feasibility Research → Prototype Development → Mature Technology

NIST

- Magnetic & Electrical Fields
- Quantum Optics & Radiometry
- Thermodynamics
- Fluid Measurement & Control
- Biochemical Sensing
- Radiation
- Mass & Force
- Dimensional Metrology
- Time & Frequency
- Vacuum
- Current, Voltage & Resistance

Chip-scale Atomic Magnetometers
SI-traceable E-field Metrology
Photonic Power Metrology
Microresonator Comb Technology
Electrical Substitution Bolometer
Quantum Light Sources & Circuits
Switches for Waveform Metrology
Photonic Thermometry
Microfluidics
Photonic Dosimetry
Emergency Response Dosimetry
Optomechanical Sensors
Cavity Optomechanics
Chip-scale Wavelength References
Integrated Cold-Atom Clocks & Sensors
Cold-atom Vacuum Standard
Silicon Quantum Ampere
Josephson Voltage Standard

Barbara Goldstein, Program Manager
Assoc Dir, Physical Measurement Laboratory
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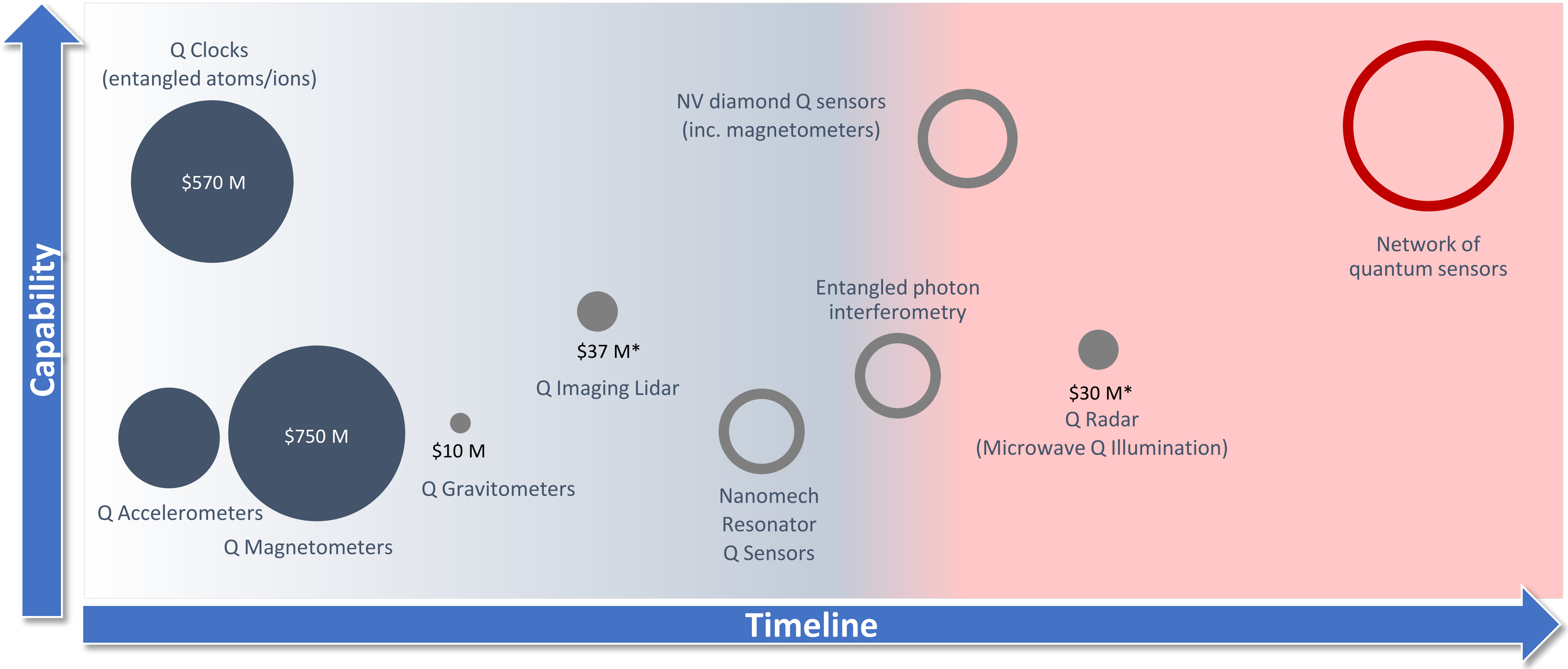
Quantum Sensing Technology/Market Evolution



- Bunker/tunnel/submarine detection
- Geological surveying,
- GPS-denied inertial PNT

Space-based situational awareness, sub-artic navigation

Low-POI, jam-resistant detection of low-reflectivity targets

Quantum GPS, Space-based omniscience

Bubble size = estimated market size in 2025; courtesy of Inside Quantum Technology

