Quantum Technology: A Financial Risk Assessment

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1 INTRODUCTION

2 BACKGROUNDS

2.1 The Rise of Quantum Technology

QC represents a paradigm shift in computational science, leveraging the principles of quantum mechanics to solve problems intractable for classical systems. This section details the historical development of quantum computing, highlights significant milestones, and surveys current trends in quantum algorithms, including applications in quantum chemistry, quantum machine learning, financial securities, computer- and cyber-securities. It also discusses other emerging applications and outlines the challenges and opportunities inherent in the field.

Early foundation

The idea of quantum computation emerged in the 1980s when Richard Feynman suggested that classical computers might struggle to simulate quantum systems efficiently due to exponential growth in required resources. He proposed the concept of quantum simulators as an alternative (Feynman, 1982). Subsequently, David Deutsch formalized the model of quantum computation by introducing the concept of a universal quantum computer (Deutsch, 1985).

Significant milestones

1994 (Shor's algorithm): Peter Shor demonstrated a quantum algorithm capable of factoring large integers exponentially faster than classical algorithms, laying the groundwork for the cryptographic relevance of quantum computing (Shor, 1994).

1996 (Grover's algorithm): Lov Grover developed a quantum search algorithm that offers a quadratic speedup for unsorted database searches (Grover, 1996).

1998 (First experimental demonstration): A two-qubit quantum computer was demonstrated using Nuclear Magnetic Resonance (NMR) technology, marking a significant experimental achievement (Cory et al., 1998).

2019 Google announced achieving "quantum supremacy", where its quantum processor, Sycamore, solved a computational problem infeasible for classical supercomputers (Arute et al., 2019).

NISQ era The current state of quantum computing is referred to as the noisy intermediate-scale quantum (NISQ) era [], characterized by quantum processors containing up to 1,000 qubits which are not advanced enough yet for fault-tolerance or large enough to achieve quantum supremacy.

Current trends in quantum algorithms

Quantum Chemistry: Quantum computers have shown promise in solving molecular electronic structure problems, a computationally demanding task for classical systems. Algorithms like the Variational Quantum Eigensolver (VQE) and Quantum Phase Estimation (QPE) are employed to determine ground and excited state energies with applications in drug discovery and material science (Peruzzo et al., 2014).

Quantum Machine Learning: Quantum computing enables accelerated data processing and model training, addressing challenges in big data and high-dimensional feature spaces. Quantum versions of Support Vector Machines and Principal Component Analysis have been proposed for tasks ranging from classification to clustering (Biamonte et al., 2017).

Cryptography: Post-quantum cryptography and quantum key distribution (QKD) are developed to secure communication against potential threats posed by quantum computers (Gisin et al., 2002).

Optimization: Quantum algorithms are explored for portfolio optimization, risk analysis, and option pricing. Techniques like Quantum Annealing have been utilized for solving optimization problems inherent in financial modeling (Orús et al., 2019).

Challenges

Scalability: Building large-scale quantum systems with high fidelity and low error rates remains an engineering hurdle.

Error Correction: Quantum error correction demands significant physical qubits to form logical qubits, increasing system complexity (Devoret & Schoelkopf, 2013).

Integration: Seamlessly integrating quantum systems with classical infrastructure poses practical challenges.

Opportunities

Advancing computational frontiers: Quantum computing offers potential solutions to problems currently deemed unsolvable in classical domains.

Cross-disciplinary impact: Applications span multiple industries, including healthcare, energy, and transportation.

Economic growth: Investment in quantum technologies fosters innovation, entrepreneurship, and a specialized workforce.

2.2 Types of Quantum Computing

This section discusses three key paradigms: discrete-variable quantum computing (DVQC), continuous-variable quantum computing (CVQC), and quantum annealing. Each paradigm is described with a focus on their underlying principles, applications, and relative advantages, supported by relevant citations.

Discrete-Variable Quantum Computing

Discrete-variable quantum computing is the most widely studied paradigm, employing quantum bits (qubits) as the basic units of information. Qubits exist in superpositions of binary states $|0\rangle$ and $|1\rangle$, manipulated using quantum gates to perform computations. Quantum circuits are modeled within the framework of the Hilbert space of finite dimension 2^n, where n is the number of qubits [**?**]. **Applications**

- **Cryptography:** Algorithms like Shor's for factoring integers threaten RSA encryption.
- **Search and Optimization:** Grover's algorithm offers quadratic speedup for database search.
- **Simulation:** Molecular and material simulations exploit discrete-variable quantum systems [**?**].

Continuous-Variable Quantum Computing

Continuous-variable quantum computing utilizes quantum systems described by continuous degrees of freedom, such as the quadratures of the electromagnetic field. Quantum information is encoded in modes of light, characterized by infinite-dimensional Hilbert spaces [**?**]. Key resources include squeezed states, homodyne detection, and Gaussian operations. **Advantages**

- **Scalability:** Optical systems provide a natural platform for implementing quantum protocols.
- **Fault Tolerance:** Error correction schemes tailored for continuous variables enable robust operations.

