THE INNOVATION INSTITUTE
at the MassTech Collaborative

MASSACHUSETTS QUANTUM COMPUTING ECOSYSTEM STUDY

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Report contents finalized April 2023.

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1. Executive Summary

Quantum computing has been a topic of intense scientific research for nearly three decades. Quantum computing is the approach to building computers in which the fundamental information units go beyond classical bits ("0 or 1") to quantum bits, which have additional features like superposition and entanglement, which enable computing power to increase exponentially as the number of bits is increased, unlike current classical computers where computing power increases linearly. Quantum computers have the potential to be orders of magnitude more powerful for certain calculations than even the best classical computers but come with additional challenges such as high error rates and the need to be kept ultra-cold. These challenges have prevented adoption of quantum technologies for practical uses, but recent years have seen research groups at universities and in the private sector achieve breakthroughs that have brought increased attention from industry and government actors.

The 2020s are seeing a strong global push in efforts to build useful quantum computers that can solve computational problems that may be impossible to solve using classical systems. Quantum computing has the potential to open up new frontiers in medicine, finance, materials science, and many other disciplines with thorny optimization and simulation challenges that would take a classical computer thousands of years to solve. Modeling the structure of proteins is one particular problem that has remained unsolvable with classical computers that is thought to be possible with quantum systems. This may enable the creation of better pharmaceuticals for diseases such as Alzheimer's and improved crops to feed a growing global population. Quantum computers may also allow more efficient routes for transportation and logistics as well as performance optimized risk management for financial firms.

The John Adams Innovation Institute ("Innovation Institute"), a division of the Massachusetts Technology Collaborative ("Mass Tech Collaborative" or "MassTech") partnered with The Quantum Insider ("TQI") to assess the overall economic and business environment influencing the growth and competitiveness of emerging quantum industry sectors in Massachusetts, the current capabilities and how they align with growth opportunities for the emerging Quantum Computing sector in Massachusetts.

Over the course of several months TQI conducted a thorough analysis of the Massachusetts Quantum Ecosystem. This included providing an **inventory** of critical Quantum Computing assets in the state, including private industry, R&D, college and university programs and workforce pipelines, supporting STEM and education/community programs, and public/private partnerships. To support this, TQI conducted a **survey** with 29 participants to understand the views of key stakeholders in the Massachusetts community. This was enriched by detailed **interviews** with 18 stakeholders across industry and academia.

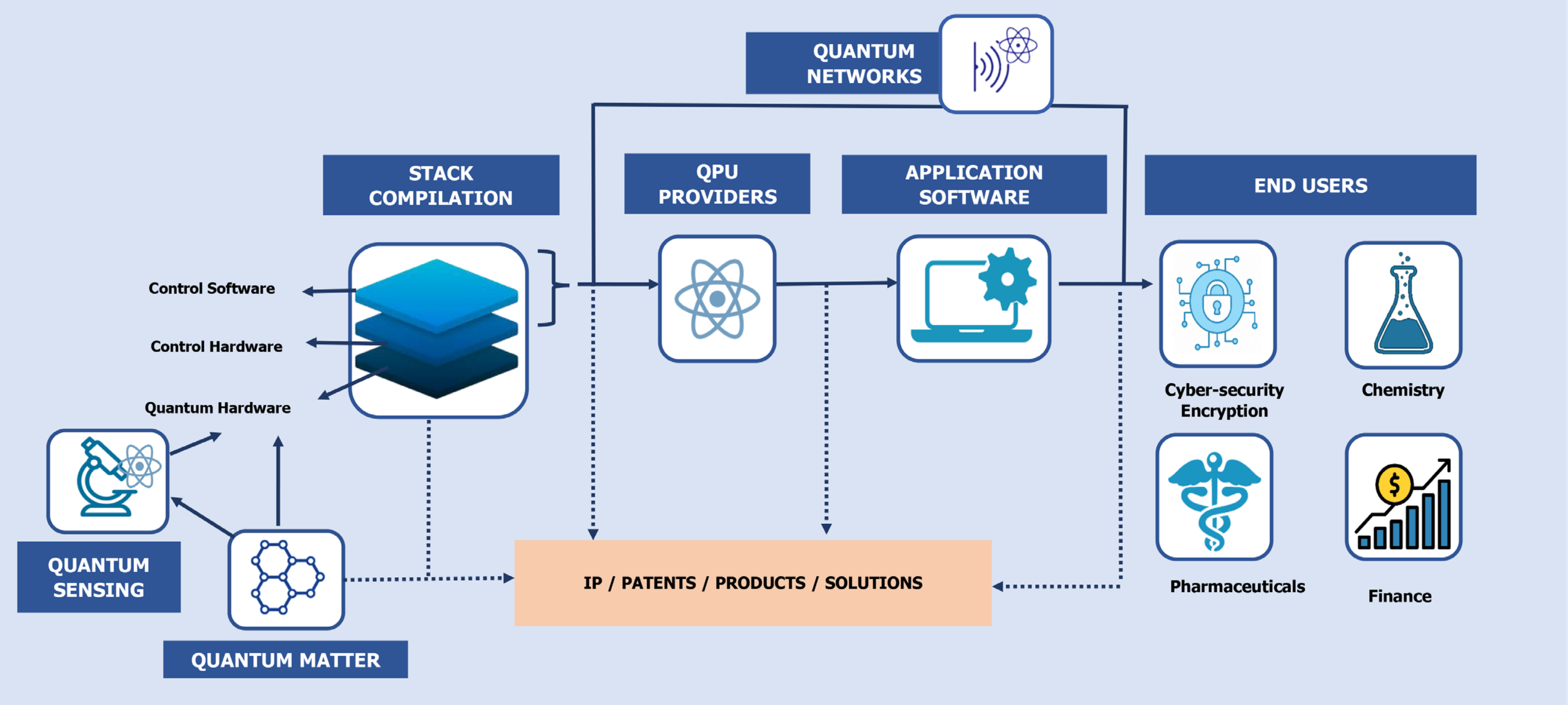
Key takeaways:

- **The Commonwealth of Massachusetts is a global hub for quantum computing.** Like in other technology verticals, Massachusetts has many of the organizations, people, and reputation to maintain this strong position. This includes world leading academic groups and investment funds from top universities, companies engaged in commercialisation of quantum computing, and research centers like MIT Lincoln Labs and AWS Center for Quantum Networking.

- **Massachusetts has a particularly strong academic community and network of groups and research centers.** The Commonwealth benefits from some of the world's leading global universities and groups measured by research impact. Research in the region covers a broad swath relevant to quantum computing and quantum technology more broadly, from near term applied quantum applications through to longer term fundamental research (e.g., fault tolerant quantum computing). This has fostered both a strong presence of quantum computing industry players and encouraged continued fundamental research.

- **There are clear opportunities for further innovation across quantum technologies.** Massachusetts has the foundation to build on strong positions across several research areas including superconducting, photonics, cold atoms, quantum sensing and quantum matter. This is a non-exhaustive list, and more specificity is provided in the appendices.

- **The Commonwealth is comparable to countries in terms of the richness of its quantum computing ecosystem.** There are at least two full stack quantum computing companies across three different processor types, highlighting the diverse range of quantum computers being developed in the region. This is despite not benefiting from equivalent dedicated national level funding (beyond the broader U.S. National Quantum Initiative and other national funding initiatives). In addition, Massachusetts is home to companies across the quantum computing supply chain (see below):



- **Massachusetts represents a good point of entry for startups and international companies looking to enter North American markets.** There are a significant number of multinational companies that have based their distribution arms or operations in the region. This is important as such multinational companies may serve as future vectors for distributing locally developed products or fund / acquire local initiatives. The Commonwealth also has a strong and dynamic pool of relevant talent, though costs in the area are high.

- **Massachusetts quantum computing ecosystem could benefit from a coordinated Commonwealth-wide initiative.** The high level of diversity and sheer number of independent research groups can mean that obtaining external funding is highly competitive. Lack of coordination and fragmented community means that respective research groups are frequently seen as competitors rather than partners, which can be counterproductive to growing the community within the respective fields.

- **Like for many ecosystems, talent migration to other hubs is a concern.** Other quantum technology hubs such as NIST Colorado, California and Maryland were seen as potentially competitive in the U.S. as well as growing coordinated ecosystem initiatives in Europe (for example Germany and the Netherlands).

- **There are significant opportunities to improve commercialization in the region.** There was consistent feedback that more could be done to facilitate the commercialization of quantum computing through initiatives to deepen the connectivity in the ecosystem. The opportunities for accelerating start-up initiatives should also be noted. This is particularly true in the field of applied quantum computing by bringing together stake holders in bio-tech, energy, quantum computing and algorithm development. Interdisciplinary initiatives such as these have emerged in other quantum hubs and tend to allow for novel start-up activities.

- **A coordinated push to further develop over-arching infrastructure to address the quantum computing commercialization pipeline may be required.** Over half of interviewees expressed the need for initiatives to bring researchers and industry together. This includes platforms such as conferences, meetings and workshops. As there are several well established and resourced facilities already in Massachusetts, it might make sense initiate a "Quantum Alliance" that looks to open up further the potential for inter disciplinary research collaboration and access to facilities.

The rest of this report is structured into three sections, as follows:

Section 1:
Introduction to the Massachusetts quantum computing ecosystem provides a mapping of the key relevant stakeholders and how they interact.

Section 2:
Market Analysis provides an assessment of the strengths, weaknesses, opportunities and threats (SWOT) for the Massachusetts Ecosystem, evaluates the Commonwealth's positioning in QC against other US states and other regions globally and sets some key focus areas to leverage the assets and potential of QC and related technologies.

Section 3:
Conclusions and recommendations provides key focus areas for the Commonwealth moving forward that leverage the assets and potential of Quantum Computing and related technologies, as well as some recommendations for further work.

This work would not have been possible without the significant and important input from stakeholders across the Massachusetts ecosystem, who are acknowledged in the Appendices.

Glossary

- **Cold Atoms/Ultracold Atoms:** These are atoms, usually group one elements that are evaporated and encapsulated into a high vacuum chamber, and through laser pumping condensed into exotic phases of matter. This matter can be used in various technologies including ultra-sensitive interferometry, graviometry and accelerometry but are most notable as platforms for optical quantum computers.
- **QPU:** Quantum Processing Unit, synonymous with quantum computer, a logic processing machine reliant on quantum mechanics.
- **CMOS:** Complimentary Metal-Oxide Semiconductor, the cornerstone of contemporary silicon-based computers
- **Qubit:** Quantum Bit, the individual logic processing component of a quantum computer. These are single devices, such as in the case of superconducting QPUS, or can be individual atoms, as in the case of defect centers, trapped ions and cold atoms.
- **MNC:** Multi National Corporation
- **NISQ:** Noisy Intermediate-Scale Quantum system. The first wave of quantum computers. These systems have low logic processing capabilities due to limitations in their qubit number and quality. These are the current state-of-the-art quantum processors and allow for entry level computation.
- **Quantum Technology:** A broad range of emergent and potentially disruptive technologies that function in a way that harnesses quantum mechanical phenomena. This category of technology is broad and encompasses quantum sensors/ detectors, quantum communication technologies/networks for encrypting information and distributing it across networks and quantum computers used in logic processing.
- **Photonic:** Photonics is a branch of optics that involves the application of generation, detection, and manipulation of light in form of photons through emission, transmission, modulation, signal processing, switching, amplification, and sensing.

2. Introduction to the Massachusetts quantum computing ecosystem

a. Introduction

Quantum technology is an emerging field that harnesses the principles of quantum mechanics to create new technologies with revolutionary capabilities. Some practical use cases of quantum technology include cryptography, communication, sensing, and computing. For example, quantum computers have the potential to solve complex problems that classical computers cannot, while quantum sensors can detect small changes in magnetic fields or gravity.

This report has focused on quantum computing however, as quantum technologies depend on a related core of technologies, where relevant this report also includes a broader discussion of quantum technology activities in Massachusetts.

In terms of adoption, quantum technology is still in its early stages and is primarily being developed by research labs, early-stage start-ups and a few large companies. However, there is growing interest and investment in this field, and some experts predict that practical applications of quantum technology could become more widespread within the next decade.

The Commonwealth of Massachusetts is a hub for quantum computing and the broader areas of quantum technology. There are many academic groups, research centers, start-ups and large corporations engaged in quantum computing and closely related topics.

This section presents an inventory of the state's quantum computing assets.

Section 1.a
contains figures and charts that show the Massachusetts quantum computing ecosystem at a glance – including academic, industrial and governmental actors.

Section 1.b
outlines the quantum computing activities and organizations within academia in Massachusetts, covering the various academic organizations engaged in quantum computing and the broader areas of quantum technology. This section includes a quantum technology patent search spanning the past five years as well as a list of quantum technology initiatives pursued by the respective academic institutions.

Section 1.c
outlines the companies in Massachusetts that are pursuing quantum computing. This includes start-ups for whom quantum computing is an essential part of their value proposition, companies that supply components and other services that are "inputs" to quantum computing, and established companies seeking to expand their product offering or adopt new technologies. This section includes information on recent quantum technology patent output as well as awarded SBIR and STTR funding.

Section 1.d
describes the national labs and other research centers in Massachusetts that are engaged in quantum computing research. This section looks to highlight strengths in infrastructure and facilities that may be of potential interest to emergent quantum technology initiatives.

b. The ecosystem at a glance

Massachusetts enjoys a rich ecosystem of quantum stakeholder organizations. Figure 1 summarizes the organizations covered as part of our analysis.

An extensive list of organizations engaged in quantum computing and closely related technologies have been tabulated (see accompanying Excel document). These organizations fit into the categories shown in Figure 1. The sub-categories are explained in detail in the relevant subsection of this report or in the appendices.

The base of quantum computing is in academic groups and research centers. These research-focussed organizations drove most of the early conceptualization of quantum computing in the 80s and 90s and are still significant drivers of progress. Companies that are engaged in quantum computing are currently engaged in the pursuit of developing industry-relevant use cases of quantum computing and bringing the technology to market. These companies rely on individuals from these research-focussed organization, who have developed deep expertise of quantum computing over many years of a research career. As quantum computing companies tend to be largely in the product development phase of their lifecycle, they rely heavily on investors for capital. This also requires investors to be willing to take a bet on the potential of quantum computing. Finally, the cycle is only complete if there are users of quantum computing to sell these services to. Today, users of quantum computing are best seen as "early-adopters" – typically large companies trying to stay ahead of their competition by being ready to adopt new technologies as they are developed.