Use Cases				Quantum sensing categories and technologies																		
Use Category			Timeframe to Market and Technology Readiness Level Estimate Provided / Physics Categories	Timing		Rotation			Temperature		Acceleration				Magnetic Field				Imaging			
Commercial	Government DoD	Government Civil		CSAC	Optical clocks	NMR	Solid State (NV diamond)	Cold Atoms	Optical thermometry	Micro / Nanoscale	Absolute gravimeter	Gradiometer	Spin Qubit Sensing	Cold Atoms	NMR	hot vapor	Solid State (NV diamond)	Atoms	Ghost Imaging	Quantum Illumination	Sub-shot noise quantum illumination	Synthetic aperture
			Geological Imaging (gravitational & magnetic field)																			
x			Oil, gas and mineral exploration													✓	5y	10y				
x	x		Underground facility / tunnel discovery													3y	7y	10y				
			Sea floor mapping																			
x			Excavation planning													✓	5y	10y				
		x	Hydrology																			
x			Archeology													✓	5y	10y				

TRL Color Codes

		Basic Principles Observed and Reported
< 3	red	Potential Application Validated
3	pink	Proof-of-Concept Demonstrated, Analytically and/or Experimentally
4	teal	Component and/or Breadboard Laboratory Validated
5	blue	Component and/or Breadboard Validated in Simulated or Realspace Environment
6	green	System Adequacy Validated in Simulated Environment
7+	gold	System Adequacy Validated in Real Environment

Quantum sensors for oil, gas and mineral exploration

Sensors identified to support oil gas and mineral exploration include temperature sensors, acceleration sensors for gravitational measurement and magnetic field sensors.

Each quantum sensor is at different technology readiness levels.

- Quantum sensors for gravitational measurement are at a high TRL level, most of which have been tested in a simulated environment or in the real environment.
- Quantum sensors for temperature have been validated in in the laboratory.
- Some quantum sensors for magnetic field sensing are already in use and others are in the early stages of development.

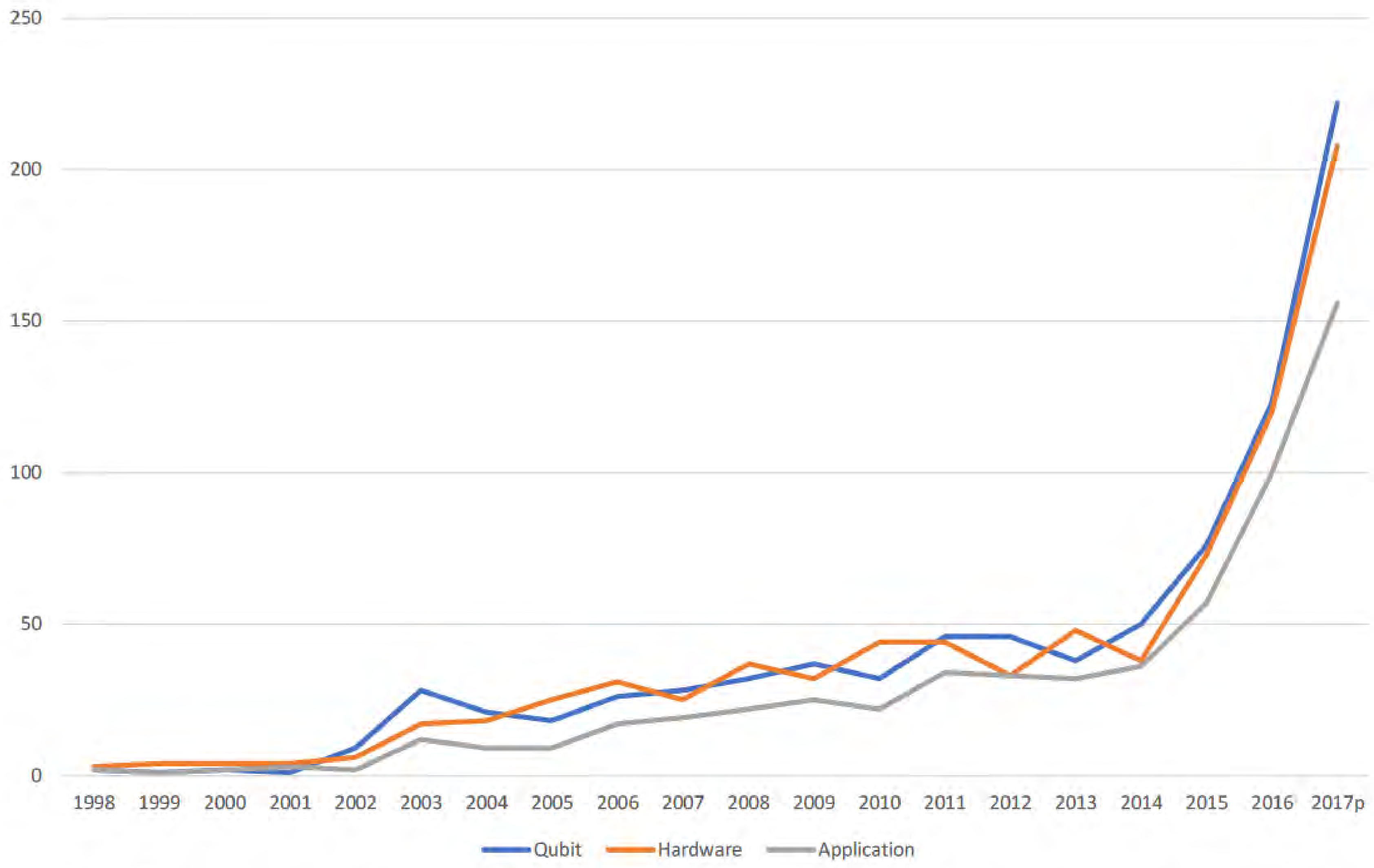
Current landscape for QIS

- Quantum computing:
  - Research is making rapid advances
  - Industry is making big bets
- Quantum sensing:
  - Applications are here/coming soon
  - Markets are variable
- Governments are making significant investments
  - EU Quantum Flagship
  - UK National Quantum Programme
  - China investing billions
- Innovation is accelerating and is occurring worldwide