Applications

- **Quantum Cryptography:** Quantum Key Distribution protocols using continuous-variable systems.
- **Gaussian Boson Sampling:** Solving sampling problems more efficiently than classical computers [**?**].

Quantum Annealing

Quantum annealing is a quantum optimization technique for finding the global minimum of complex energy landscapes. It leverages the adiabatic theorem, where a quantum system initialized in the ground state of a simple Hamiltonian evolves into the ground state of a more complex problem Hamiltonian [**?**]. Unlike gate-based quantum computing, it focuses on optimization rather than universal computation.

Features

- **Hardware Implementations:** Systems like D-Wave are designed for quantum annealing.
- **Problem Types:** Well-suited for combinatorial optimization and constraint satisfaction problems.

Applications

- **Portfolio Optimization:** Minimizing risk-reward ratios in finance.
- **Logistics and Scheduling:** Finding optimal solutions for supply chains and manufacturing processes.
- **Machine Learning:** Quantum Boltzmann machines for unsupervised learning tasks [**?**].

2.3 Types of Quantum Computers

Superconducting Quantum Computers

Superconducting quantum computers utilize superconducting circuits to implement qubits. These qubits are fabricated from superconducting materials, which exhibit negligible electrical resistance at cryogenic temperatures. The superconducting nature allows for long coherence times, crucial for maintaining quantum states during computations. Superconducting qubits are typically designed as **Josephson junctions**, which enable precise manipulation of quantum states. Quantum gates are implemented via microwave pulses that control the qubit state transitions. Coherence and fidelity are enhanced using advanced error-correction schemes.

- **Scalability:** The technology benefits from integration with well-established silicon fabrication techniques.
- **Speed:** Superconducting circuits offer fast gate operations, on the order of nanoseconds.
- **Ecosystem:** Significant industrial and academic investment facilitates rapid technological advancements.

Optical Quantum Computers

Optical quantum computers harness **photons** as qubits, leveraging their quantum properties such as polarization, frequency, or phase. Photons' inherent stability and minimal environmental interaction make them promising candidates for quantum information carriers. Photonic qubits are manipulated using devices like **beam splitters**, **phase shifters**, and **polarization rotators**. Quantum gates are realized through linear optical networks and nonlinear optical interactions. Techniques such as **quantum teleportation** enable distributed quantum computation.

- **High Stability:** Photons exhibit negligible decoherence over long distances.
- **Networking Potential:** The compatibility with optical fibers facilitates integration into quantum communication networks.
- **Room-Temperature Operation:** Unlike many quantum technologies, optical quantum computers do not require cryogenic cooling.

Ion Trap Quantum Computers

Ion trap quantum computers confine charged atoms (**ions**) using electromagnetic fields and employ their quantum states as qubits. These systems rely on the exceptional isolation of ions from external disturbances, leading to highly stable qubits. Ions are confined in a vacuum chamber within a linear or Penning trap. Quantum gates are performed via **laser pulses** that manipulate the internal states and Coulomb-mediated interactions among ions. Precision and fidelity are hallmarks of this approach.

- **Precision:** Ion traps demonstrate high gate fidelity and long coherence times.
- **Universal Gates:** Multi-ion operations enable universal quantum computation.
- **Benchmark Standards:** Ion traps serve as a reference standard for comparing other quantum systems.

Photonic Quantum Computers

Photonic quantum computers also employ photons as qubits but emphasize photonic integrated circuits for scalability. Their architecture is distinct due to advancements in optical interconnects and integrated photonics. Photonic qubits are created and processed using **waveguides**, **microring resonators**, and other photonic elements on chips. This approach minimizes bulk optical components, enhancing integration and reducing system complexity.

- **Integration:** Leverages advancements in photonic chip design for compact, scalable systems.
- **Versatility:** Compatible with hybrid systems combining photonic and electronic components.
- **Error Mitigation:** Reduced sensitivity to certain types of environmental noise.

Neutral Atom-Based Quantum Computers

Neutral atom-based quantum computers manipulate individual atoms trapped using optical or magnetic potentials. The qubits are encoded in the electronic or nuclear states of these atoms. Neutral atoms are trapped in **optical tweezers** and arranged into grids or lattices. Quantum operations are performed via laser-induced interactions, with **Rydberg states** enabling high-fidelity entanglement.

- **High Qubit Density:** Neutral atom traps allow compact qubit arrangements.
- **Reconfigurability:** Flexible atomic arrangements support dynamic circuit design.
- **Room-Temperature Operation:** Like photonic systems, these systems operate without requiring extreme cooling.

2.4 The Quantum Technology's Roadmaps

2.4.1 Hardware-focused Analysis

IBM roadmap

2024: Expand the utility of quantum computing by improving the quality and speed of quantum circuits, enabling the execution of 5,000 gates with parametric circuits.