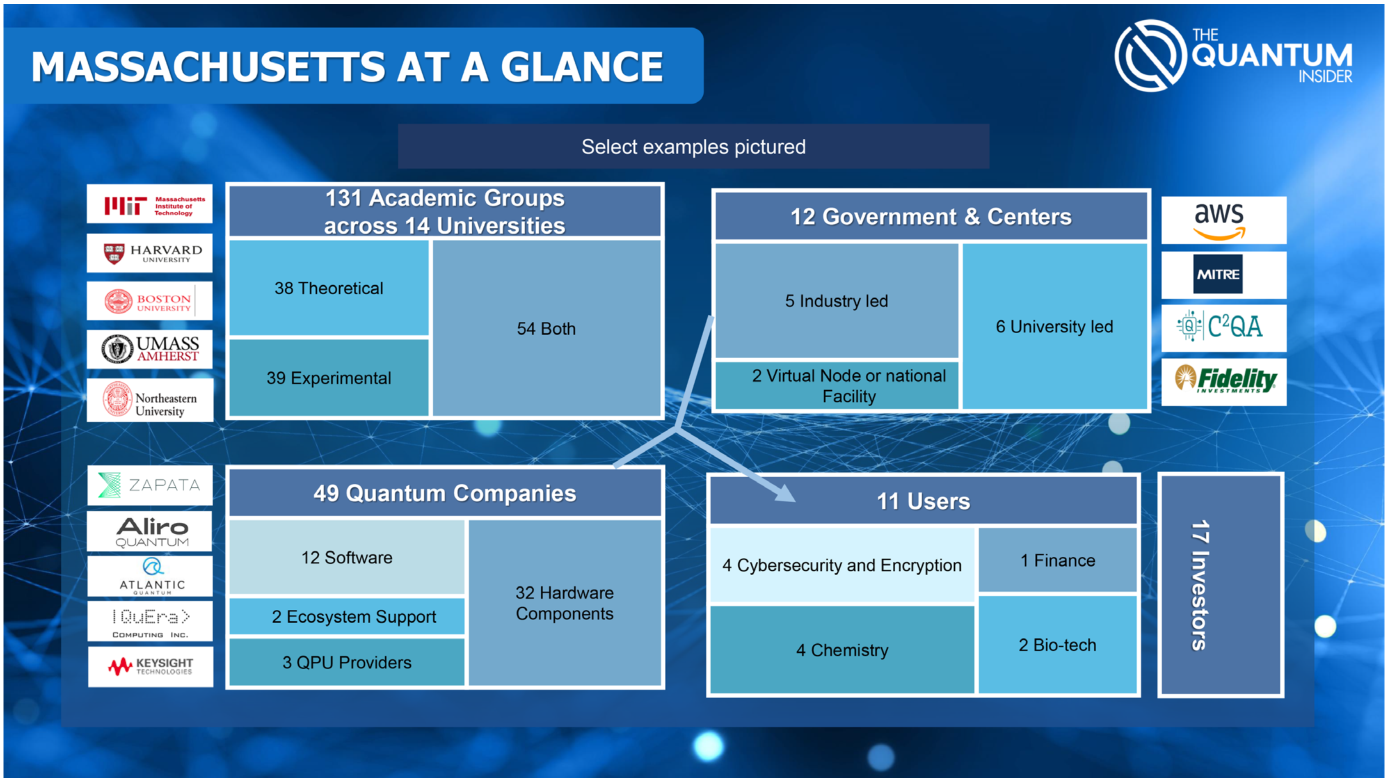


FIGURE 1 - THE MASSACHUSETTS QUANTUM COMPUTING ECOSYSTEM AT A GLANCE

Academic groups

- An academic group is an organizational unit in universities typically led by one Principal Investigator (PI) who is a professor at the university. Academic groups have research staff, graduate students and sometimes also a handful of undergraduate students or visiting faculty. The groups are united by research interests, and supervision by the PI. Academic groups are funded by the university and any research grants held by the Principal Investigator.

- From the 14 doctorate-granting universities in Massachusetts, 131 research groups have been identified whose activities are related to quantum technology.

Quantum Companies

- 49 companies with activity in quantum computing have been identified. This ranges from start-ups and small-medium-enterprises that focus primarily on quantum computing, all the way to large multinational companies which have a research division in quantum computing that is based in Massachusetts.

Research Centers (Governmental, Academic and Industrial)

- Research Centers organize, consolidate and empower researchers towards specific goals. They consist of many research groups, which collaborate closely and share expertise and resources. Research centers can be on-premise institutions or virtual organizational entities.
- No fewer than 12 research centers in Massachusetts created either by governmental or industrial organizations which have a focus closely related to quantum computing have been profiled.

Users

- Companies that are early adopters of quantum computing form an important part of the industry. These companies are typically large multinational corporations (MNCs) who want to stay ahead of their competitors in adopting new technologies. Apart from funding and interest, they bring domain-expertise and requirements that informs quantum computing practitioners on how they can build their solutions to cater to real industrial needs.
- At least 11 companies that have expressed significant interest in adopting quantum computing as "users" of the technology have been found. Here enterprises that have publicly announced adoption or integration of quantum computing, those that have initiated in-house quantum specific operations and those with formal collaboration with quantum computer providers have been included. Users are distinct as they are not involved in developing or producing components of the quantum stack, but rather focused on application of existing contemporary quantum systems.

Investors

- A total of 17 organizations based in Massachusetts that have invested in at least one quantum computing company have been identified.
- These organizations are venture capital funds, venture arms of large companies and university investors.
- There is not sufficient public disclosure to identify the precise amount of funding provided by Massachusetts based venture capital funds.
- Massachusetts companies have also received investment from organizations outside of the state.

c. Academia

At the core of any quantum computing hub today is a strong academic base. This is because of the nascency and deeply technical nature of the field. An academic base is important for the research developments that are needed to bring quantum computing to maturity, and for training the quantum workforce.

Research in universities continues to be a primary driver of progress in quantum computing. Research groups also train scientists and engineers (typically in the form of post-graduate students and research faculty) who have the deep technical expertise required to work in quantum computing. Moreover, research and development roles in quantum computing companies are primarily filled by PhD and Master's degree holders with substantial experience in quantum computing.

The organizations that constitute this academic base are research universities, research centers and academic groups.

The Commonwealth of Massachusetts has a strong reputation for excellence in research. Massachusetts has 114 colleges and universities1 out of which 15 are research universities (i.e. doctorate-granting universities in the Carnegie Classification).[2] The two universities with the largest number of researchers engaged in quantum technology research are Harvard and MIT – each with their own coordinated quantum technology efforts – the Harvard Quantum Initiative (HQI) and the MIT Center for Quantum Engineering (MIT CQE) respectively. Together, these initiatives account for more than 100 senior academics working across various aspects of quantum technologies (MIT CQE has 68 members,[3] and HQI has 45).[4] Many of these individuals have organized academic groups of their own. Our research identified 25 such groups in MIT and 39 in Harvard (see accompanying Excel document).

Boston University is also a hub for quantum technology research with some 20 research groups engaged in related activities. There is currently no indication of a coordinated quantum initiative at Boston University.

Most of the other research universities in Massachusetts have some activities relating to quantum technologies. It was found that at least 12 of 15 of these universities had actives research groups working in the broader area of quantum technology (with the exceptions of Suffolk University and University of Massachusetts, Dartmouth).

Doctorate-granting universities in Massachusetts (Carnegie Classification)

1. Boston College
2. Boston University*
3. Brandeis University
4. Clark University
5. Harvard University*
6. Massachusetts Institute of Technology*
7. Northeastern University
8. Suffolk University
9. Tufts University
10. University of Massachusetts, Amherst
11. University of Massachusetts, Boston
12. University of Massachusetts, Dartmouth
13. University of Massachusetts, Lowell
14. UMass Chan Medical School
15. Worcester Polytechnic Institute

**Indicates 10 or more academic groups in quantum computing*

A total of 29 groups that work directly in quantum information technologies (including quantum computing, quantum information theory, quantum communications and quantum networks) were identified. There are four research areas that are especially well represented – quantum photonics, superconducting qubits, ultracold atoms, and quantum information theory (including quantum computer science and quantum algorithms).

In total 131 academic groups in Massachusetts that work in topics related to quantum computing have been identified. Our methodology involved a careful review of all academic groups in the Physics, Electrical Engineering, Computer Science, Chemistry and Mathematics departments at the 14 research universities. Note that 84 of these academic groups come from just three universities (MIT, Harvard and Boston University), all of which are located within just a couple of miles of each other. Moreover 108 of 131 groups are in the Greater Boston area.

Figures 2 and 3 demonstrate the academic groups connected to the relevant research universities.

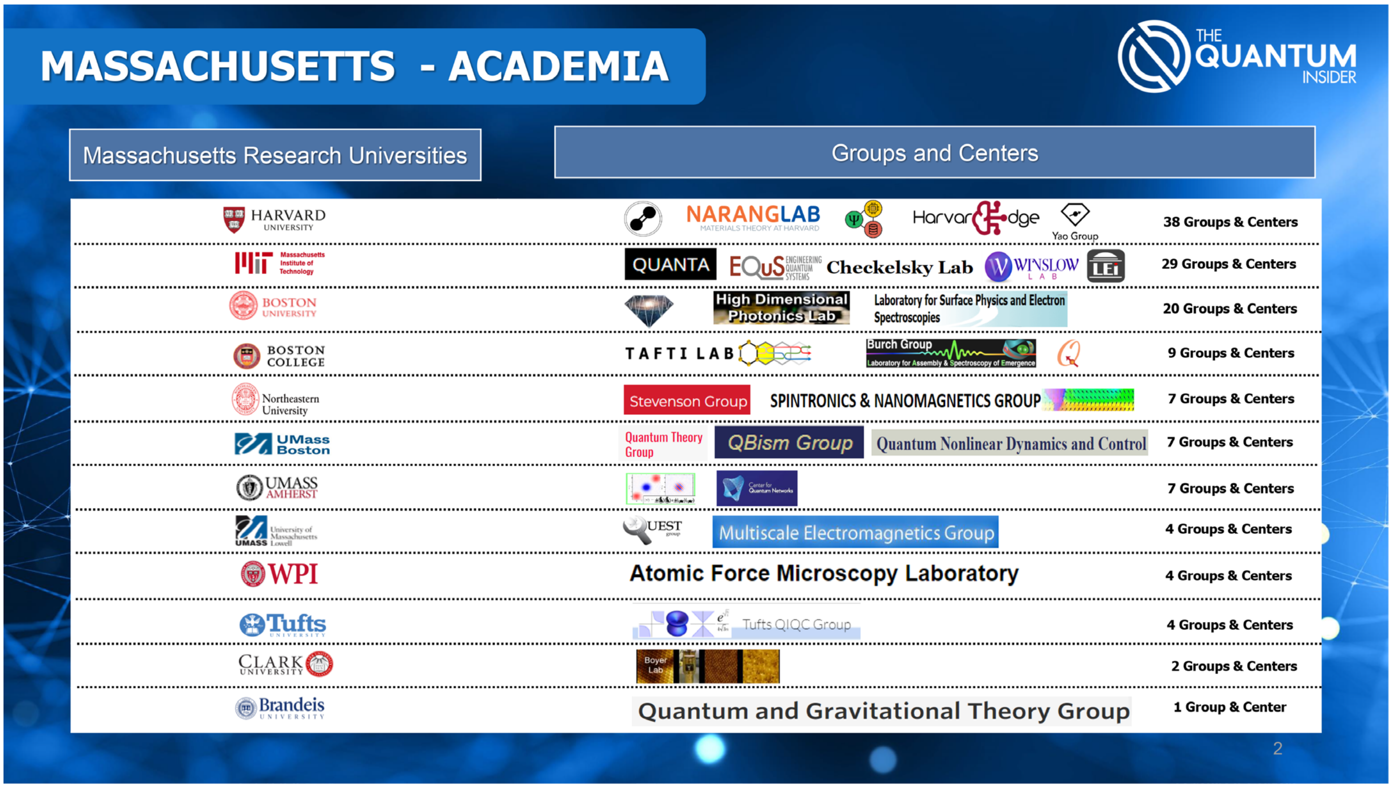


FIGURE 2 MASSACHUSETTS ACADEMIC GROUPS

FIGURE 3 MASSACHUSETTS RESEARCH UNIVERSITIES MAP

Focus areas

The 131 research groups included in this pool are from a diverse range of focus areas. This diversity happens to be one of the unique features of the Massachusetts ecosystem and the groups whose research and capabilities are relevant to quantum technologies have been identified. This includes groups working directly in quantum computing but also groups that do not directly work in quantum computing, but in related fields such as quantum sensing, quantum matter or quantum photonics. Such groups might produce technologies that support quantum computing and are relevant to the quantum technology in general. Moreover, if a coordinated quantum computing effort is pursued in Massachusetts, these are the groups most likely to pivot their research focus to join such an effort. The list of focus areas included in quantum technology are:

Quantum Applications

- **Quantum information science:** This focus area involves the applied quantum computing, the development of quantum algorithms for near-term quantum processors. This field sees the overlap of contemporary computer science, quantum device/qubit research and software development.
- **Quantum sensing:** A very diverse focus area looking at a range of technologies which can include photonic detectors (single photon detectors), thermal sensors, interferometers, gyroscopes, accelerometers, and ultra-sensitive magnetometers. This focus area can also include quantum sensor for biological application.

Quantum Computing Systems

- **Superconducting qubit research:** As superconducting quantum processors are one of the most popular and important technologies to the quantum computing field, the research groups conducting work in the area have deliberately outlined. This research involves developing novel qubits, scale quantum circuits and novel techniques to control or integrate these into larger systems and importantly, error correction and mitigation for superior devices.

- **Supporting quantum computing and alternative systems:** This area is distinct from "qubit research" as it looks more at control and measurement rather than individual devices. This typically involves larger arrays of qubits and quantum circuits, the engineering to solve current bottlenecks in scalability and refine techniques for connectivity between connected device ensembles. This can be through different platforms such as superconducting or trapped ion/ neutral atoms.

- **Quantum optics:** This grouping includes optical quantum technologies such as quantum computing systems (Ion traps and neutral atoms), quantum networks, communication as well as integrated photonics research. These focus areas have been grouped together because of the reliance on laser technology. These focus areas share many similarities in needs of facilities or infrastructure as well as allow for interdisciplinary collaboration opportunities.

Other research

- Quantum matter: This focus area involves research at a material level and typically encompasses nano-materials, nano-electronics, device fabrication, experimental and theoretical condensed matter research. This typically deals with raw/ synthetic materials and the processing of these materials into devices to study exotic physical phenomena in pursuit of next generation technologies.

- Other: Several groups that are not directly involved with quantum technology research but close enough to be considered peripheral and potentially important to the field have been included. This includes certain efforts in computer science, materials research, advanced engineering (such as radio frequency technologies) and soft matter/biomaterials.