Quantum Computing Patent Families by Category and Publication Year

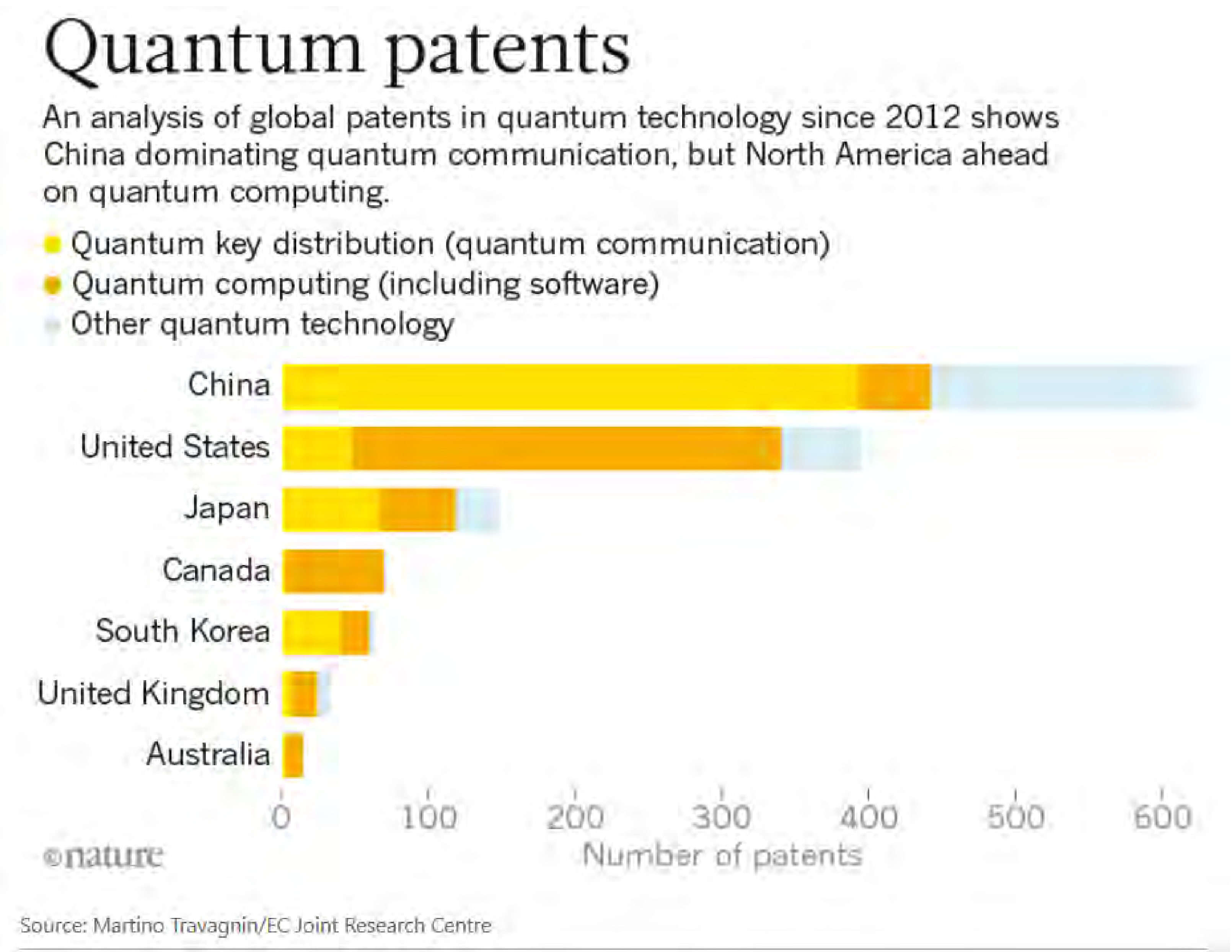
- The jump in the number of patent families in 2003 was driven primarily by documents related to qubit technologies, followed by hardware type and applications.

- Publications related to qubit technology and hardware have seen the greatest amount of growth over the period of rapid expansion that began in 2015 followed by applications.