2025: Demonstrate quantum-centric supercomputing through the integration of modular processors, middleware, and quantum communication to enhance quality, execution, speed, and parallelization of quantum circuits.

2026: Automate and increase the depth of quantum circuits, achieving 7,500 gates through advancements in circuit quality.

2027: Scale quantum computing by improving qubits, electronics, infrastructure, and software to reduce footprint, cost, and energy usage, enabling circuits to handle 10,000 gates.

2029: Deliver a fully error-corrected system with 200 qubits capable of executing 100 million gates.

2033+: Achieve quantum-centric supercomputers with thousands of logical qubits capable of running 1 billion gates, unlocking the full power of quantum computing.

IonQ roadmap

2019 – Harmony A pioneering quantum computer launched with a custom form factor. It utilizes **Ytterbium qubits** and has *2 systems in production*.

2021 – Aria A widely accessible, high-performance quantum computer launched with the same custom form factor as Harmony. It also uses **Ytterbium qubits**, with *2 systems in production*.

2023 – Forte A commercially available, higher-performing system launched with **Ytterbium qubits**. Only *1 system in production*.

2024 – Forte Enterprise A hybrid-enabled, data-center-ready quantum system, transitioning to a *standard data center form factor*. **Barium qubits** introduced, with *5 systems in production planned*.

2025 – Tempo A system designed for *commercial advantage*, retaining the data-center-ready design. Exact production and specifications remain unknown.

2025+ – Future Systems Planned systems aimed at delivering **broad commercial advantage**, using advanced qubit technologies. Production details and technical specifications are to be announced.

D-Wave Advantage2 System Roadmap

TABLE 1: List of companies, their websites, and stock indices in quantum technology

Company	Website	Stock Index	
1	1QBit	https://1qbit.com/	-
2	AOSense	https://aosense.com/	-
3	Algorithmiq	https://algorithmiq.fi/	-
4	D-Wave Systems	https://www.dwavesys.com/	NYSE: QBTS
5	Google Quantum AI	https://quantumai.google/	NASDAQ: GOOGL*
6	IBM Quantum	https://www.ibm.com/quantum	NYSE: IBM
7	IonQ	https://ionq.com/	NYSE: IONQ
8	IQM Quantum Computers	https://www.meetiqm.com/	-
9	ISARA Corporation	https://www.isara.com/	-
10	Microsoft Azure Quantum	https://quantum.microsoft.com/	NASDAQ: MSFT
11	NVIDIA	https://www.nvidia.com/solutions/quantum-computing/	NASDAQ: NVDA
12	Pasqal	https://www.pasqal.com/	-
13	PsiQuantum	https://www.psiquantum.com/	-
14	QC Ware	https://www.qcware.com/	-
15	Quantum Delta NL	https://quantumdelta.nl/	-
16	Quantum Machines	https://www.quantum-machines.co/	-
17	Rigetti Computing	https://www.rigetti.com/	NASDAQ: RGTI
18	Strangeworks	https://strangeworks.com/	-
19	Zapata Computing	https://zapata.ai/	-
20	G.A.I.A QTech, Vietnam	-	-

Q2 2022: Demonstration of a **500+ qubit prototype**[†], showcasing the new architecture, available in the Leap service.

Q1 2023: Calibration of early **400-qubit prototypes** using the new fabrication stack.

Q4 2023: Introduction of a **1200+ qubit prototype**, exhibiting significant performance improvements over the existing Advantage system.

Next Step: Deployment of **4800-qubit QPUs**, as part of the early Advantage2 production system.

Rigetti Computing's Roadmap

2025: Rigetti aims to develop a 100-qubit system by the end of 2025. This includes a 36-qubit system composed of interconnected 9-qubit chips, with a target of achieving 99.5% two-qubit fidelity.

336-qubit Lyra™ system: Rigetti plans to develop a 336-qubit Lyra™ system as a future goal in their roadmap.

Tiling of Quantum Processing Units (QPUs): Rigetti focuses on tiling QPUs to scale its technology effectively.

Novera QPU: Rigetti's first commercially available quantum processing unit (QPU) is the Novera QPU, which contains 9 qubits.

Multi-chip quantum processor: Rigetti has developed the industry's first multi-chip quantum processor designed for scalable quantum computing systems.

Fab-1: Rigetti designs and manufactures its chips in-house at Fab-1, the industry's first dedicated quantum device manufacturing facility.

PASQAL roadmap

2022-2023: The quantum computing platform supports a range of features designed for both research and practical applications. The hardware platform consists of up to 200 qubits, with addressability via Z add, and a base repetition rate of 1 Hz. To enhance development, hardware-accelerated libraries, such as the Algorithm Blueprint, are available. The quantum processors used are Orion Alpha, capable of approximately 3 million gates. The platform also fosters community engagement, with the Pulser platform recently launched. Factories have been established in France to support production and research activities. A total of 500 QPU hours are available for users to explore and utilize the system's capabilities.