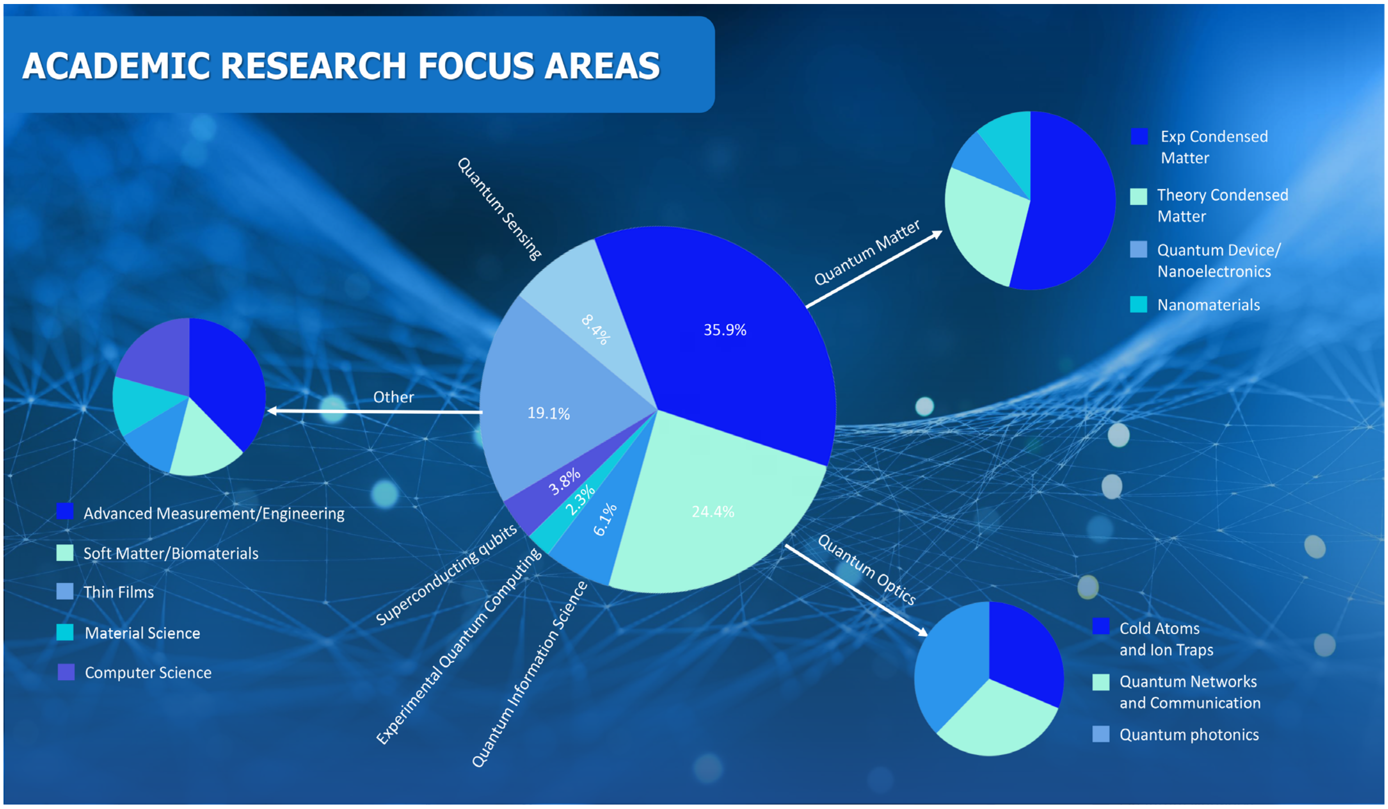


FIGURE 4 HIGH LEVEL OVERVIEW OF QUANTUM TECHNOLOGY RELATED RESEARCH ACROSS 14 UNIVERSITIES IN MASSACHUSETTS

Research into quantum technology in Massachusetts is vast. There are groups representing topics across almost all contemporary aspects of quantum computing (and more broadly, quantum technology) as well as strong activity in peripheral research focus areas that feed into quantum-tech. This diversity is shown above in figure 4 where a breakdown of the quantum technology related research landscape is given. As can be seen, significant research activity is being directed towards quantum matter (35%) and quantum optics (24%) categories. Although quantum sensing (8%) has been listed as an individual category, this field typically overlaps or connects quantum matter and quantum optics. Although the number of research groups working in superconducting technologies (specifically qubits 4%) is lower than in optical technologies there is significant work being conducted in these groups and enough diversity to justify their own category.

Furthermore, the cold atoms and ion trap subcategories may also be absorbed into experimental quantum computing, however, have been kept separate as these topics are sometimes related to broader quantum technologies outside of quantum computing (e.g., significant indication of cold atoms being used in interferometry and gravimetry sensing, which falls outside of pure quantum computing).

Lastly, the peripheral "other" category accounts for approximately 20% of the research groups identified. As mentioned before, these are included as they are focused on areas that can directly feed into quantum technology and may in future boost quantum related activities if given incentive/opportunity.

Broader quantum initiatives

Another notable point regarding academic groups is that they are frequently members of larger centers that coordinate research efforts in a single direction. The following table lists a selection of universities in Massachusetts and their memberships in various quantum centers and initiatives.

University	Quantum Initiatives
Harvard	• Harvard Quantum Initiative • AWS Center for Quantum Networking • Participation in Quantum Systems Accelerator • Center for Ultracold Atoms • Harvard-Max Planck Quantum Optics Center • Center for Nanoscale Systems • Center for Integrated Quantum Materials
MIT	• MIT Center for Quantum Engineering • MIT Lincoln Labs • Participation in Co-design center for quantum advantage coordinated by Prof. Isaac Chuang. • Partner in Q-NEXT • MIT RLE and MIT LL are members of the Quantum Systems Accelerator, participation coordinated by William Oliver and Eric Dauler • MIT Research Laboratory of Electronics • Center for Ultracold Atoms
Boston University	• BU Photonics Center
UMass Boston	• Part of a project to install quantum computing labs at UMass Boston and Western New England University. Three Massachusetts-based businesses are also part of this program (Millimeter Wave Systems, Quantum Microwave, and JanisULT). This initiative was supported by the Massachusetts Technology Collaborative
UMass Amherst	• Participation in Center for Quantum Networks coordinated by Prof. Don Towsley • Seed fund of at least $5 million supporting Quantum Information Systems research
Tufts University	• Participation in the Quantum Systems Accelerator, coordinated by Peter Love
Northeastern University	• Has seen the recently established Experiential Quantum Advancement Laboratories (EQUAL) at the Innovation Campus, in Burlington, MA another initiative driven by the Massachusetts Technology Collaborative

FIGURE 5 SELECT UNIVERSITY ACADEMIC GROUPS AND INITIATIVES

As outlined above, Harvard and MIT are clear academic leaders in quantum technology in Massachusetts and indeed globally. A recent report by RAND Europe found that MIT and Harvard lead the world in quantum computing and simulation research impact, measured as the total number citations for their publications in these fields since 2017[5].

The below figures demonstrate the reach and importance of MIT and Harvard.

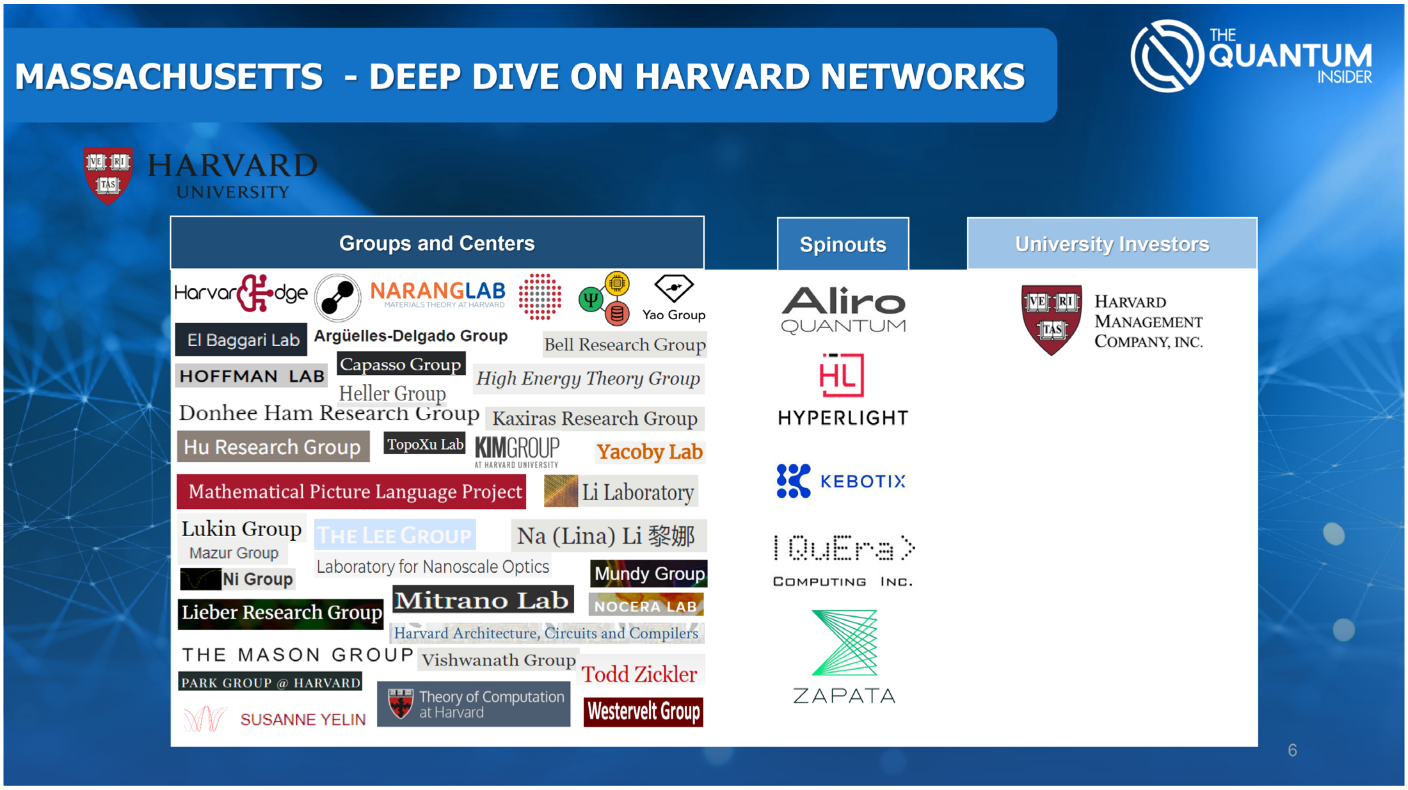


FIGURE 6 HARVARD QUANTUM ECOSYSTEM

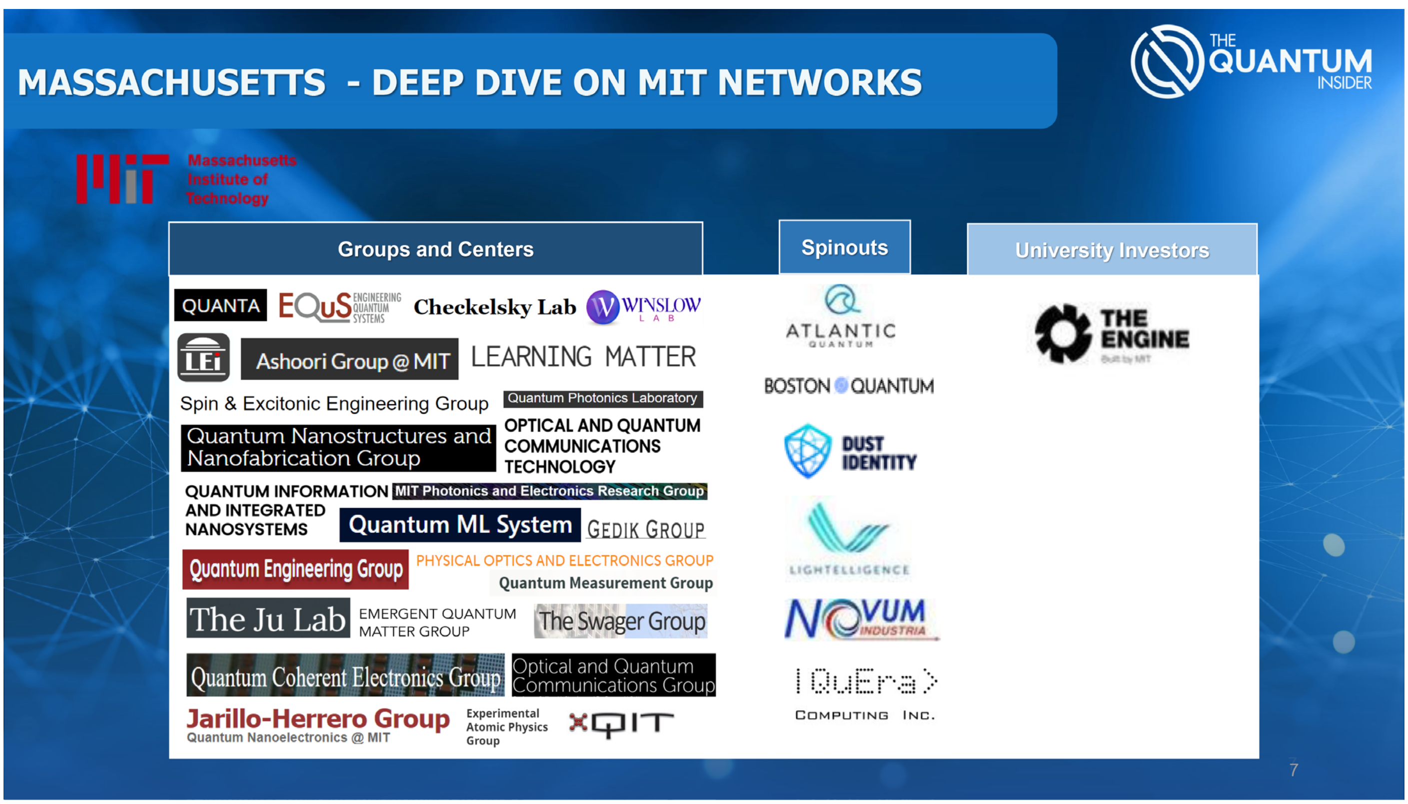


FIGURE 7 MIT QUANTUM ECOSYSTEM

Patent output per university

An important metric of research impact is the patent output from the respective universities. A patent search to identify quantum technology pioneers was therefore undertaken. This search identified patents based on the technology domain or focus area previously described. It was found that of the 131 research groups identified, 55 had filed patents related to quantum technology in the past five years. This amounted to 444 patents in total. Of the 15 Universities tracked, only 7 had generated quantum technology related patents. Massachusetts Institute of Technology was a clear leader in patent output with a total of 196 and an additional 34 generated from Lincoln Labs. This was followed by Harvard University (164), Northeastern University (8) the University of Massachusetts Amherst (3), and Boston University (2) .