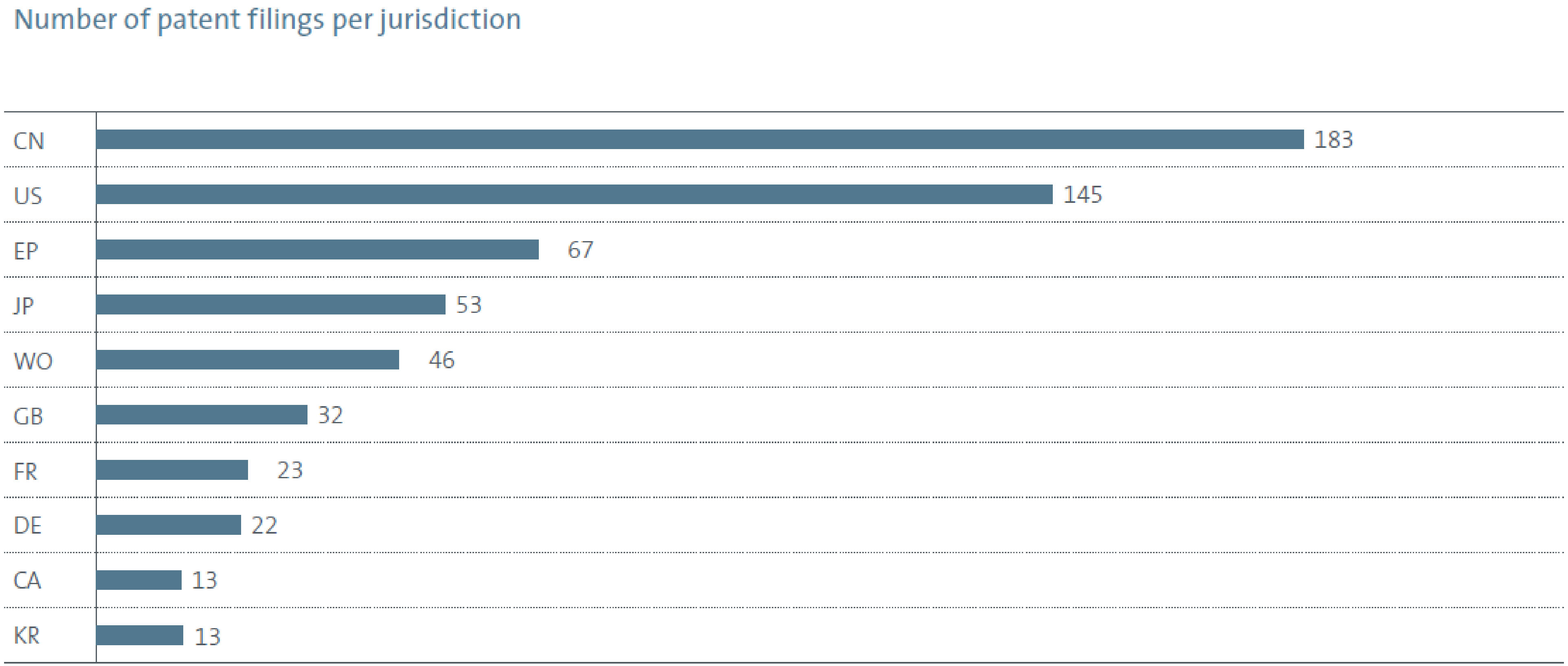
Note: Based on 1,952 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category; Currently 293 documents for 2017.

Source: Patinformatics http://patinformatics.com/wp-content/uploads/2017/10/Quantum-Computing_Full_Report_Final_opt.pdf=



Source: *Nature*, Oct 2, 2019 https://www.nature.com/articles/d41586-019-02935-4

Quantum metrology and sensing patents (2000-2017)



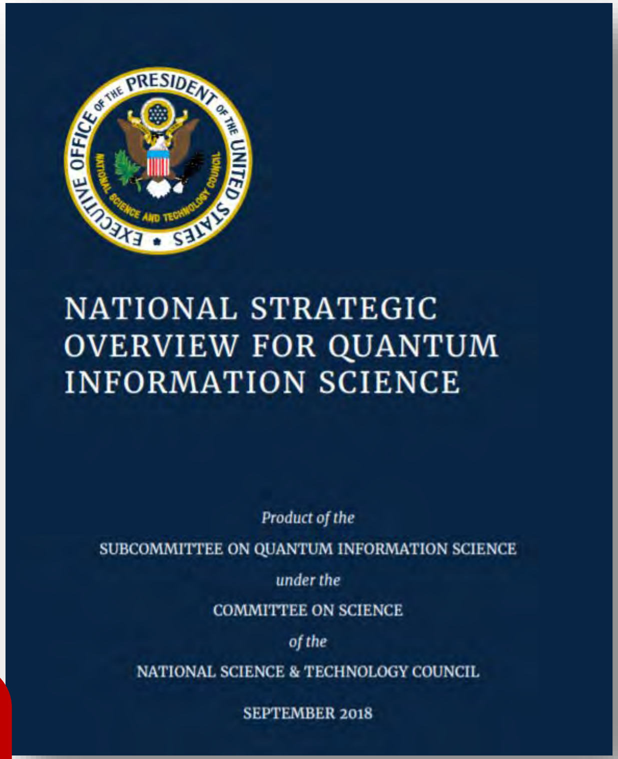
The chart above includes priority and subsequent patent filings for each jurisdiction. It thus provides an indication of the markets which applicants consider important.

The data shows that, in quantum metrology and sensing, the leading patent authorities are China (CN), the United States (US) and the European Patent Office (EP).[11]

Source: *Landscape study on patent filing: Quantum metrology and sensing*, European Patent Office (2019)

US Government's growing effort

- NSF Big Ideas included Quantum Leap (2016)
- DOE BRN workshop on quantum materials (2016)
- Govt-wide research spending ~$200M-$250/yr
- National Strategic Overview for Quantum Information Science released (Sept 2018)
- Quantum Economic Development Consortium (QED-C) established; partnership with NIST and industry (Oct 2018)
- National Quantum Initiative Act signed (Dec 2018)
- NSF and DOE QIS programs launched



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

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

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

An Act

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

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

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the "National Quantum Initiative Act".