2024-2025: The quantum computing platform offers advanced capabilities for a wide range of applications. It supports up to 1,000 qubits, with address-ability via Z+X add, and a base repetition rate of 3 Hz. Significant advancements have been made, including atom shuttling and ultra high-fidelity gates. Hardware-accelerated libraries are available to aid in algorithm development. The platform features two types of quantum processors: Orion Beta, capable of approximately 5 million gates with on-premise delivery, and Orion Gamma, with around 10 million gates, also available for on-premise delivery. Factories have been established in Canada and Factory 3 to support continued innovation. A range of 5,000 to 30,000 QPU hours is available to users for research and experimentation.

2026-2027: The quantum computing platform is designed for large-scale applications, supporting up to 10,000 qubits with addressable 1Q and 2Q gates, and a base repetition rate of 10 Hz. A major advancement in the platform is the scalable logical qubit architecture, enabling more efficient and powerful computations. The quantum processors available include Vela, capable of approximately 40 million gates, and Pegasus, which can handle up to 200 million gates. Users have access to between 60,000 and 250,000 QPU hours for their projects. Additionally, the platform has introduced new

[†]The key distinction between the qubits used in D-Wave quantum computers and those in other quantum computers lies in the computational model employed. D-Wave utilizes an adiabatic quantum computation model, which maintains qubits in their lowest energy state during processing. This model enables qubits to naturally relax into their ground state, which contrasts with other quantum computing approaches that often require active error correction to maintain coherence and minimize noise. The adiabatic approach thus simplifies the quantum computing process by leveraging the inherent stability of low-energy states, making it a unique feature of D-Wave's system.

community features, including the Learn and Collaborate platforms, to enhance knowledge-sharing and collaboration among users.

2028+: The quantum computing platform supports over 100,000 qubits, with a base repetition rate of 100 Hz, enabling high-performance computations. The key quantum processor in use is the Centaurus FTQC QPU, which features more than 128 logical qubits and is capable of executing over 200 million gates. Users have access to between 500,000 and 550,000 QPU hours for their research and development. The platform also launched Qadence, a new community initiative that includes solvers and emulators to facilitate collaborative problem-solving and simulation tasks.

2.4.2 Software-focused Analysis

Qskit an open-source quantum computing software development framework by IBM, supports quantum algorithm development and execution on IBM's quantum processors. Its roadmap emphasizes improving developer usability, enhancing computational power, and fostering a global quantum computing ecosystem. Strategic goals of the business includes three goals: democratizing quantum computing access, improving error mitigation techniques, supporting hybrid quantum-classical workflows. There are five key milestones in its development:

1) *Hardware integration*: Continued alignment with IBM's hardware roadmap, enabling access to increasingly large and reliable quantum systems. Target systems include quantum processors with over 1,000 qubits by 2025.
2) *Runtime enhancements*: Focus on reducing quantum program execution times through optimized runtime environments.
3) *Algorithm libraries*: Expansion of prebuilt quantum algorithm libraries for chemistry, optimization, and machine learning.
4) *Education and ecosystem development*: Expanding educational resources to support the growing quantum developer community, including comprehensive documentation and interactive tutorials.

NVIDIA a leader in GPU development, focuses on advancing AI hardware and software ecosystems. Its roadmap prioritizes high-performance computing (HPC), AI acceleration, and edge computing solutions. NVIDIA's strategic goals include: maintaining leadership in AI hardware acceleration; driving convergence of HPC, AI, and visualization technologies; fostering partnerships to integrate NVIDIA technologies across industries. The key technologies of NVIDIA are

1) *Hopper and grace architectures*: Development of GPUs and CPUs with improved throughput, energy efficiency, and memory bandwidth. Hopper GPUs target large-scale AI training workloads, while Grace CPUs cater to HPC applications.
2) *CUDA ecosystem expansion*: Enhancements to the CUDA toolkit for streamlined programming, enabling deeper integrations with AI and HPC frameworks.
3) *Omniverse platform*: Accelerating the adoption of digital twins, real-time 3D collaboration, and AI-powered simulations.
4) *AI-on-Edge*: Development of AI inference chips optimized for low-latency applications, including autonomous vehicles and robotics.

Google AI highlights advancements in foundational AI research, product integration, and ethical AI development. The organization leverages its expertise to improve search, cloud services, and AI-powered consumer products. Their strategic goals are to dominate the generative AI market; to improve AI capabilities across Google's consumer and enterprise products and to be the leader in ethical and responsible AI development. Key milestones in the development of Google AI includes

1) *Generative AI models*: Scaling up large language models (LLMs) like Bard and advancements in generative AI for creative tasks.
2) *Tensor Processing Unit (TPU)*: Iterative improvements in TPU hardware for training and deploying AI models at scale.
3) *Google DeepMind*: Expanding fundamental research in reinforcement learning, neural networks, and AI safety.
4) *AI in Cloud Services*: Enhancements in AI-based tools like Vertex AI, designed to simplify ML model development and deployment.
5) *Ethical AI*: Strengthening AI governance frameworks and advancing fairness, transparency, and accountability in AI systems.