There are a few notable prolific inventors' worth highlighting:

Dirk Englund- MIT (36), Federico Capasso – Harvard (51) and Timothy Swager-MIT (74) making up a substantial proportion of MIT's total patent output. This is an indication that high output can be heavily driven at the individual researcher level, and not necessarily an overarching University strength.

Although the patent output seems to be dominated by the higher ranking (and resourced) universities, significant quantum technology work is emerging from the smaller Universities; note the contribution of Swastik Kar (8) to the patent output of Northeastern University as well as Chen Wang (1) and Joseph Bardin (2) The University of Massachusetts Amherst.
The figure below shows the progress of quantum technology patent filing over the five-year period and an overview of focus areas the patents are being generated from.

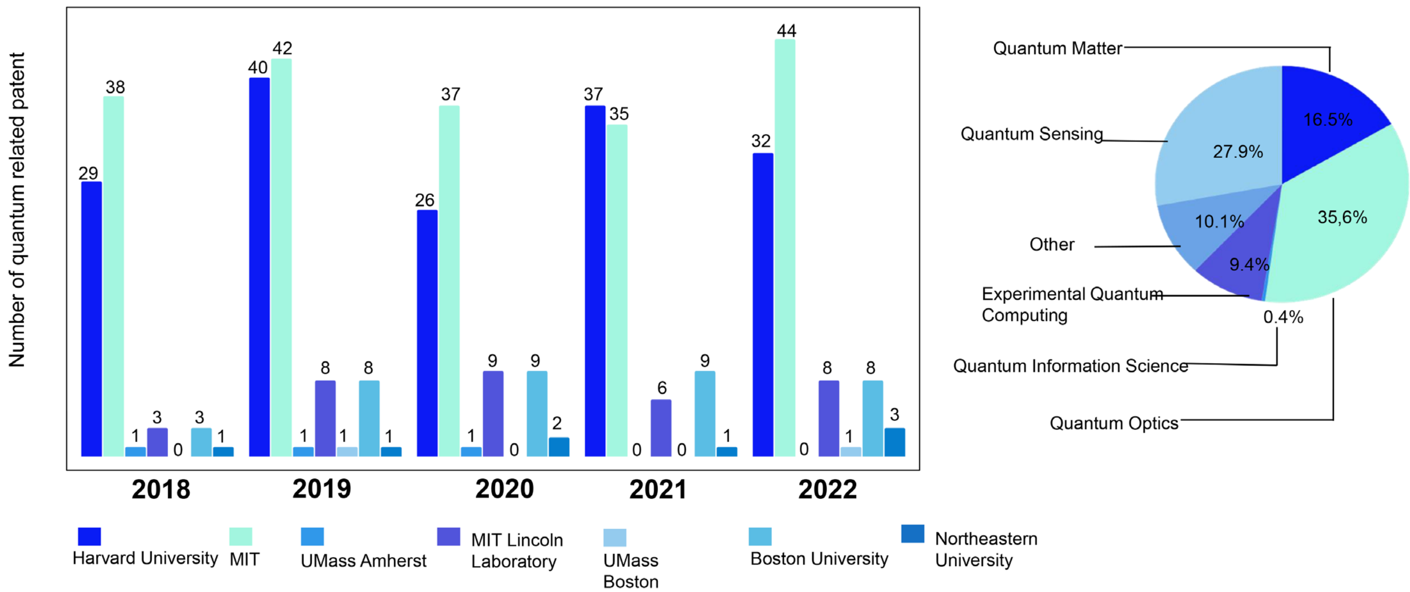


FIGURE 8 QUANTUM TECHNOLOGY PATENT OUTPUT BY UNIVERSITY 2018-22

d. Quantum Companies

Our research has identified 49 companies relevant to quantum computing in the Massachusetts ecosystem. This number includes small to medium enterprises as well as multi-national corporations. In the selection process a holistic-as-possible list was attempted and therefore companies that are already heavily involved in quantum activities as well as some that are not currently involved but have the potential to enter the industry have been included. This is based on trends observed in other quantum technology ecosystems.

To better understand this ecosystem, we investigated the pipeline involved in developing a quantum processor, starting from suppliers of niche hardware components all the way through to end users was investigated. There is a diverse range of enterprises that support or play a major role at all stages of this pipeline. This includes companies that are involved in:

1. **Stack compilation:** companies providing services or supplying equipment/material for the quantum hardware, the control and measurement equipment and the control software used to build and run the quantum processors.

2. **QPU providers:** companies who compile, maintain, and provide access to the full stack QPU.

3. **Software developers:** companies developing software solutions for QPU interfacing, measurement, and control, exploring near term (general) quantum algorithms, and quantum software for specific applications.

4. **End users:** subset of enterprises that is derived from both the "Companies" and "Centers and Government" groupings. The entities identified here are different from software developers as they are not involved in any aspect of the control or interfacing software, but rather purely with accessing quantum computers and exploring potential use cases of interest.

5. **Quantum networks:** Companies focused on providing solutions that link quantum computers together – either for the purpose of building larger quantum computers by combining the computational power of smaller quantum computers, or for the purpose of quantum communication applications such as in quantum information security.

6. **Quantum sensing:** generally, heavily reliant on quantum matter, photonics and optical research. Characterized by single devices typically optical detectors, extreme temperature thermometers, ultra-sensitive magnetometers, accelerometers, and gyroscopes. These are near term technologies and some of the earliest examples of quantum technology for real world real application.

7. **Quantum matter:** This category has been added due to the large proportion of research being conducted in quantum matter at the Universities. The companies involved with quantum matter typically act as suppliers of specialized equipment, typically advanced analysis, fabrication or processing systems. These are not directly related to quantum computing but do heavily support the peripheral sciences.

One very important point of this categorization of companies is that it highlights the potential areas where products, solutions and intellectual property can be generated. This can serve to guide our understanding of where opportunities for new collaborations and networks could be developed in the region.

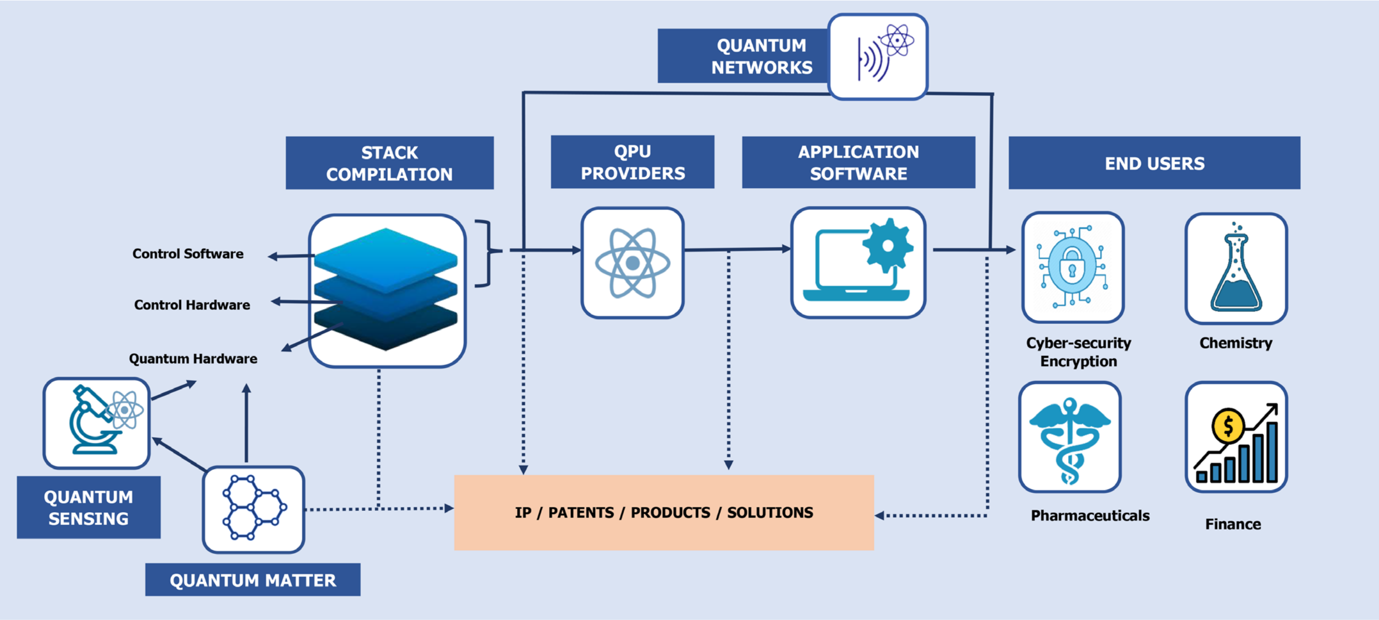


FIGURE 9 - QUANTUM ECOSYSTEM OVERVIEW AND TECHNOLOGY PIPELINE

Patent output for companies

As with the academic groups, a patent search for quantum technologies emerging from the companies profiled has been conducted. This source of information lends insight into the strengths and overall health of the eco-system. In this search the focus has been restricted to only the companies that are headquartered in Massachusetts or have significant operation that spin out or produce IP/patents.

This list included a total of 21 companies out of our total list of 49. Of the 21 companies profiled only 16 filled patents related to quantum technology within the last five years. Clear leaders in patent production were Raytheon (97), Photonic Systems (38) and Draper (35).

An interesting observation from the patent search is that a wide variety of technologies are being explored, however a significant proportion of the patents were related to quantum sensing and photonic technologies. This may be an indication where early opportunities for product commercialization lie in the region.

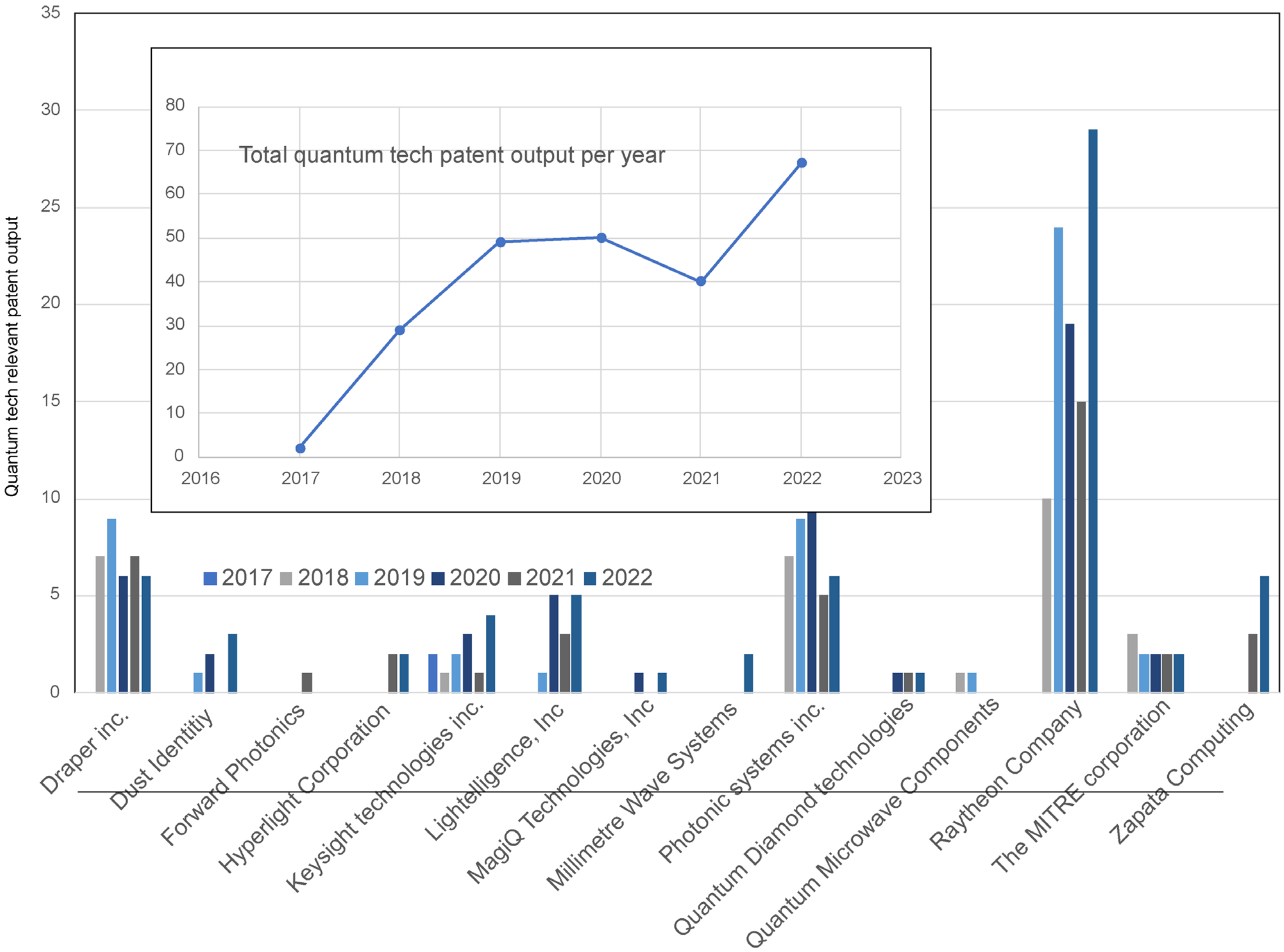


FIGURE 10 PATENTS RELATED TO QUANTUM TECHNOLOGY GENERATED BY COMPANIES IN THE MASSACHUSETTS REGION

*Patent search was restricted to only include patents directly or strongly associated to quantum technology. These are not a reflection of total patent from the respective companies but rather an indication of quantum related output.

SBIR funding

Another metric of note is the successfulness of these enterprises to draw funds such as Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. This is shown below:

Company	Number of awards	Grand Total funding(US$)
Aliro Technologies, Inc.	5	651,884
Dust Identity, Inc.	4	1,538,583
Forward Photonics LLC	18	11,658,755
Janis Research Co.	2	73,290
MAGIQ TECHNOLOGIES, INC.	35	11,734,392
Millimeter Wave Systems, LLC	4	2,065,659
Photonic Systems, Inc.	66	8,441,926
Quantum Diamond Technologies Inc	5	1,755,566
QuEra Computing Incorporated	2	299,981
Grand Total	**141**	**38,220,036**

FIGURE 11 SBIR FUNDING FOR MASSACHUSETTS ORGANIZATIONS FROM THE PERIOD OF 2002 TO 2022

The scope of this report did not include a review of DIU (Defense Innovation Unit) or AFWerx (Air Force Research Laboratory Innovation Arm) funding.