(b) TABLE OF CONTENTS.—The table of contents of this Act is as follows:

Industry Depends on a Supply Chain: Semiconductor Analog

First semiconductor transistor, 1947

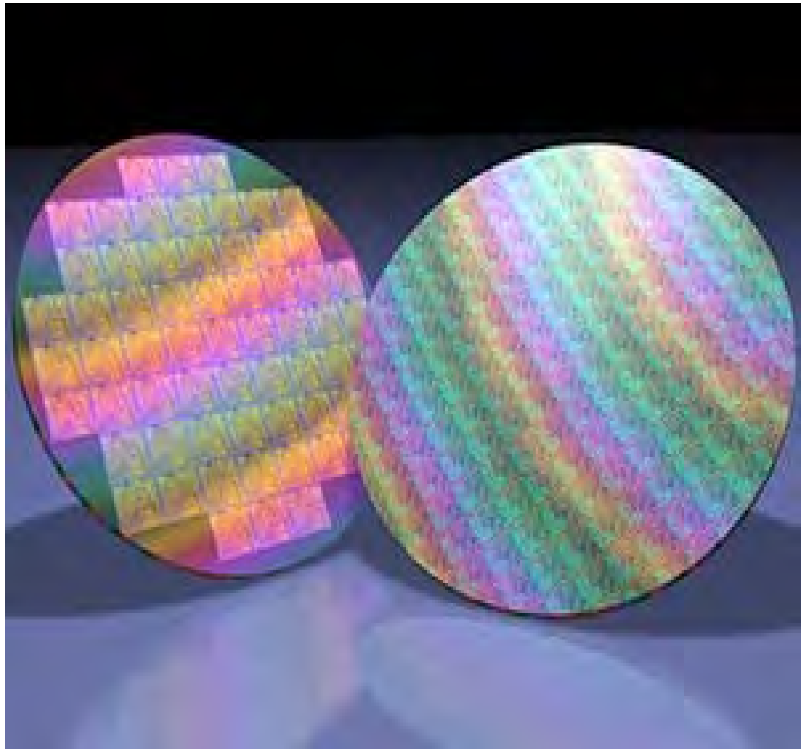
FROM LAB TO FAB

Supply Chain of Enabling Technologies

Wafer processing
- Wet cleans
- Photolithography
- Ion implantation
- Wet and dry etching
- Plasma ashing
- Thermal treatments
- Chemical vapor deposition (CVD)
- Physical vapor deposition (PVD)
- Molecular beam epitaxy (MBE)
- Electrochemical deposition (ECD)
- Chemical-mechanical planarization (CMP)
- Wafer testing
- Wafer backgrinding

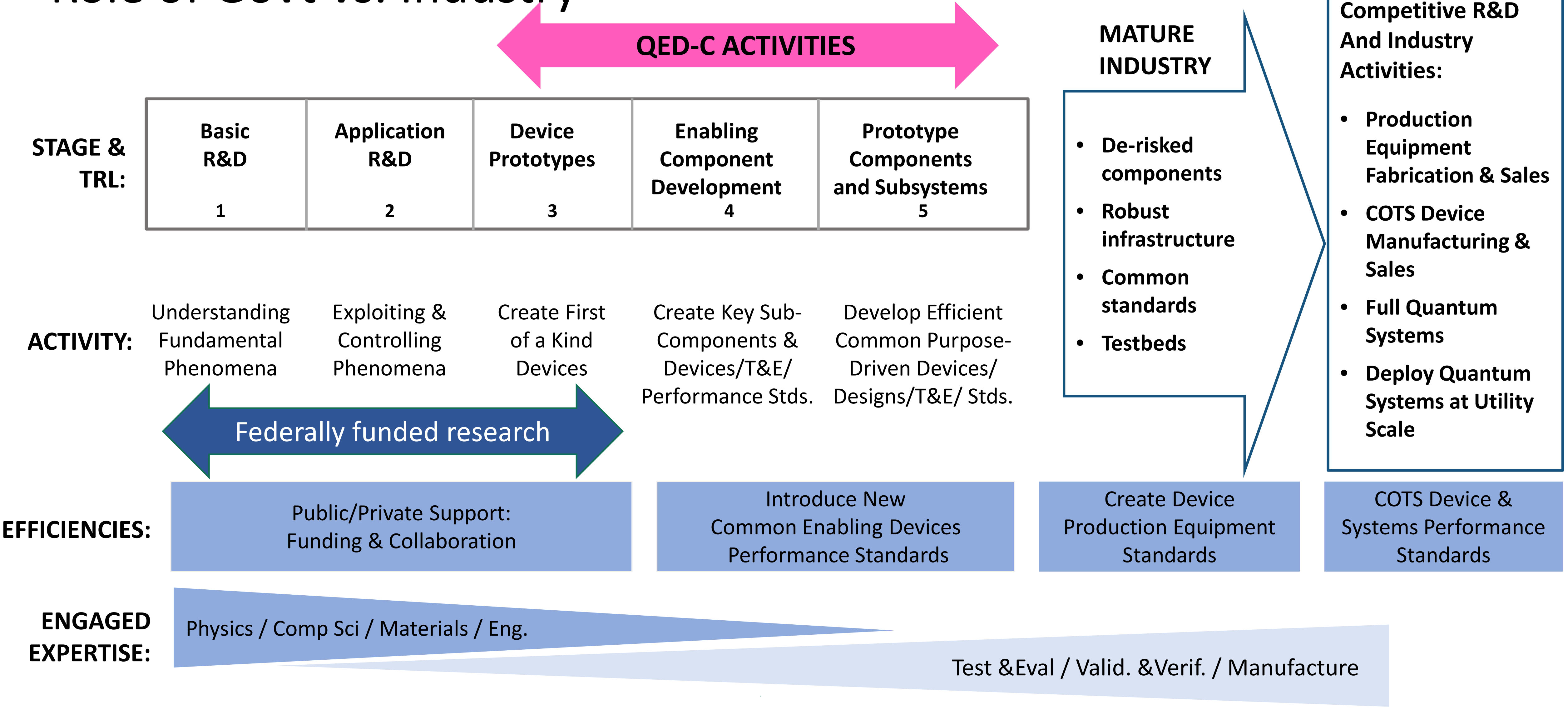
Die preparation
- Wafer mounting
- Die cutting