2.4.3 Application-oriented Analysis

Cloud-Based quantum platforms

1) *IBM Quantum* offers Platform-as-a-Service (PaaS) solutions that enable developers to build and deploy quantum algorithms using Qiskit on IBM's quantum processors. Users can access to quantum systems via IBM cloud and develop applications with Seamless hybrid quantum-classical workflow integration.
2) *Azure Quantum* provides a comprehensive quantum PaaS combining hardware diversity with a robust software ecosystem, such as the accessibility to multiple quantum hardware vendors; tools and libraries for algorithm development in Q#[‡], and simplified deployment for quantum-inspired solutions leveraging classical resources.

Quantum communication and sensors

1) *AOSense* specializes in precision quantum sensors, leveraging quantum mechanics to improve measurements in navigation and timing. The technology behinds the fin is atom interferometry for ultraprecise gyroscopes, accelerometers, and clocks. Their applications include defense, aerospace, and geophysics.
2) *Quantum Delta NL*, a Dutch initiative[§], focuses on quantum communication and sensing technologies to drive economic growth. Their program focuses on developing of quantum networks and cryptographic

‡?
§?

TABLE 2: Comparison between Qiskit, NVIDIA, and Google AI

Feature	Qiskit	NVIDIA	Google AI
Primary Focus	Quantum Computing	AI **Hardware and Acceleration**	Generative AI and AI Research
Hardware Integration	IBM Quantum Systems	GPUs and TPUs	TPUs and Cloud Services
Software Ecosystem	Quantum SDK, Algorithm Libraries	CUDA, Omniverse, AI Platforms	TensorFlow, Vertex AI, Bard
Key Innovations	Hybrid Quantum-Classical Workflows	Hopper GPUs, AI-on-Edge	Generative AI, AI Safety
Ethics/ Governance	Limited	Focused on energy efficiency	Core to roadmap

solutions. Their innovations founded on integration of photonics for long-distance quantum communication. Their research strategies is to partner with academic and industrial leaders across Europe.

Business solutions

1) *Zapata Computing* offers quantum software platforms, such as Orquestra, to enable business-oriented quantum applications like optimization, machine learning, chemistry simulations and integration of quantum algorithms with classical workflows.
2) *Strangeworks* focuses on simplifying quantum computing adoption through accessible development tools, such as single platform supporting multiple quantum hardware backends and educational tools, prototyping, and quantum-enabled workflows.

Cryptographic solutions *ISARA Corporation* is a leader in post-quantum cryptography (PQC), offering cryptographic solutions resistant to quantum threats. Their core products are PQC algorithms and tools for secure system migration. Their key markets are financial services, government, and critical infrastructure. It is notatble that they are an active participation in NIST's PQC [] standardization initiatives¶.

Healthcare and medical science applications

1) *Algorithmiq* specializes in quantum algorithms for solving complex problems in drug discovery and molecular simulations, concentrating on precision medicine and drug optimization. They are in partnerships with pharmaceutical companies for quantum-enabled solutions.
2) *QC Ware* develops algorithms tailored for quantum chemistry and bioinformatics applications. Their approaches is to combine machine learning with quantum-enhanced techniques for optimization and analysis in genomics and protein folding.
3) *Zapata Computing*'s Orquestra platform is also utilized in healthcare applications, which are drug discovery, clinical trials optimization, and systems biology simulations.

3 Framework Overview

3.1 Research Strategy

To achieve the goal, we propose a research strategy, which follows the the below step

1) We will introduce the portfolio including ten assets (stocks and ETFs) in Section 3.2 and Table 3. A preliminary analysis of these assets will be performed, including correlation analysis and AI-enabled forecasting.
2) We will analyze financial risks for the constructed portfolio from two aspects: (1) the potential gains (Section 4.1) and (2) the potential loss, stratified by risk categories (Section 4.2).
3) Then, we will perform the risk assessment using qualitative and quantitative evaluation in Section 4 and 5, respectively.
4) Next, we propose five fundamental aspects to construct FRM framework of investments on quantum technologies, which enables robust and sustainable approaches.
5) Finally, we will discuss broader impacts of the technologies for societies with policy and regulation should be done to advance the technologies. At the end, we would like to give our prediction for the future of quantum machinery.