Notable points and trends

Massachusetts has multiple locally produced quantum computers

- There are at least two QPU (i.e., full stack) providers with operations in Massachusetts. Atlantic Quantum an MIT spin-off working on fault-tolerant superconducting processers and QuEra, a Harvard spin-off focused on neutral atoms.
- Furthermore, QuEra is one of only six cold atom providers in the world. Recently, another cold atom provider Pasqal launched a North American office in Boston, meaning that two of the world's six cold atom providers are based or have significant operation in Massachusetts. This may be an indication of potential opportunities for supporting services around cold atom technologies in the future. This is significant as cold atoms have potential use beyond quantum computing and play a significant role in atomic clocks, ultra-sensitive gyroscopes, accelerometry and gravity detectors.
- Atlantic Quantum is exploring the superconducting qubit modality. This is thanks to well established facilities and expertise specific to superconducting processing and device fabrication. This is significant as superconducting quantum processors are currently some of the most advanced, well researched and accessible of NISQ systems. Although there is no clear-cut winner across quantum processor modalities, superconducting systems are likely to remain highly relevant to the field for some time and having local suppliers and producers of such technologies in Massachusetts can help secure opportunities as the field continues to evolve.
- MITRE has initiated the Quantum Moonshot program which sees the inclusion of over 40 researchers and involves collaborations with Sandia National Labs and Princeton University. This initiative looks to develop a fully universal, scalable quantum computer and integrated quantum network. This is the second of only two large scale integrated photonic quantum processor programs in the United States and leverages local expertise in photonics/optics.

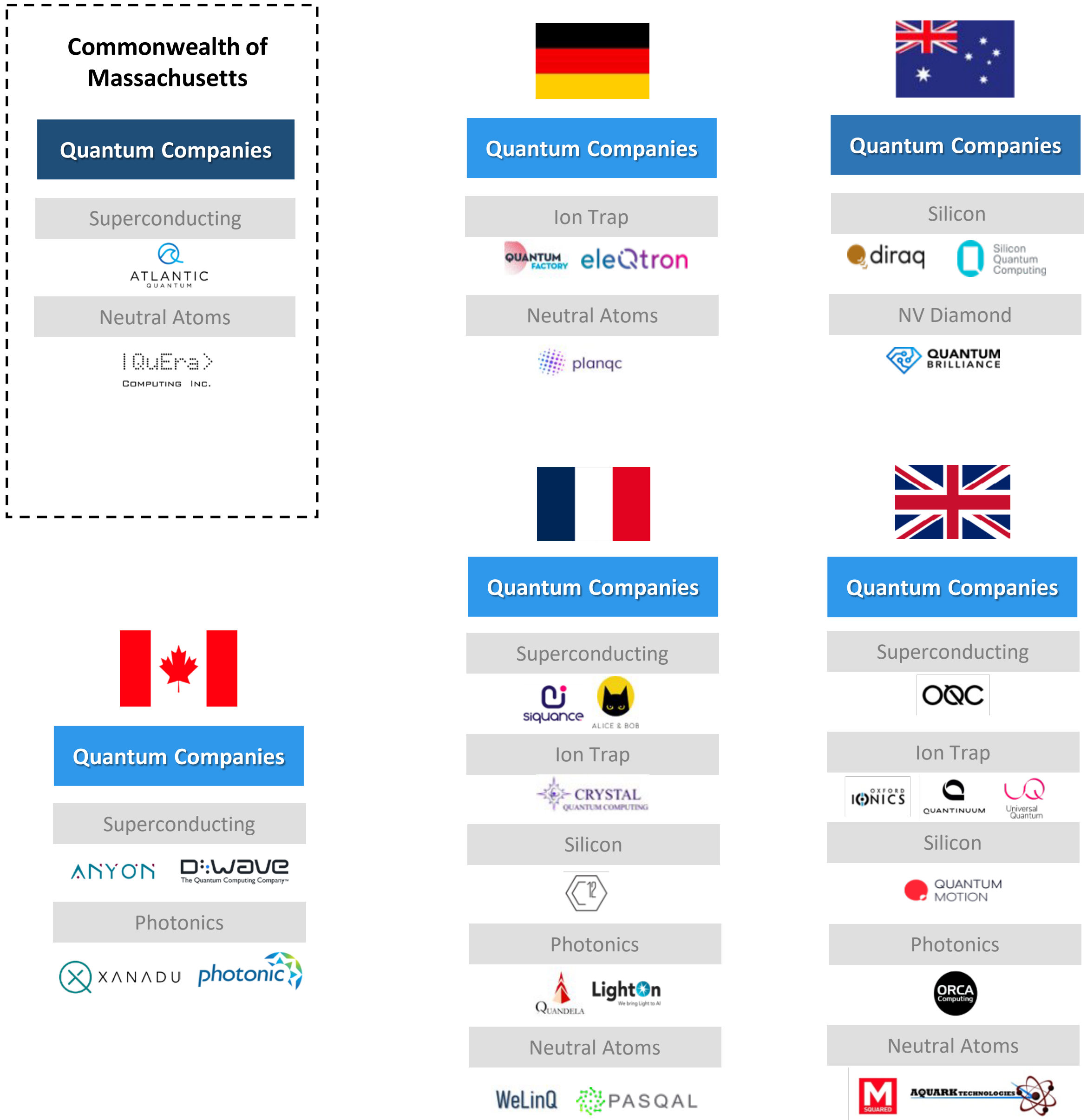


FIGURE 12 MARKET MAP COMPARING QPU PROVIDERS IN MASSACHUSETTS AND SOME COUNTRIES WITH COMMERCIAL QUANTUM COMPUTING OFFERINGS

- The fact that there are at least two full stack QPU providers and the MITRE moonshot initiative is significant as it highlights the diverse range of quantum computers being developed in the Commonwealth. As shown in figure above, the number of quantum computing providers is equivalent to that of some countries such as Germany, Australia and Canada, but does however lag behind countries such as France and the UK. Note that the list above only includes established QPU providers and not entire number of academic quantum computing programs.

- A further note on this is that Massachusetts now houses three different types of quantum processors, making it a highly diverse region. In general, it is expected that regions focus on a single or closely related group of technologies due to local expertise/infrastructure. This is not the case for Massachusetts where multiple very different technologies are being simultaneously advanced.

- The number of quantum computing providers and quantum computing activities in general can be correlated to private investment. It is noteworthy that Massachusetts has an ecosystem comparable to some countries, despite not having a coherent state quantum strategy.

Massachusetts has relevant infrastructure and networks:

- Regarding companies involved in supplying hardware components, some of these companies are manufacturing and developing products or technologies locally, others are suppliers of unique / niche instruments manufactured abroad / other states in US. The distinction is important as local producers may be more open to academic collaboration and potential technology development projects.

- There are several organizations involved in prototyping and manufacturing that make use of local infrastructure. This is particularly true for enterprises involved in photonic and microwave technologies and includes notable examples such as Raytheon, Quantum Microwave, Draper, Analog Devices and MITRE.

- There is a strong indication that Massachusetts is a preferred point of entry to the North American markets. It was seen that a significant number of international companies with vested interest in quantum computing tend to have their North American distribution / operations based in Massachusetts. This is significant as such multinational companies may serve as future vectors for distributing locally developed products or fund / acquire local initiatives. From the list of companies surveyed a total of 15 multinational companies with significant operations in Massachusetts have been identified.

Massachusetts has a vibrant photonic eco-system which supports quantum activities:

- There is a strong supply chain with local distributors of optical and photonic components used in producing quantum technologies as well as prototype facilities for photonic circuits. From the list of companies, there has been a total of 28 companies identified as suppliers/producers or heavily reliant on photonic technologies. The interest in photonics is driven by an impressively large number of research groups involved in photonic research, with activities that range in technology readiness levels. i.e., from deep tech to commercially available products. From the list of academic research groups profiled, a total of 40 are directly involved in quantum optics and photonics with an additional 11 focused on quantum sensing. A notable example of a large photonics initiative is the Boston University Photonic Center which is home to 26 faculty laboratories and four shared facilities including the Optoelectronic Processing Facility, the Precision Measurement Laboratory, the Focused Ion Beam/Transmission Electron Microscopy (FIB/TEM) Facility, and the MSE Core Facilities. Surprisingly, despite this, Boston University and the Photonic Center lack a formal quantum initiative.

- There is also a notable presence of specialized companies that focus on telecoms and use or develop CMOS (Complementary Metal Oxide Semiconductor) integrated photonic technologies. Although these are not traditionally quantum, the application of such devices for interfacing qubits has started to draw significant attention over the past three years and is likely to be involved in near term quantum computers. This means there may be significant opportunities in the near term for photonic products/solutions being developed in Massachusetts. A notable example of a local enterprise following this direction is MITRE.

- The focus area of photonics has already been recognised as a regional strength and has attracted significant attention and funding. A good example of this is the Massachusetts Manufacturing Innovation Initiative (M2I2) which saw over $20M invested on business expansion and educational projects to secure the Commonwealth's advanced manufacturing leadership in photonics. This has allowed for connecting manufacturers with universities, other companies, and R&D Centers, Federally Funded R&D Centers (FFRDCs), and the Manufacturing USA communities. The initiative helped develop multi-million-dollar education and prototyping centers in advanced photonics, fabrics, robotics, and flexible electronics.

The Massachusetts eco-system is rapidly growing:

- The emergence of several corporate entities actively supporting the quantum computing ecosystem, particularly through a specialist division for consulting, technology transfer, patenting, and assisting fund transfer is worth noting. This is an interesting point as technology transfer in this domain is generally restricted to universities due to the novelty and emergent nature of quantum computing/technology. This serves as an indication of the significance of quantum tech in the region and that the Massachusetts eco-system is maturing to a point of commercial relevance attracting interest beyond research environments and immediate supporting industries.

- Massachusetts is also the home of several current and potential end users of quantum computing. This list is comprised of comprises companies involved in cyber security, biotech and chemistry. Some of these are local companies, however there is a significant proportion of international corporations. Larger companies with significant resources at their disposal tend to establish centers and research facilities where their interests in quantum computing is explored.

- A strong indication that the quantum ecosystem is growing is the large number of job listings for individuals with a background in quantum computing, post quantum cryptography and quantum simulation. This can be seen from readily accessible job listing websites such as Indeed.com, Glassdoor and LinkedIn. The number of "Quantum" job listings over the months August to December 2022 averaged at 50 (Indeed.com), 45 (Glassdoor) and 100 (LinkedIn). Through the interview correspondence it was established that start-ups and larger companies can in general easily hire physicists and engineers with relevant education and background thanks to the large number of universities in the region, however, struggle to hire software developers. This is apparently due to software developers finding higher salaries and better offers in other industries.

The table below gives an overview of the companies that have been profiled and shows the general categorization scheme based on relevance to hardware or where/how they fit into the QPU development pipeline.

Technology detail	Producers or main drivers	Supporting Companies involved or potential to get involved	Comments
Superconducting Quantum computer	Atlantic Quantum (full stack providers)	Keysight, Janis, Quantum Microwave, Raytheon BBN, Abbess Instruments, Zurich Instruments, Superconducting systems inc., Novum Industria, mm wave	Suppliers available for all levels of superconducting QPU stack, also supporting services for superconducting materials processing, novel cryogenic magnets and cooling systems.
Trapped ion and neutral/cold atom quantum computer	QuEra, PasQal (full stack providers)	Boston electronics, Draper, Energetiq, Hyperlight, Forward photonics, NKT photonics, Photonis, TelAztec LLC, Thor Labs Scientific	Bulk of this list is composed of optical hardware suppliers. Essentially lasers, single photon detectors, and sensors that are essential for developing the QPU
Integrated Photonics	Raytheon BBN, MITRE	Analog Photonic, Effect photonics, IPG photonics, lightelligence, Photonic systems inc., Spark photonics, Physical sciences Corp.	Diverse range of suppliers, prototyping facilities, fibre technologies and material processing infrastructure and testing facilities relevant to quantum photonic technologies.
Quantum communication, quantum networks and quantum key distribution	Aliro Quantum, Quantum diamond technologies, AWS, Dust Identity,	MagiQ, QNuLabs, Qabacus	Diverse list that includes companies pursuing novel technologies (hardware and software) for Quantum communication and networking

Technology detail	Producers or main drivers	Supporting Companies involved or potential to get involved	Comments
Quantum matter	Atlantic Quantum (full stack providers)	Thermo Fisher, Zeiss, Jeol	Low technology readiness level, highly relevant to quantum sensing. Companies supporting these activities are typically focused on advanced materials testing and engineering/ manufacturing.
Application software	Zapata Computing, AWS, Boston Quantum, MagiQ, QSimulate, Cryptosense, Kebotix, Riverlane		Software solutions can be application or industry specific or general quantum computing usage eg. benchmarking and interfacing.
Ecosystem support	BCG, Foley Hoag LLP		Involved in patenting and technology transfer and quantum industry consulting services

FIGURE 13 MASSACHUSETTS COMPANY CATEGORIZATION

*Note that quantum sensing has been absorbed into the other respective streams due to overlap in company dominant quantum activity.

Case studies

Below is a tabulated list of five case studies that looks to bring deeper insight into locally based companies that have successfully broken into quantum technology. These companies have been selected as case studies due to their relevance to the global quantum technology landscape, the fact that they are capitalizing on opportunities within the ecosystem, and because they play a significant role in the eco-system/micro-networks. This list tries to identify key factors that may have led to these companies' perceived significance.

ZAPATA

Technology detail	Producers or main drivers	Comments
Total Disclosed Funding US$67.4m City: Boston Zapata develops quantum software and algorithms for business.	Zapata develops quantum software and algorithms for business. Its core proposition is Orquestra which they describe as the first unified quantum operating environment. This allows users to compose quantum-enabled workflows and execute them across classical and quantum technologies. The business also looks to actively help customers use quantum computers for real world problems.6 In October 2022 the business launched a cyber security offering. Developed by Zapata in 2018 and patented in 2022, Variational Quantum Factoring (VQF), is a hybrid quantum-classical heuristic algorithm that could realistically compromise some instances of RSA encryption in the next five years using NISQ devices. VQF can be a helpful tool in assessing vulnerabilities to near-term quantum threats, so its customers can become quantum resilient.[7]	Zapata is a local quantum computing start-up that spun out of Harvard University. The company has grown significantly and now also has offices in Toronto, Tokyo and London. The company interacts with several universities in Massachusetts as well as several international universities. Zapata has proven capability in securing funding from VC (both within and outside Massachusetts), the private sector and also in the form of joint funding through research projects with academic partners. They have also recently initiated collaboration or partnerships with hardware providers in the hopes of developing application specific algorithms. Although initially involved in variational algorithms for chemistry, they have branched out into quantum machine learning. Zapata has a diverse network, a range of activities in NISQ and more far-term prospects, is already a prominent player in this space and likely to be involved in any formal quantum computing initiatives in the region.

|QuEra⟩ COMPUTING INC.