IC packaging
- Die attachment
- IC bonding
- IC encapsulation
- IC testing



Modern semiconductor transistors

All segments of R&D continuum require support: Role of Govt vs. Industry



Managed by SRI International

QED-C Purposes

- Identify and develop strategies to address gaps in the following
  - Enabling technologies
  - Standards, benchmarks and performance metrics
  - Workforce
- Identify economically important applications
- Facilitate industry coordination and interaction with Government agencies
- Provide the Government with a collective industry voice, e.g., to guide R&D investment priorities, identify economically significant use cases, inform regulatory policy and develop a quantum-ready workforce

QED-C LOI Signatories (as of 11/15/19)

Corporate

- Advanced Research Systems
- Aliro Technologies
- Amazon
- AO Sense
- ARM Research
- AT&T
- Atom Computing
- BAE Systems
- Boeing
- Boston Consulting Group
- BP
- Bra-Ket
- CEC Security
- Citi
- ColdQuanta
- Corning
- Cryomech
- D-Wave
- Entanglement Institute
- EZ Form Cable
- Fieldline
- FLIR
- GE Global Research
- General Dynamics Mission Systems
- Google
- Holzworth Instrumentation
- Honeywell
- HPD
- Hyperion Research
- IBM
- Inside Quantum Technology
- Intel
- IonQ
- Janis Research
- Keysight
- KMLabs
- L3 Harris
- Lake Shore Cryotronics
- Lockheed Martin
- Marki Microwave
- Microchip/Microsemi
- Microsoft
- Montana Instruments
- NuCrypt
- Photodigm
- Photon Spot
- Physical Science Inc.
- Psi Quantum
- PQ Secure Technologies
- QC Ware
- QPRI
- Qrypt
- Quantum Circuits
- Quantum Computing
- Quantum Computing Report
- Quantum Design
- Quantum Microwave
- Quantum Opus
- Quantum Thought
- Quantum Xchange
- Qubitekk
- Qulab
- Qunnect
- Raytheon-BBN
- Rigetti
- Riverside Research
- Rydberg Technologies
- Sivananthan Laboratories
- SkyWater Technology Foundry
- Speqtral Quantum Technologies
- SRI International
- Stable Laser Systems
- Strangeworks
- Takeda
- Toptica
- Twinleaf
- United Technologies Research Center
- US Advanced Computing Infrastructure
- Vescent Photonics
- Young Basile Hanlon & MacFarlane
- Zapata Computing
- Zyvex Labs

Managed by SRI International

Academic

- Caltech/INQNET
- Colorado School of Mines
- George Mason University
- Georgia Institute of Technology
- Purdue University
- Rochester Institute of Technology
- Stanford University
- SUNY Polytechnic Institute
- University of Arizona
- University of Buffalo
- University of Chicago
- University of Colorado
- University of Maryland
- University of Wisconsin

Other

- American Physical Society
- Federal Reserve Bank of Philadelphia
- OSA
- SEMI
- SPIE
- Universities Space Research Association

Breakdown of QED-C Participants (as of Nov 2019)

- 100 entities have signed LOI—
  - 80 Corporations
  - 14 Academic Institutions
  - 6 Professional Societies/ NGO's
- Stakeholder Groups—
  - Quantum 'makers' – hardware/software for computing, sensors, communication
  - Suppliers – lasers, cryogenics, electronics, etc.
  - Quantum end users
  - Standards developers, service providers & professional societies
  - Research institutions, including universities, DOE labs, etc.
  - Government agencies (NIST, DOE, NSF, DOD)