3.2 The Portfolio

TABLE 3: List of quantum technology indices, their types, symbols, and exchanges

Index	Type	Symbol	Exchange
Alphabet	Stock	GOOGL	NASDAQ
IBM	Stock	IBM	NYSE
IonQ	Stock	IONQ	NYSE
Microsoft	Stock	MSFT	NASDAQ
Nvidia	Stock	NVDA	NASDAQ
Quantum Computing Inc.	Stock	QUBT	NASDAQ
Rigetti Computing	Stock	RGTI	NASDAQ
D-Wave Quantum	Stock	QBTS	NYSE
Defiance Quantum ETF	ETF	QTUM	NYSEARCA
Global X Future Analytics Tech	ETF	AIQ	NASDAQ

References

4 A Qualitative Risk Assessment

4.1 Financial Opportunities

4.1.1 Market Potential

The market potential of quantum technology is immense, poised to reshape industries and economies over the next decade, some short depicted via big firms' visions discussed in Section 2.4. With rapid advancements in quantum computing, communication, and sensing, the stage is set for a transformative era driven by innovation and strategic investments. We give a comparison of the quantum technology segments in Table 8.

At the forefront of this revolution is quantum computing, which holds the promise of solving optimization problems [], accelerating drug discovery [], transforming financial modeling [], and revolutionizing cryptography []

¶

TABLE 4: Summary of Risks: Severity and Likelihood

Index	Risk Type	Description	Severity	Likelihood
1	Technological Risk	Failure to develop or obsolescence	High	Moderate
2	Regulatory Risk	Uncertain regulatory landscape and compliance costs	High	High
3	Market Risk	Lack of demand and delayed adoption	High	High
4	Operational Risk	Supply chain and talent shortages	Moderate-High	Moderate
5	Financial Risk	High R&D costs and valuation challenges	Moderate-High	Moderate
6	Cybersecurity and Privacy Risk	Data security risks and cryptographic vulnerabilities	High	High
7	Geopolitical Risk	Trade restrictions and national security concerns	High	Moderate-High
8	Ethical and Social Risk	Public backlash and inequality in access	Moderate	Moderate