Technology detail	Producers or main drivers	Comments
Total Disclosed Funding (US$) $17.0m City: Boston QuEra Computing uses ground-breaking research on neutral atoms, developed at Harvard University and the Massachusetts Institute of Technology, as the basis for a world-leading scalable, programmable quantum computer solution.	The company's hardware uses arrays of neutral atoms where hundreds of atoms are cooled and then arranged by laser fields in a small vacuum chamber. While the chamber is at room temperature, pulsed laser techniques cool the atoms down to ultra-low temperatures (sub-milli kelvin). QuEra's system can arrange hundreds of neutral atoms into sub-millimeter arrays. QuEra connects its neutral-atom qubits by "Rydberg blockade." 8 Amazon Braket, the quantum computing service from AWS, launched Aquila, the neutral-atom QPU from QuEra Computing with up to 256 qubits. It is designed for solving optimization problems and simulating quantum phenomena in nature, enabling researchers to explore a new analog paradigm of quantum computing.[9]	Being involved in developing quantum computing hardware, QuEra has a strong interaction with local suppliers and supporting services. QuEra has strong links to well reputed academic groups and formal collaborations with industry, notably in the photonics space. As a full stack developer/provider QuEra must source expertise in experimental physics, engineering as well as software development, meaning they are an ideal node for multi-disciplinary collaboration/partnerships. It is expected that their activities will drive cold atom computing technologies and research in the region.

KEYSIGHT TECHNOLOGIES

Technology detail	Producers or main drivers	Comments
Keysight Technologies is publicly traded (NYSE) City: Santa Rosa, CA but with significant operations in Cambridge Kendall Square innovation district (MA) Recently established a quantum software center in MA for researching control interfacing and quantum benchmarking.	Keysight's Quantum Control System (QCS) combines dedicated quantum control hardware and full-stack software capabilities to provide an easy-to-use solution for the control and readout of quantum devices. The following items highlight QCS features.10 Full DDC and acquisition of microwave, base-band, and digital signals used to control and read out qubits. Simple-to-use API and GUI interfaces give quick access to textbook quantum experi-ments and custom pulse sequences. Tight integration between hardware and software to provide complete control and readout solution.	Keysight is a large, multinational company and have offices all over the world. Although the Massachusetts operation is limited to around 50 people, the activities are significant as it involves dedicated to quantum tech. This is in the form of a center for quantum software. Although collaboration with academia is limited, they do play a vital role in providing components necessary for different qubit modalities. Besides hardware distribution, the local operations are actively involved in providing solutions for quantum tech benchmarking and will be closely following any advancements made in local quantum technologies. Keysight has previously acquired companies that make progress in areas of interest, par-ticularly quantum computing.

QUANTUM MICROWAVE

Technology detail	Producers or main drivers	Comments
Self-funded City: Hingham Quantum Microwave develops and manufac-tures cryogenic microwave components for quantum computers.	Quantum Microwave develops and manufac-tures cryogenic microwave components for quantum computers. Their products include cryogenic bias tees, cryo diplexers, cryo filters, cryo attenuators, cryo terminations, cryo image reject mixers, and cryo directional couplers.[11]	Quantum Microwave is a prime example of a local company that emerged to primarily serve the quantum computer industry. The company is interested in innovation, actively looking for collaboration with academia and has strong interaction with a range of large industry players.

FIGURE 14 COMPANY CASE STUDIES

e. National Labs and other centers

In addition to the diverse research and industrial activities, there are several formally organized centers that look at bridging the gap between industry and academia. From the initial overview, it was found that the most natural way to categorize these centers is by leadership strategy and overall research direction. There are three categories: university-led initiatives, industry-led initiatives and national facilities/government labs. The following highlights some initial observations regarding such centers.

Industry led initiatives

Industry funded centers tend to have very specific directives or research topics. These are typically directly related to respective funding companies' interests and typically focused on the application of Quantum computing.

Notable examples of this category include:

- **AWS center for quantum networking:** This newly created center will look directly into advancing Amazons opportunities in quantum internet and communications. This center forms the third leg of Amazons nationwide quantum research investment.[12]

- **BASF research center:** Although still at an early stage, chemistry simulation is one of the most significant applications being explored for near term quantum computers. BASF have invested in a research center called NORA (Northeast Research Alliance), which is specifically focused on chemistry simulations, classical techniques as well as emergent quantum simulations. Venture Capital has also been invested in Massachusetts based Zapata who specialize in quantum algorithm development. The BASF research center operates across Harvard University, MIT and University Massachusetts Amherst

- **Fidelity Center for Applied Technology (FCAT):** Fidelity investments[13] has a dedicated technology innovation center based in Boston. This center focuses on novel computational technologies that may disrupt financial sector. Although Fidelity has only recently initiated Quantum computing research, they have already published several white papers related to NISQ computing (in finance) and have a formal collaboration with Maryland based Ion trap QPU providers IonQ.

University-led initiatives

University-led centers enjoy more freedom in their research pursuits. As a result, these centers direct more attention towards fundamental research and less towards lower technology ready applications. There is a notable emphasis on quantum matter and material science. The ethos of such centers is to explore the frontiers of science in hopes of achieving breakthroughs which cannot be easily anticipated. This also means that such research does not always have immediate application and may be difficult to connect to existing technology platforms even in quantum technology space. Massachusetts has seen some success in quantum technologies emerging from basic science and moving to commercialisation, however this does take considerable time and serious investment.

An interesting example is the Photonics Center at Boston University, which has a large faculty and boasts diverse research activities closely related to quantum computing. Despite this, there is no formal quantum computing track at this center.
The bulk of quantum related centers are located at MIT and Harvard.

The university led facilities have more diverse funding sources (or are more open to disclosing this information). Sources of funding include direct funding from respective universities, philanthropy, industry and government.
The table below gives a breakdown of the relevant university led centers with notable activities in quantum tech.

Center	Focus	Location	Description
MIT Research Laboratory of Electronics	Interdisciplinary research in many areas	MIT	The Research Laboratory of Electronics (RLE) is committed to creating a stimulating and supportive environment for innovative research. As MIT's leading entrepreneurial interdisciplinary research organization, RLE provides leadership, administrative services and strategically deploys resources to achieve directives. MIT RLE currently pursues seven major research themes. • Atomic Physics • Information Science and Systems • Quantum Computation and Communication • Energy, Power and Electromagnetics • Photonic Materials, Devices and Systems • Nanoscale Materials, Devices and Systems • Biomedical Science and Engineering MIT RLE has 40 research groups.
Center for Ultracold Atoms	Cold-atom quantum simulators	MIT and Harvard	CUA research exploits the growing power of controlling bosonic and fermionic fluids of ultracold atoms and photons. These techniques are applied to problems of central interest in condensed matter physics, and quantum information science. The research program is organized about three major themes: • Quantum Gases of atoms and molecules • Atoms and photons • Atom-like and Hybrid systems An NSF Physics Frontier Center. There are 15 PIs with groups in the CUA.

Center	Focus	Location	Description
Harvard-Max Planck Quantum Optics Center	Various branches of quantum science and technology	Harvard (and Max Planck Institute of Quantum Optics in Garching, Germany	The Center is a bilateral collaboration between Harvard University Department of Physics and the Max Planck Institute of Quantum Optics in Germany. Research areas: • Quantum Simulation • Quantum Dynamics • Quantum Information Science • Quantum Networks • Quantum Phases of Matter • Quantum Sensing and Metrology • Ultracold Quantum Chemistry ~10 senior academics based in Harvard are involved in this collaboration.
Center for Nanoscale systems	Fabrication, imaging, and characterization of nanoscale structures.	Harvard	Center for Nanoscale Systems (CNS) is a shared-use core facility at Harvard University. Their scientific focus is the study, design and fabrication of nanoscale structures and their integration into large and complex interacting systems. Areas of current exploration at CNS: Photonics and Optical Computing, Biomimetics, Low-Temperature Physics, Graphene and other 2-D Materials, Diamond-based nano-scale sensors and computing elements, Photo-voltaics, Fuel-Cells, Energy Storage, and many more. Read more about the experimental facilities here.
Boston University Photonics Center	Photonics	Boston University	The Boston University Photonics Center generates fundamental knowledge and develops innovative technology in the field of photonics. Research areas: • Biophotonics • Lasers, Nonlinear Optics, and Quantum Photonics • Nanophotonics • Neurophotonics • Photonic Materials and Devices Read more about the experimental facilities here.

Center	Focus	Location	Description
Harvard Quantum Initiative	Various branches of quantum science and technology	Harvard	The Harvard Quantum Initiative in Science and Engineering (HQI) is a community of researchers with an intense interest in advancing the science and engineering of quantum systems and their applications. 45 senior academics are members of HQI.
MIT Center for Quantum Engineering	Various branches of quantum science and technology	MIT	The MIT-CQE is dedicated to the academic pursuit and practice of quantum science and engineering to accelerate the practical application of quantum technologies for the betterment of humankind. 68 senior academics are members of MIT-CQE.
Center for Integrated quantum materials	Quantum Materials for signal processing and computation	Harvard	The Center for Integrated Quantum Materials (CIQM) is an NSF Science and Technology Center studying new quantum materials with 'non-conventional' properties that may be valuable in signal processing and computation. CIQM includes about 40 senior academics, most based in Massachusetts, and many with research groups of their own.
Experimental Quantum Advancement Laboratories (EQUAL)	Innovation focused on applied quantum sensing and quantum materials	Northeastern University	This laboratory will focus on researching quantum sensors and related technologies and they will seek partnerships with other researchers in industry, government, and academia. The project will also help provide workforce training and will help Northeastern's efforts to offer new Ph.D. and Master's degree programs in Quantum Information Science and Engineering

FIGURE 15 UNIVERSITY LED CENTERS WITH NOTABLE ACTIVITIES

National initiatives and laboratories

This category of centers has been separated from the others because they are directly relevant to national directives and thus enjoy access to significant resources including funding, infrastructure and wide networks.

Several examples of such centers focused on quantum computing are:

- **The Co-Design Center for Quantum Advantage (C2QA).** Although this initiative is headquartered at Brookhaven National Labs in Upton, New York, the center has satellite or virtual nodes across the country. This is probably one of the country's largest and most direct initiatives for the promotion of quantum computing related research. There is a significant presence of Massachusetts based researchers involved in the C2QA at various levels, including in steering the quantum programs. The focus areas being pursued at the C2QA include three research thrusts: Software and Algorithms, Devices, and Materials.

- **MIT Lincoln Laboratory.** This is a national facility with a diverse range of research directions. Mostly focused on technological advancement in areas such as telecommunications, cyber-security, space systems and space technology, and a large division for quantum technologies. MIT Lincoln labs have an impressive infrastructure with specialties in micro/nano fabrication. Their quantum activities have been collated under the umbrella of Quantum information and Integrated Nano-systems14 and features advanced research (at high technology readiness levels) in niche areas such as development of superconducting quantum processors, trapped ion processors, diamond-based magnetometers, integrated photonics and superconducting single flux quantum technology (SFQ). Lincoln Labs also houses a significant number of researchers involved in radio frequency research, which can directly feed into the development of superconducting and semiconducting quantum processors.

- **Draper inc.** is a research and development organization that specializes in the development of advanced technologies for a range of industries, including defense, space, and biomedical. In recent years, Draper has become increasingly involved in the field of quantum technology, with a focus on developing practical applications for quantum sensing, communication, and computing. Some of Draper's activities in quantum technology development include the development of quantum-enhanced navigation systems for submarines and other underwater vehicles, the creation of quantum key distribution systems for secure communication, and the development of quantum computing hardware and software. Draper also works with academic and industry partners to advance the state of quantum technology through research and collaboration.

- **MITRE Corporation** is a not-for-profit organization that operates research and development centers for the United States government, with a focus on defense, healthcare, and aviation. Recently, MITRE has expanded its research into the field of quantum technology, working to advance the state of quantum computing, sensing, and communication. Some of MITRE's activities in quantum technology development include the creation of quantum-resistant encryption methods to protect against cyber-attacks, the development of quantum-inspired algorithms to improve machine learning and artificial intelligence, and the exploration of new applications for quantum sensors in fields like biomedical imaging and national security. MITRE also collaborates with government agencies, academic institutions, and industry partners to advance the state of quantum technology and promote its adoption.

3. Market analysis

This section of the report provides an analysis of the Strengths, Weaknesses, Opportunities and Threats (SWOT) associated with the quantum computing economic development opportunities in Massachusetts. This is based on the review of the quantum ecosystem, a survey and focused interviews with relevant stakeholders.

Building on insights collected in the extensive ecosystem mapping in section 1, a list of individuals of interest in the Massachusetts quantum computing ecosystem was identified and interviewed 18. This list of interviewees included research group leaders, start-up CEOs, quantum application specialists and individuals involved in promoting quantum computing in the state. In addition, a survey was prepared and sent only to C-suite executives, department heads and senior academics in the industry. This survey involved 20 questions and was filled out in detail by 29 respondents. The figure below shows an overview assessment of the response to the interviews and survey.