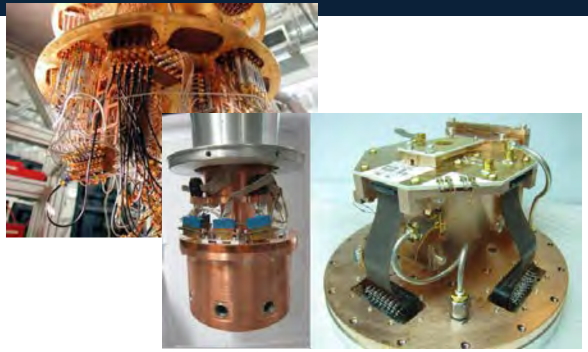
QED-C Activities

- Quantum Workforce Survey
- Standards Needs Survey
- Use Cases and Market Projections
- Enabling Technology Identification
- Focused Technical Workshops

Enabling Technology Workshops

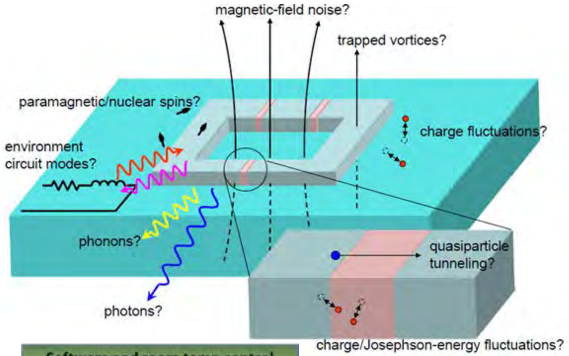
Cryogenics

QED-C Cryogenics for QIST



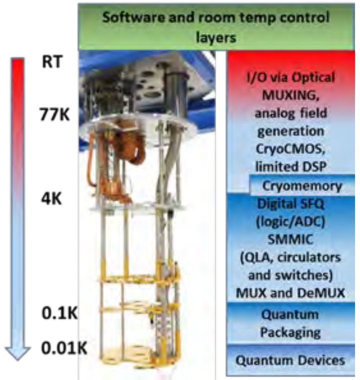
Materials

Characterizing Defects in Superconducting Qubits



Scalable control systems

Electronics and Microwave Components for Quantum Control

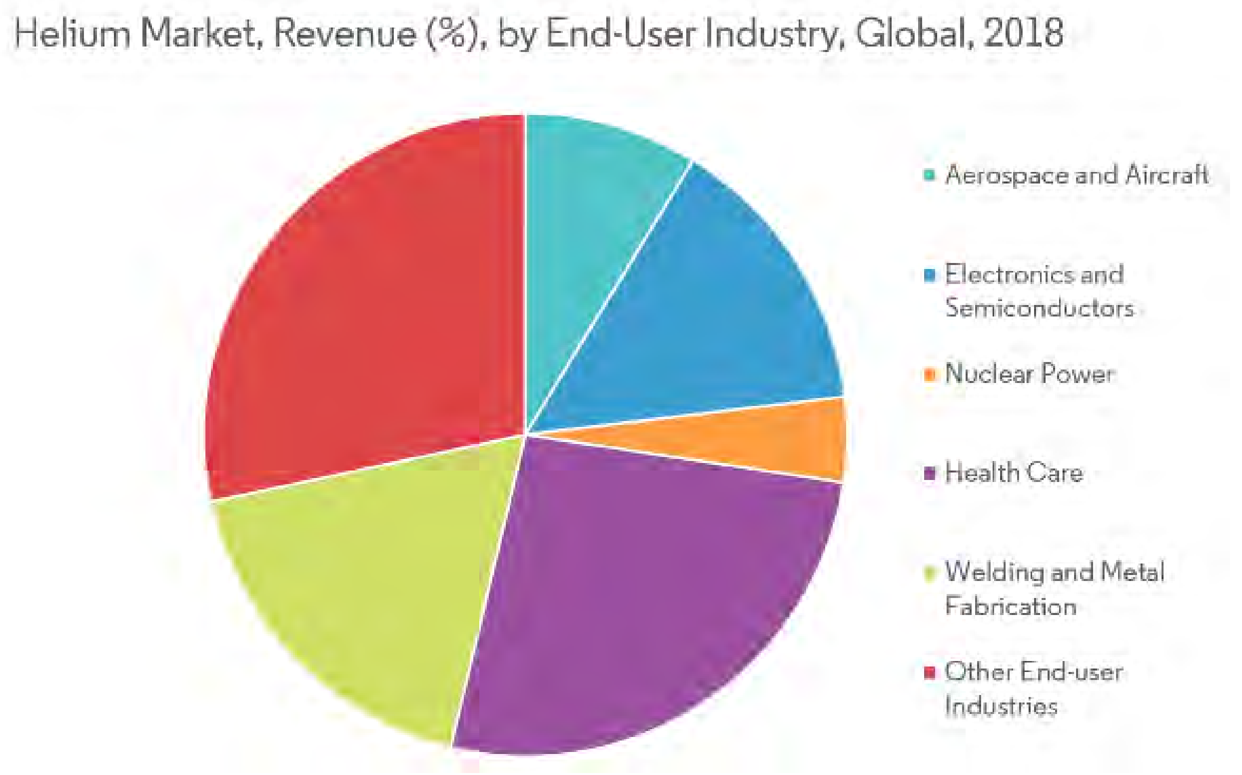


QED-C impact is growing

- Engaging the broad quantum ecosystem
- Identifying enabling technology barriers and strategies to overcome them
- Focused on growing the quantum economy
- Informing NQI agencies and other stakeholders