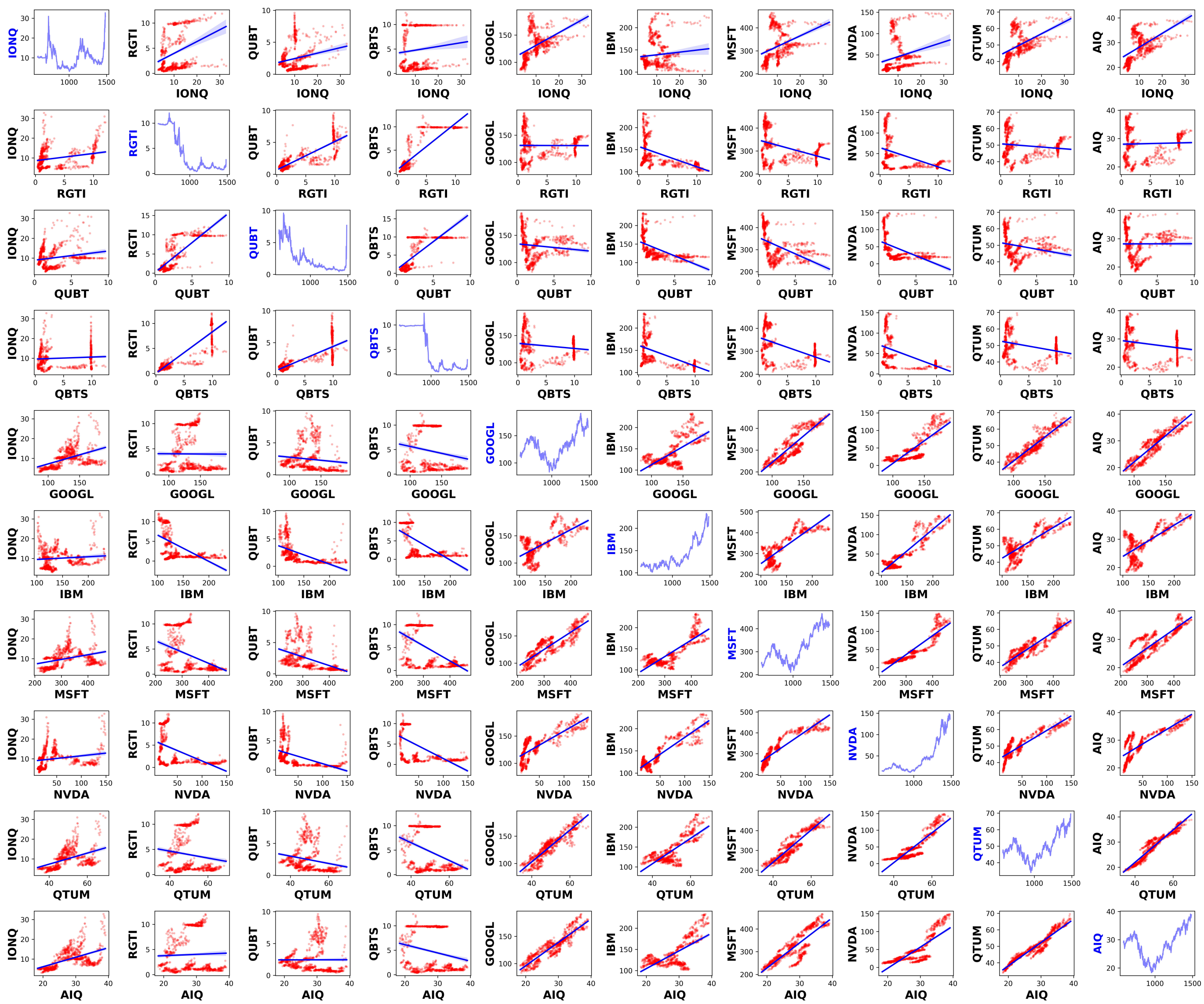

Fig. 1: Exploratory Data Analysis of Portfolio in Table 3. The diagonal plots show the time series of quantified stock prices from 04/22/2021 to 11/25/2024 ($n = 906$ observations) The off-diagonal plots show the pair-wise scatter plots of the stock prices with a simple linear regression model

TABLE 5: Risk Matrix: Prioritization of Risks Based on Severity and Likelihood

L/S	Low	Moderate	High
Low	-	Ethical and Social Risk	-
Moderate	Financial Risk	Operational Risk	Technological Risk
High	-	Market Risk	Regulatory, Cybersecurity, Geopolitical Risks

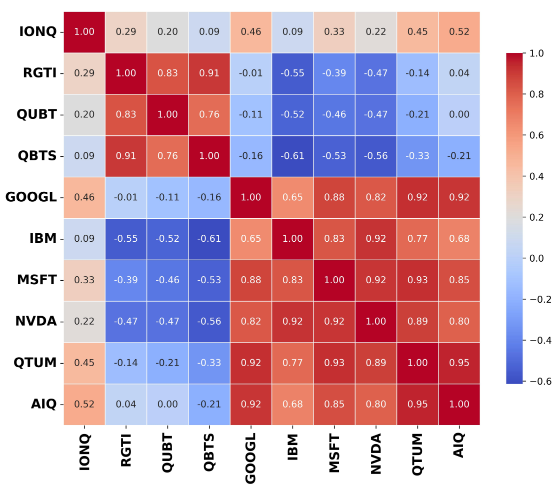

Fig. 2: Heatmap of correlation between stock prices in Table 3. The red depicts high correlation, whereas blue depicts low correlation

and machine learning []. The market for quantum computing, currently valued at about $1 billion in 2023, is projected to soar to $20–50 billion by 2030[||], fueled by breakthroughs in hardware and algorithms. Key players like IBM, Google, Rigetti, and IonQ, along with numerous startups, are leading the charge in unlocking the full potential of quantum machines. Equally transformative is quantum communication, which promises ultra-secure data transfer through technologies like Quantum Key Distribution (QKD) [] and the development of a quantum internet. This sector, valued at $0.5 billion in 2023, is expected to exceed $10 billion by 2035 as governments and industries prioritize cybersecurity in an increasingly interconnected world[**]. Advances in photonics and satellite technologies are pivotal in driving this growth, addressing the rising threats to data security. Quantum sensing and metrology offer unparalleled precision in measuring physical quantities, with applications spanning healthcare, navigation, and geophysics. By 2030, the market for quantum sensors is anticipated to surpass $5 billion, with early adoption in fields like defense, oil exploration, and medical diagnostics. These sensors' extraordinary sensitivity and accuracy provide advantages over traditional methods, enabling new possibilities in critical industries.

[||] ?

[**] ?

The burgeoning quantum ecosystem is also powered by substantial research and development investments. Governments across the globe are prioritizing quantum technologies as a strategic imperative. China, for instance, has committed over $10 billion to its national quantum research hub, while the United States, under the National Quantum Initiative Act, is investing billions in fostering innovation. The European Union's Quantum Flagship program, with a €1 billion budget over a decade, underscores the global race to lead in this cutting-edge domain. Commercial adoption of quantum technologies spans a variety of industries. In financial services, quantum algorithms can optimize portfolios, enhance fraud detection, and improve high-frequency trading. In healthcare, they are accelerating breakthroughs in protein folding, personalized medicine, and drug simulation. Logistics benefit from traffic optimization and streamlined supply chains, while energy applications include power grid optimization and material science advancements. We summarize initiative programs on quantum technologies in Table **??**.

However, realizing the full potential of quantum technology is not without its challenges. The scalability of quantum hardware, the development of fault-tolerant systems with error-correcting algorithms, and seamless integration with classical computing infrastructure remain significant hurdles. Additionally, high research and development costs and the complexity of the technology call for continued collaboration between academia, industry, and governments. Despite these challenges, the quantum technology market represents a transformative opportunity. With a projected market size of $100–200 billion by 2040, the industry is poised to redefine global innovation. As startups, corporations, and governments join forces to overcome barriers, quantum technology's transformative potential becomes ever more evident, promising a future of unparalleled possibilities.