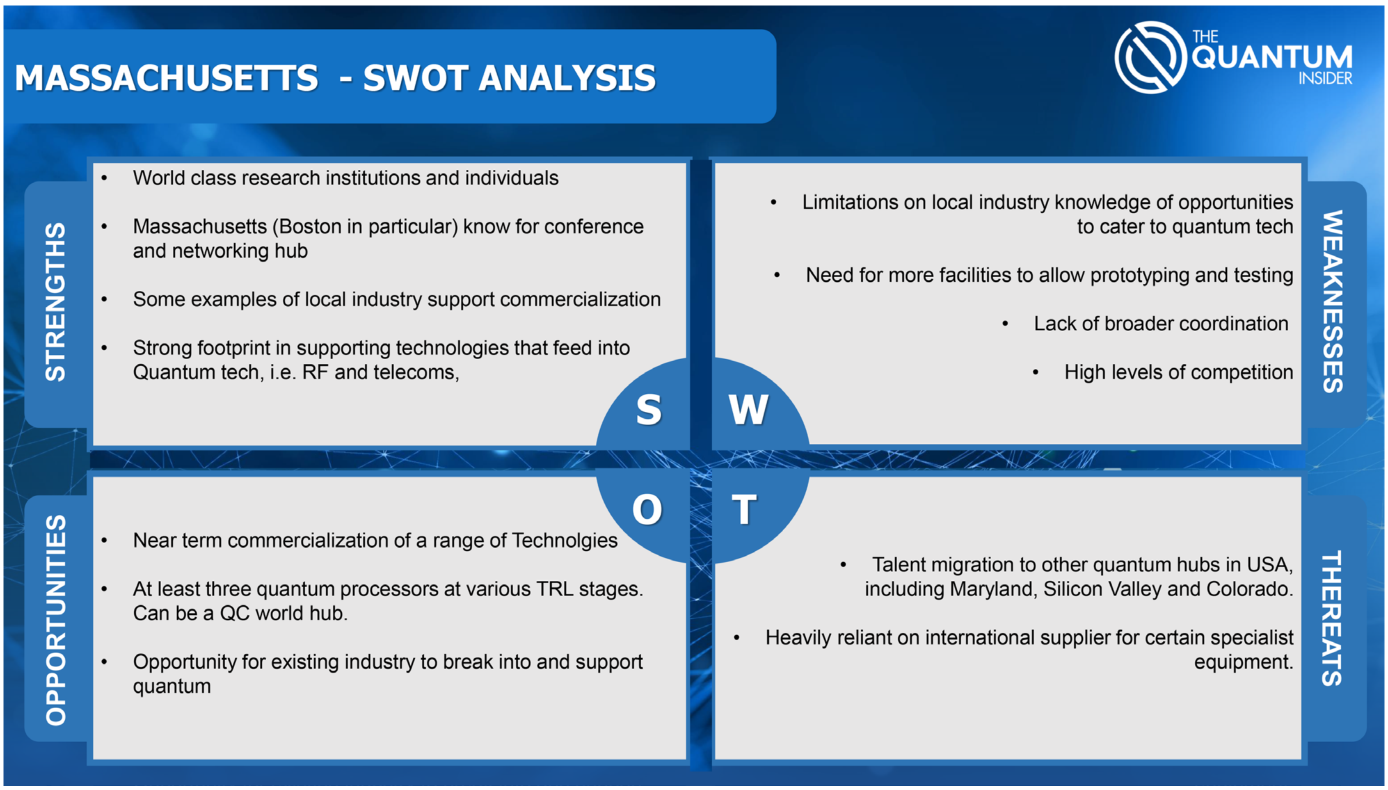


FIGURE 16 SUMMARY SWOT ANALYSIS

a. Strengths

- Massachusetts is a node for international conferences and hosts some of the most impactful conferences (e.g. Quantum. Tech Boston) on a yearly basis. This makes an ideal location for networking as it already brings a multitude of prominent researchers in quantum tech to the state.
- Industry has capitalized on the networking hub of Massachusetts and several corporations have demo labs and sales operations based in the region. There is a strong presence of international quantum tech players in the state.

- Massachusetts has a rich and vibrant academic community underpinned by some of the world's leading research universities and experts in the quantum computing community.

- The research environment is further emphasised by the presence of some of the most prominent and pioneering figures in quantum computing and quantum tech.

- There is a high level of diversity within quantum technology research which includes all contemporary streams of quantum research; quantum matter, quantum sensors, quantum networking/communication and quantum computation.

- Survey respondents pointed to a strong supplier network. This includes both local providers as well as international corporations that provide specialized equipment.

- Massachusetts is home to several research centers and laboratories that contains infrastructure relevant to the various quantum tech streams. This means that the research is largely self-contained and not materially reliant on facilities outside of the State.

- Massachusetts has some good university-backed deep-tech investors.

FIGURE 17 SELECT SURVEY RESPONSES

b. Opportunities

- Opportunity to catalyze formation of private companies as academic spinouts is still largely untapped. This appears to be the most important near-term opportunity.

- Other near-term opportunities may be in the field of quantum sensing, this falls in a unique position between quantum matter and device fabrication, having a lower infrastructure footprint than full stack quantum computing and caters to a range of applications including, space and bio, making them potentially easier to market.

- Strong footprint in Radio Frequency and microwave technologies, as well as telecoms. There are significant opportunities for these industries to cater to emergent quantum technologies which are reliant on such systems. Good examples of this include the integrated photonics, CMOS and silicon photonics, which are largely used in classical system but increasingly finding applications within quantum tech.

- There is already indication of some blue-sky R&D, collaboration between research and local industry for optical quantum control, addressing scalability of optical quantum systems and improved microwave components for cryogenic systems. These activities can therefore be strengthened through targeted or coordinated efforts.

- There is a global trend for algorithm and software developers within quantum computing to collaborate with hardware producers. From the correspondence it was seen that this trend is also emerging in Massachusetts and more of this inter-industry collaboration is expected to occur. This is likely to lead to many new opportunities in applied quantum computing.

- Longer term Quantum Matter is particularly well positioned; however, spin-off and commercialization from this research is limited as this usually falls under a low technology readiness level.

- Appendix section "further opportunities" provides some further specific areas for exploration.

c. Weaknesses

- Despite having a strong academic environment with good international networks, the community seems to be fragmented. The high level of diversity within the Commonwealth means that there are many research directions and being pursued. This means that respective groups within quantum tech may not be aware of collaboration opportunities within the broader community of Massachusetts.

- The high level of diversity and sheer number of independent research groups can mean that obtaining external funding is highly competitive. Lack of coordination and fragmented community means that respective research groups are frequently seen as competitors rather than partners, this can be counterproductive to growing the community within the respective fields.

- There is a lack of coordination in the form initiatives that look to accelerate or foster better interaction. Although there is a strong potential for networking, this is largely done directly through individual players with no targeted platform for bringing together players in the broader quantum tech eco-system. This includes bringing together researchers but also connecting academia and industry. At least 50% of the interviewees expressed the need for initiatives to bring researchers and industry together. This includes platforms such as conferences, meetings and workshops.

- There is a lack of education within the local industry on the opportunities within quantum tech and how to ensure they are better equipped to serve the community. Much of the equipment used in developing quantum tech is supplied from international vendors with local supplier often being overlooked.

- There is also a notable proportion of correspondents interested in further developing infrastructure for prototyping. As there are so many different levels to target the commercialization aspect (from materials, fabrication, prototyping and manufacturing across a diverse range of systems) it is unlikely one single existing facility can cater to the broader community. A coordinated push to further develop over-arching infrastructure to address the commercialization pipeline may be required. This can be in the form of National lab/facility as expressed by some correspondents.

- Quantum computing companies that are involved with full stack production struggle to source and hire software developers.

FIGURE 18 SELECT SURVEY RESPONSES

d. Threats

- Talent migration to other quantum technology hubs such as NIST Colorado, California and Maryland.

- There are several unique materials, specifically related to photonics and lasers that are directly sourced from China and parts of Asia. More specifically:

  - In photonics circuits materials such as Lithium Niobate are imported from China
  - Quantum networks require diamond photonics containing color center qubits. There is no reliable industrial source for the growth of diamond containing color centers in the U.S. Diamond substrates for diamond growth are sourced from Russia or the UK.
  - Carbon based quantum matter technologies require hexagonal boron nitride (usually sourced from Japan) and high purity graphite imported from Europe.
  - The isotope He3, used in cryogenic systems.

- Despite the presence of a strong industry and specialized technology producers, the community are still highly reliant on international hardware and equipment developers and are therefore vulnerable to the socio- and geo-political climate. This is particularly true for:

  - Dilution refrigeration and milli-Kelvin cooling technologies which are imported form the UK or Finland. This is despite a few US based alternatives being available.
  - There is also an indication that advanced laser technologies such as Femto-second lasers (Titanium-Sapphire) obtained from various parts of Europe.
  - High precession single photon detectors and emitters are being imported from Switzerland.

FIGURE 19 SELECT SURVEY RESPONSES

4. Conclusion and Opportunities to grow the Ecosystem

This report has provided an assessment of the Massachusetts quantum ecosystem. This is the first work of its kind done in the region and we hope and anticipate that it will spur further research in the area.
This report defines several areas for further exploration and potential actions, all of which may be verified through workshops with relevant interest groups in the Massachusetts region:

- There is a definite need for a coordinated wide-scale effort to consolidate and connect various quantum technology stakeholders in Massachusetts. This should include academia but also the national laboratories and private industry. There appears to be few platforms that allow for communication and interaction between these three spheres despite their respective individual strength and presence in Massachusetts.

- This effort may also look at mapping out infrastructure gaps that could further promote product development and commercialization. Although the state has several impressive and well-funded centers, institutes, and labs, these typically work in isolation. Initiating a broader focused initiative and connecting these centers through a collaborative program could be beneficial in identifying these gaps to commercialization.

- Massachusetts has a lot to offer in terms of technology development. There are indications of near-term opportunities such as in quantum sensing and quantum matter, but also ambitious projects engaged in far-term prospects such as developing fault tolerant quantum computers. A more rigorous research project into the specifics of these opportunities may help pinpoint which are best positioned to drive economic growth. At a high level at least two main flavours of technology have been identified that are expected to be of particular significance to the global quantum computing industry: low temperature microwave technology (superconducting qubits and single flux quantum devices), and secondly optical systems such as integrated photonics (photonic memories/qubits and networks) and cold atoms. These initiatives should be monitored as points of national importance.

- The opportunities for accelerating start-up initiatives should also be noted. This is particularly true in the field of applied quantum computing by bringing together stake holders in bio-tech, energy, quantum computing and algorithm development. Interdisciplinary initiatives such as these have emerged in other quantum hubs and tend to allow for novel start-up activities.

- The coordinated attempt at bringing together relevant players in the quantum tech space should look at addressing equitable access to infrastructure. As there are several well established and resourced facilities already in Massachusetts, it may be possible to initiate a "Quantum Alliance" that looks to open up further the potential for inter disciplinary research collaboration and access to facilities.

Appendix: Scope

The Massachusetts Quantum Computing study will:

- Provide a baseline survey and assessment of Massachusetts innovation capacity in Quantum Computing based on an agreed upon set of economic development factors.
- Provide an inventory of critical Quantum Computing assets in the state, including but not limited to private industry, R&D, college and university programs and workforce pipelines, supporting STEM and education/community programs, and public/private partnerships.
- Provide predictive market and economic development research to inform further investment and economic growth.
- Prioritize key focus areas for the Commonwealth moving forward that leverage the assets and potential of Quantum Computing and related technologies.

#	Workstream
1	Develop a comprehensive assessment of the Quantum Computing landscape in Massachusetts and evaluate against the competitive positioning and initiatives underway in other regions across the United State and globally.
2	Conduct independent research on the strengths, weaknesses, opportunities and threats associated with the Quantum Computing economic development opportunities in Massachusetts.
3	Create an inventory and comprehensive reference of all Quantum Computing assets and participants in the Massachusetts Quantum Computing ecosystem.
4	Produce a well-researched and extensive report on the status of Quantum Computing in Massachusetts that informs, documents, and assesses the Quantum Computing opportunity in Massachusetts; supplemented with a portfolio of supporting communications that provides information and various perspectives on the Massachusetts Quantum Computing assets - i.e.. presentations; executive summary; infographics, etc.

Appendix – further opportunities

This section builds on the Opportunities section of the SWOT analysis to provide more technical details on opportunity areas in the Massachusetts region

As mentioned previously, there is a rich and diverse range of quantum technologies being pursued in Massachusetts. Moreover, these technologies span some of the earliest examples of usable quantum tech, through to more advanced and far off technologies. The following sections aims to provide a high-level overview of some of these technologies and also a brief list of inventors generating patents in these areas. This section looks to give an idea of opportunities for technology development. Superconducting technologies

Probably the most well-known and widely used quantum processors are based on superconducting qubits. These are already widespread and drivers of early adoption and NISQ application. As this is still an emerging technology, there are some barriers to Fault tolerance and issues around scalability that are currently at the forefront of research into this field. Relevant areas of innovation include increasing qubit quality and number (state of the art systems are around few hundreds and by 2025 expected to be 1000).

Superconductivity, being a low temperature phenomenon requires cryogenic cooling equipment. The control and readout of devices based on superconductivity (such as qubits and single flux quantum logic processors) requires high frequency electronics. This is a strength of MA where a significant presence in companies focused on high frequency technologies and RF solutions can be found. Some of the trends for innovation in NISQ era superconducting systems include the following topics:

Technology domain	Invention	Inventor
Cryogenic component connectivity	Photonic bus for coherent interfaces between a superconducting quantum processor, spin memory, and photonic quantum networks.	Prineha Narang, Dirk Englund
	Qubit and coupler circuit structures and coupling techniques	Oliver; William
Improved qubits	High coherence, small footprint superconducting qubit made by stacking up atomically thin crystals	Oliver; William
Measurement and control	System and method for controlling superconducting qubits	Chen Wang
Superconducting circuits for classical logic processors or interfacing Improved qubits Improved qubits	Superconducting nanowire-based programmable processor	Karl K. Berggren
	Interconnect structures for assembly of semiconductor structures including superconducting integrated circuits	Oliver; William
	Superconducting integrated circuit	Jonilyn L. Yoder, Oliver; William
Superconducting components	Squid-based traveling wave parametric amplifier	Matthew Bell

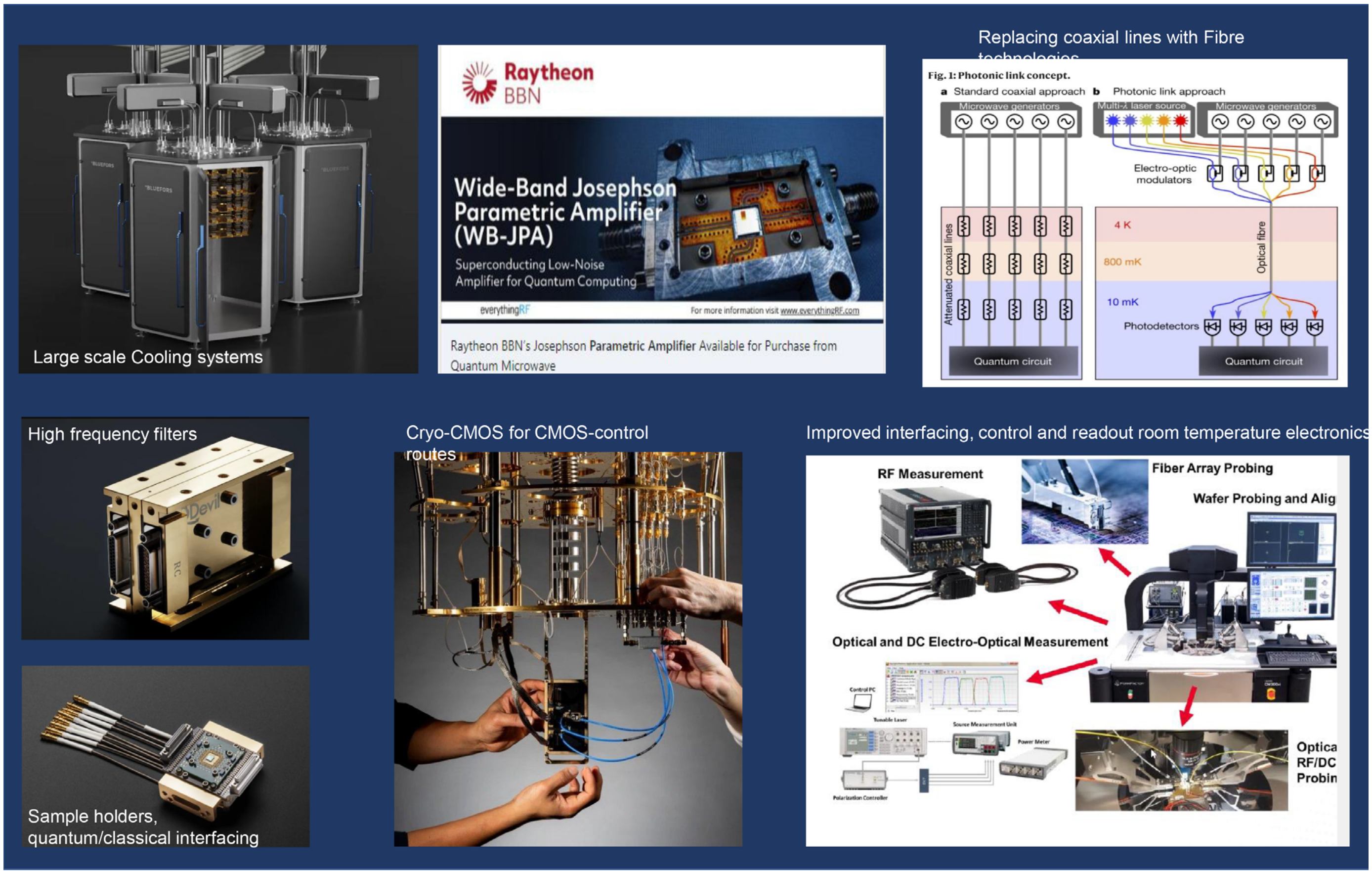


FIGURE 20 COMPILATION OF EXAMPLES OF COMPONENTS BEING DEVELOPED TO FACILITATE AND IMPROVE CURRENT SUPERCONDUCTING QUANTUM COMPUTING SYSTEMS

Integrated photonics

Integrated photonics refers to the integration of optical components, such as lasers, detectors, and waveguides, onto a single chip. This technology is becoming increasingly important for a variety of applications, including telecommunications, data processing, and quantum technologies. Note that these are some of the first QPUs to demonstrate quantum supremacy/primacy in Gaussian Boson Sampling experiments and are undoubtably expected to become more important for general quantum information processing in the near future.