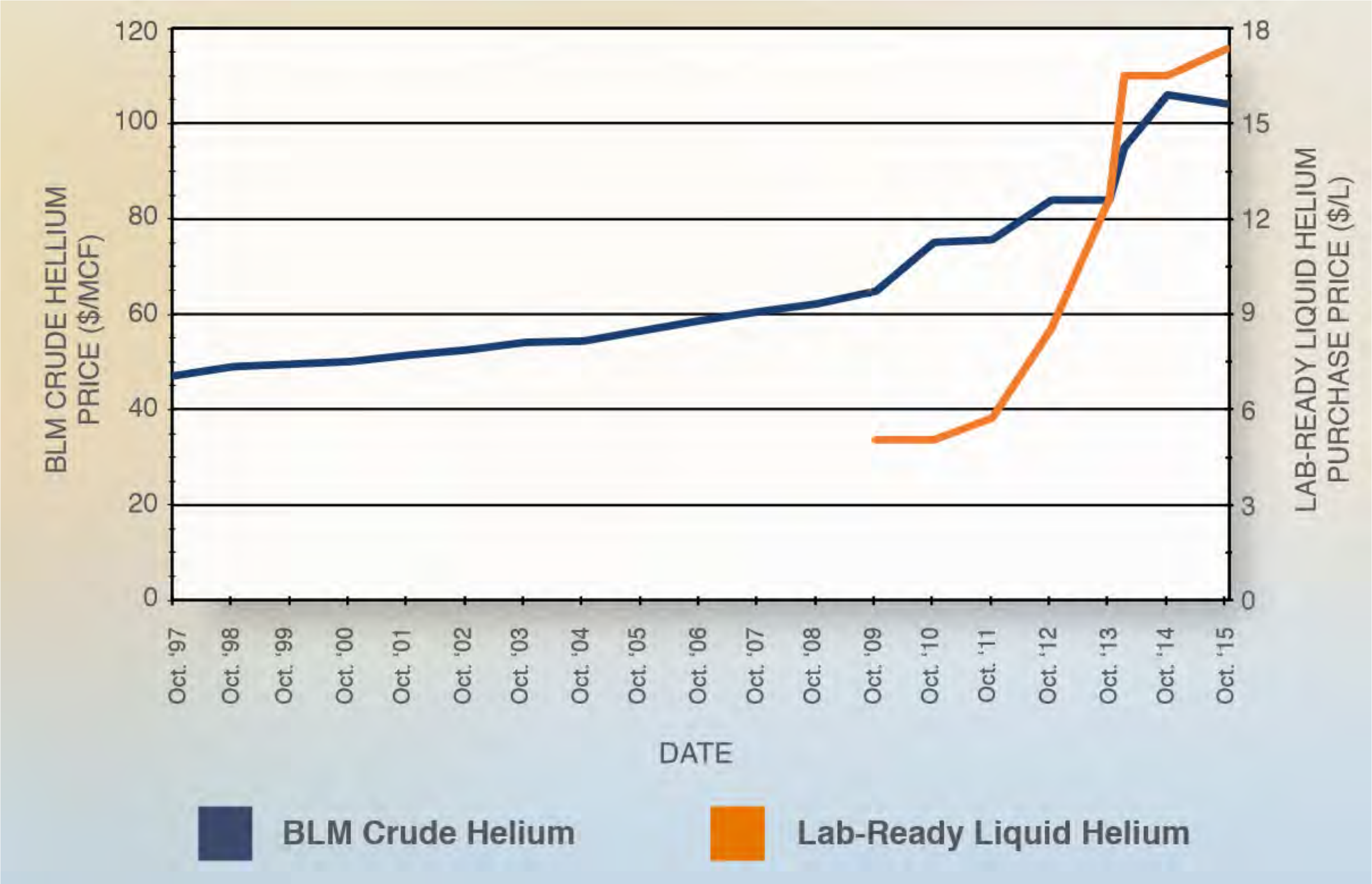
Helium: A DOE-related issue that is critical for QIST

- Ultra-low temperature systems use ^3He and ^4He
- Helium is a byproduct of natural gas production (mostly ^4He); US produces 75% of global supply
- ^3He is produced by radioactive decay of tritium (managed by DOE)
- Most users do not recycle helium
- Federal Helium Reserve is slated to shut down



Source: Mordor Intelligence

Helium prices over time



Source: *The U.S. Research Community's Liquid He Crisis*, 2016

San Antonio Express-News

NEWS WEATHER BUSINESS POLITICS SPORTS LIFESTYLE

BUSINESS

Global helium market faces more uncertainty as government prepares to sell its stockpile stored in Texas

Laura Garcia | June 21, 2019 | Updated: June 21, 2019 3:31 p.m.

TAKE AWAYS

- **Quantum technologies for sensing and computing are advancing rapidly**
- **Private sector sees large and disruptive potential and is investing in application development**

…But markets are still mostly in the future

- **Government and industry need to collaborate**
- **PS – Helium is critical for NQI**

For information:

Go to: https://quantumconsortium.org/

Contact: Celia Merzbacher, celia.merzbacher@sri.com