There appears to be a huge capacity for photonic technologies in MassachusettsA. Not only are there several photonic technologies being explored and commercially available, but a well-resourced infrastructure that includes foundries and prototype development facilities. Some relevant research into this technology domain include:

Technology domain	Invention	Inventor
Photon detector	Impedance matched superconducting nanowire photodetector for single- and multi-photon detection	Karl K. Berggren
	Superconducting nanowire avalanche photodetectors with reduced current crowding	Karl K. Berggren

Technology domain	Invention	Inventor
Photon emission	Scalable feedback control of single-photon sources for photonic quantum technologies	Dirk Englund
Optical qubit control	Optical holographic addressing of atomic quantum bits	Dirk Englund
	On-chip detection of spin states in color centers for metrology and information processing	Dirk Englund
Integrated photonic components	Integrated electro-optic devices for classical and quantum microwave photonics	Marko Loncar
	Apparatus and methods for optical neural network	Dirk Englund
	Apparatus and methods for photonic integrated resonant accelerometers	Paul W. Juodawlkis
Fiber technologies	Ultrashort pulse fiber laser employing Raman scattering in higher order mode fibers	Siddharth Ramachandran

FIGURE 21 COMPILATION OF EXAMPLES OF COMPONENTS BEING DEVELOPED TO FACILITATE AND IMPROVE CURRENT PHOTONIC QUANTUM SYSTEMS

Cold atoms

Cold atom technology refers to the study and manipulation of ultra-cold atomic systems, typically at temperatures close to absolute zero. In this state, the atoms exhibit unique quantum mechanical properties that make them useful for a variety of applications. These technologies are characterized by vacuum chambers and laser or optical sub-systems. Cold atoms can be used for:

- Precision Measurement: Cold atoms can be used to perform highly precise measurements of physical quantities, such as time and frequency, acceleration, and gravity. This makes them useful for applications such as navigation, material characterization, and fundamental physics experiments.
- Quantum Simulation: Cold atoms can be used to simulate and study the behavior of quantum systems, which can provide insights into a variety of phenomena, including quantum phase transitions and many-body physics.
- Atom Interferometry: Cold atom interferometry is a technique that uses ultra-cold atoms to perform highly precise measurements of physical quantities, such as acceleration and gravity. This makes it useful for applications such as navigation, material characterization, and fundamental physics experiments.
- Quantum Computing: Cold atoms are being explored for use in quantum computing, as they can serve as quantum bits (qubits) and exhibit long coherence times, which are important for the stability and performance of quantum computers. Only six companies in the world that provide (or attempt to provide) cold atom QPUs, one is founded and based in MassachusettsA, another recently opened up north American operation in the CommonwealthMA. The fact that two QPU providers are based in MassachusettsA is significant and indicates that the CommonwealthMA may develop a prominent presence in the evolution of this technology.

Technology domain	Invention	Inventor
QPU	Neutral atom quantum information processor	Vladan Vuletić
Optical components for QPU	Semiconductor laser with intra-cavity electro-optic modulator	Vladan Vuletić
Measurement and control of optical qubits	Pulse sequence design protocol	Mikhail Lukin
Cold atom sensing	Cold atom interferometry	Draper inc.

Quantum Sensing

Quantum sensing is a rapidly growing field that leverages the principles of quantum mechanics to build highly precise and sensitive measurement devices. These devices have a wide range of applications, including navigation, imaging, and medical diagnostics.

As these are single component technologies, they generally have a smaller infrastructure requirement and overall footprint, this makes them ideal for near-term exploration and development as evident by the fact that quantum sensors are some of the most readily available examples of real-life application quantum technologies.

These technologies are characterized by highly interdisciplinary research that generally encompasses metrology, quantum matter and can include biology (quantum bio sensing). Massachusetts seems to be particularly strong in quantum magnetometry, the technique of sensing ultra-small magnetic fields and fluctuations.

Technology domain	Invention	Inventor
Diamond technologies	High-resolution magnetic field fingerprinting of integrated circuit activity with a quantum diamond microscope	Marko Loncar
Magnetometry	Microwave resonator readout of an ensemble solid state spin sensor	Isaac Chuang
	Ferrimagnetic Oscillator Magnetometer	Danielle A. Braje
Thermometry	Nanometer scale quantum thermometer	Mikhail Lukin
Metrology	Quantum metrology based on strongly correlated matter	Mikhail Lukin
Electrical sensors	Nanoscale scanning sensors	Amir Yacoby

Quantum matter

Quantum matter refers to materials and systems that exhibit quantum mechanical behavior and exhibit unique physical properties as a result. Some examples of quantum matter include superconductors, quantum magnets, and topological insulators.

- Quantum Computing: Quantum matter is used in the development of quantum computers, which have the potential to solve problems that are currently beyond the reach of classical computers.
- Sensing: Quantum matter can be used to build highly sensitive sensors for applications such as medical imaging, navigation, and material characterization.
- Energy: Researchers are exploring the use of quantum matter in the development of energy-efficient technologies, such as superconducting power transmission and quantum thermodynamics.

Technology domain	Invention	Inventor
Superconducting materials	Systems and methods for hybrid superconducting medium comprising first and second layers with different superconductor to induce a proximity effect between thereof	Karl K. Berggren
Novel nanoelectronics	High-resolution magnetic field fingerprinting of integrated circuit activity with a quantum diamond microscope	Philip Kim

Technology domain	Invention	Inventor
Integrated exotic materials	Integrated impedance-matched photonic zero-index metamaterials	Eric Mazur
	Far-infrared detection using Weyl semimetals	Nuh Gedik
	Low noise ultrathin freestanding membranes composed of atomically-thin 2D materials	Swastik Kar
	Current rectification based on noncentrosymmetric quantum materials	Pablo Jarillo-Herrero
	Chemi-resistive sensors based on carbon nanotubes and transition metal complexes	Timothy M. Swager
Computational	Machine learning for quantum material synthesis	Raytheon Technologies

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- Andrei Ruckenstein (Chair of the Department of Physics, Boston University)

Appendix: About MassTech and The Quantum Insider

About MassTech

Mass Tech Collaborative is an independent public instrumentality of the Commonwealth of Massachusetts focused on strengthening the competitiveness of the tech and innovation economy by driving strategic investments, partnerships, and insights. MassTech brings together leaders from industry, academia, and government to advance technology-focused solutions that lead to economic growth, job creation, and public benefits in Massachusetts. The Innovation Institute, a division of MassTech, works to improve conditions for growth in the Commonwealth's innovation economy by acting as an agent of the state to identify and promote new ideas and collaborative strategies that drive economic growth in key innovation clusters. For more information about MassTech and the Innovation Institute see: www.masstech.org or https://innovation.masstech.org.

About The Quantum Insider

The Quantum Insider ("TQI", the "Business") is the leading provider of market intelligence on the quantum technology industry. The business was founded in 2018 with a mission to provide reliable information on a market that was rife with disinformation and complexity. Since then, TQI has served some of the world's leading quantum organizations, governments and multinational corporations. The Business is headquartered in Toronto, Canada and is comprised of a team of ~30 people. Alex Challans, CEO, was previously a Director in a UK-based private equity fund and brings a wealth of commercial experience to his client projects. He leads a team of data analysts and consultants who are adapt at providing clear reports for their clients. This team includes a mix of quantum computing experts (PhD level) and commercial experience. The core of the business is to provide leading market intelligence on the quantum technology ecosystem.

The Quantum Insider was commissioned by MassTech to write this report. The Quantum Insider is responsible for all content.

Appendix: Key survey questions

- What is your full name?
- What organization are you affiliated with? (Please state the primary one)
- What is the type of this organization?
- What is your role in the organization?
- What is your organization's level of engagement with quantum technologies (i.e., quantum computing, quantum sensing or quantum cryptography)?
- Would your enterprise be interested in breaking into the quantum technology industry?
- Would your enterprise be interested in extending operations to support (e.g., become a supplier to) the quantum technology ecosystem?
- Does your enterprise have the flexibility to pursue new technology innovations relevant to the quantum computing ecosystem
- How much academic collaboration does your enterprise pursue to further its research and innovation agenda?
- How regularly does your enterprise apply for funding from Government, venture capital or philanthropy?
- What are the focus areas of your organization that are related to quantum computing? If your organization is large and spans many aspects of quantum computing please answer on behalf of your department or research group. (Example responses: quantum algorithms for finance, ion-trap quantum computation, etc.)
- How much funding has your organization received from Massachusetts-based funding organizations (public and private)? If your organization is large and spans many aspects of quantum computing please answer on behalf of your department or research group.
- Which organizations provided this funding? (Q12 How much funding has your organization received from Massachusetts-based funding organizations (public and private)? If your organization is large and spans many aspects of quantum computing please answer on behalf of your department or research group.)
- If you have received funding from outside the state of Massachusetts, where has it come from? (e.g., federal funding, venture capital outside Massachusetts)
- Has a majority of your funding come from within the state or outside the state?
- Given that the majority of your funding comes from elsewhere, has this result in any pressure to relocate?
- Do you think the funding pipelines for quantum computing are adequate in Massachusetts?
- What can be done to make better funding pipelines for quantum computing in Massachusetts?
- Why is your organization in Massachusetts?
- Compared to the state of Massachusetts, what other regions (globally or within the US) do you consider similarly well positioned or better positioned in quantum computing?
- List the institutions (if any) where your close collaborators in the field quantum computing are based. (Please include institutions from around the world)
- In your opinion, what can the State of Massachusetts do better to improve its positioning in commercializing quantum computing?
- Are there any components/services critical to your organization's quantum computing effort that are sourced from outside the USA? If so, are any of these components or services difficult to source? Please provide examples.
- How many of the research and engineering employees in your organization were hired from within Massachusetts?
- How many of the research and engineering employees in your organization were hired from within the USA?
- Do you feel that there are scientists and engineers in Massachusetts who are well prepared for careers in quantum computing?
- In your experience, has it been difficult to hire for quantum computing roles?
- What difficulties have you faced in hiring for quantum computing roles?
- If you have any other ideas or feedback for quantum computing strategy and initiatives in the state of Massachusetts, please provide them here.

Appendix: Notes on Category nomenclature and patent search methodology

Theoretical vs Experimental Groups:

Theoretical and Experimental groups have some important differences. Experimental groups have significantly larger infrastructure and capital requirements than Theoretical groups. Taking a workforce perspective - experimentalists also bring unique lab experience that is difficult to substitute since there may only be a small number of research facilities worldwide that have certain experimental setups, whereas the barrier to entry in theory is a lot lower and there is typically more competition. At a coarse-grain level of analysis we may see the role of Experimental groups in quantum computing as the development of hardware and the role of Theoretical groups in quantum computing as the development of software and other enabling theories. Many groups in Massachusetts working in quantum technologies involve both Experimental and Theoretical research.

Focus area:

As an additional categorization scheme beyond theoretical and experimental, we have categorized academic research groups by focus area. This was done to draw insight into the link or relationship between the academic research and emergent trends and opportunities in industry. We find that this categorization scheme can also be used to help define how close to quantum a patent is.

Methodology for patent search:

We used the USPTO database of registered trademark and prior pending applications. The search was restricted to company assignees and inventors within our initial profiled list. We have screened the patent search results to further restrict the patents to only those directly or closely related to quantum technology. Any patents from the respective companies or inventors found to be far from quantum were neglected. Our patent search was restricted to the last five years.

Appendix: End Notes

1. Wikipedia: https://en.wikipedia.org/wiki/List_of_colleges_and_universities_in_Massachusetts

2. Carnegie Classifications: https://carnegieclassifications.acenet.edu/lookup/lookup.php

3. MIT CQE: https://cqe.mit.edu/people/

4. Harvard University: https://quantum.harvard.edu/hqi-members

5. Rand Org: https://www.rand.org/content/dam/rand/pubs/research_reports/RRA1800/RRA1899-1/RAND_RRA1899-1.pdf

6. Quantum Computing Report: https://quantumcomputingreport.com/zapata-enters-the-quantum-cybersecurity-market/

7. Zapata Computing: https://www.zapatacomputing.com/post-quantum-cybersecurity/

8. Quera: https://www.quera.com/news

9. AWS Amazon: https://aws.amazon.com/blogs/quantum-computing/amazon-braket-launches-aquila-the-first-neutral-a

10. Keysight: https://www.keysight.com/us/en/products/modular/pxi-products/quantum-control-system.html

11. Quantum Microwave: https://quantummicrowave.com/

12. Aws Amazon: https://aws.amazon.com/blogs/quantum-computing/announcing-a-research-alliance-between-aws-and-harvard-university/

13. https://fcatalyst.com/observations/quantum

14. https://www.ll.mit.edu/r-d/advanced-technology/quantum-information-and-integrated-nanosystems