4.1.2 Cost-Benefit Analysis

Cost-benefit analysis (CBA) is a crucial component in assessing the viability of risk management strategies for investments involving emerging technologies like quantum technology. In the context of quantum technology, this analysis must consider a wide array of factors due to the high level of uncertainty, novelty, and potential for disruptive innovation that quantum technologies bring. The following is our CBA analysis:

The benefits: The benefits of adopting quantum technology in investment risk management are less straightforward but potentially very high thank to five main reasons:

1) **Enhanced computational power:** Quantum computing could provide breakthroughs in solving complex financial models, optimization problems, and simulations that are currently impractical or impossible with classical computing methods. This capability can lead to better risk assessments, more efficient portfolio management, and faster decision-making processes.
2) **Improved security:** Quantum cryptography promises a level of data security that could be crucial for safeguarding sensitive investment strategies and financial transactions against future cybersecurity threats, especially in the context of quantum-resistant encryption.

TABLE 6: Risk Quantification Table: Scores for Likelihood, Impact, and Total Risk

Risk	Likelihood (1–5)	Impact (1–5)	Total Score	Priority
Regulatory Risk	5	5	25	Immediate Attention
Market Risk	5	5	25	Immediate Attention
Cybersecurity Risk	5	5	25	Immediate Attention
Geopolitical Risk	4	5	20	High Priority
Technological Risk	3	5	15	Proactive Monitoring
Operational Risk	3	4	12	Proactive Monitoring
Financial Risk	3	4	12	Proactive Monitoring
Ethical and Social Risk	2	3	6	Long-term Strategy

TABLE 7: Exposure Assessment Table: Quantifying Potential Exposure to Risks in Quantum Technologies

Risk	Investment Amount ($M)	Cost of Failure ($M)	Probability (0–1)	Potential Exposure ($M)
Regulatory Risk	50	100	0.8	4000
Market Risk	60	120	0.7	5040
Cybersecurity Risk	40	80	0.9	2880
Geopolitical Risk	30	70	0.6	1260
Technological Risk	70	90	0.5	3150
Operational Risk	20	50	0.4	400
Financial Risk	15	40	0.3	180
Ethical and Social Risk	10	30	0.2	60

TABLE 8: Comparison of Quantum Technology Segments

Segment	Estimated Value by 2030	Revenue Drivers	Challenges	Growth Potential
Quantum Computing	$130 billion	Hardware, software, QaaS, defense, research	High R&D costs, scalability, hardware limits	Very high
Quantum Communication	$10 billion	Secure communication, government, telecom	Infrastructure cost, integration with legacy systems	High
Quantum Sensing/Metrology	$10 billion	Healthcare, defense, environmental monitoring	High development costs, niche applications	Moderate-high
Quantum Cryptography	$3 billion	Cybersecurity, finance, defense, government	Implementation cost, regulatory issues	High
Quantum Materials/Hardware	$10-15 billion	Material sales, research partnerships	High discovery and development costs	Moderate-high

3) **Innovation and competitive advantage:** Early adoption of quantum technology can offer a competitive edge by enabling more accurate predictions, better pricing of derivatives, and new risk management strategies that leverage quantum computing's potential.
4) **Long-term cost savings:** Over time, quantum technologies might reduce the costs associated with classical risk management methods, such as large-scale Monte Carlo simulations [] or the processing of vast amounts of financial data.
5) **Market expansion:** Quantum technologies might open new investment opportunities or markets by providing solutions to currently unsolvable problems in industries like pharmaceuticals, materials science, and logistics, where quantum-based insights could lead to groundbreaking innovations.

The cost: A central aspect of the CBA for quantum technology investments is evaluating the associated cost/potential loss in term of risks or uncertainties, which can be categorized into five types (later we will discuss them in details):

1) **Technology risk**: The development of quantum technologies is still in its infancy. There is a risk that the technology may not mature as expected, leading to sunk costs in R&D and infrastructure.
2) **Market risk**: Given the nascent stage of quantum technology, there is a high degree of uncertainty regarding its commercial applications and market demand. The timing of when quantum solutions will become mainstream is uncertain.
3) **Regulatory risk**: As quantum technology poses new challenges in areas like encryption, governments may enact unforeseen regulations that could either limit or accelerate the technology's adoption, with financial implications.
4) **Integration risk**: Integrating quantum technology into existing financial systems poses significant challenges, particularly in terms of compatibility with classical systems, knowledge gaps in quantum algorithms, and the need for specialized talent.
5) **Adoption risk**: Investors must consider the pace at which quantum technology will be adopted by other financial institutions and industries. Slow adoption could delay the expected benefits.

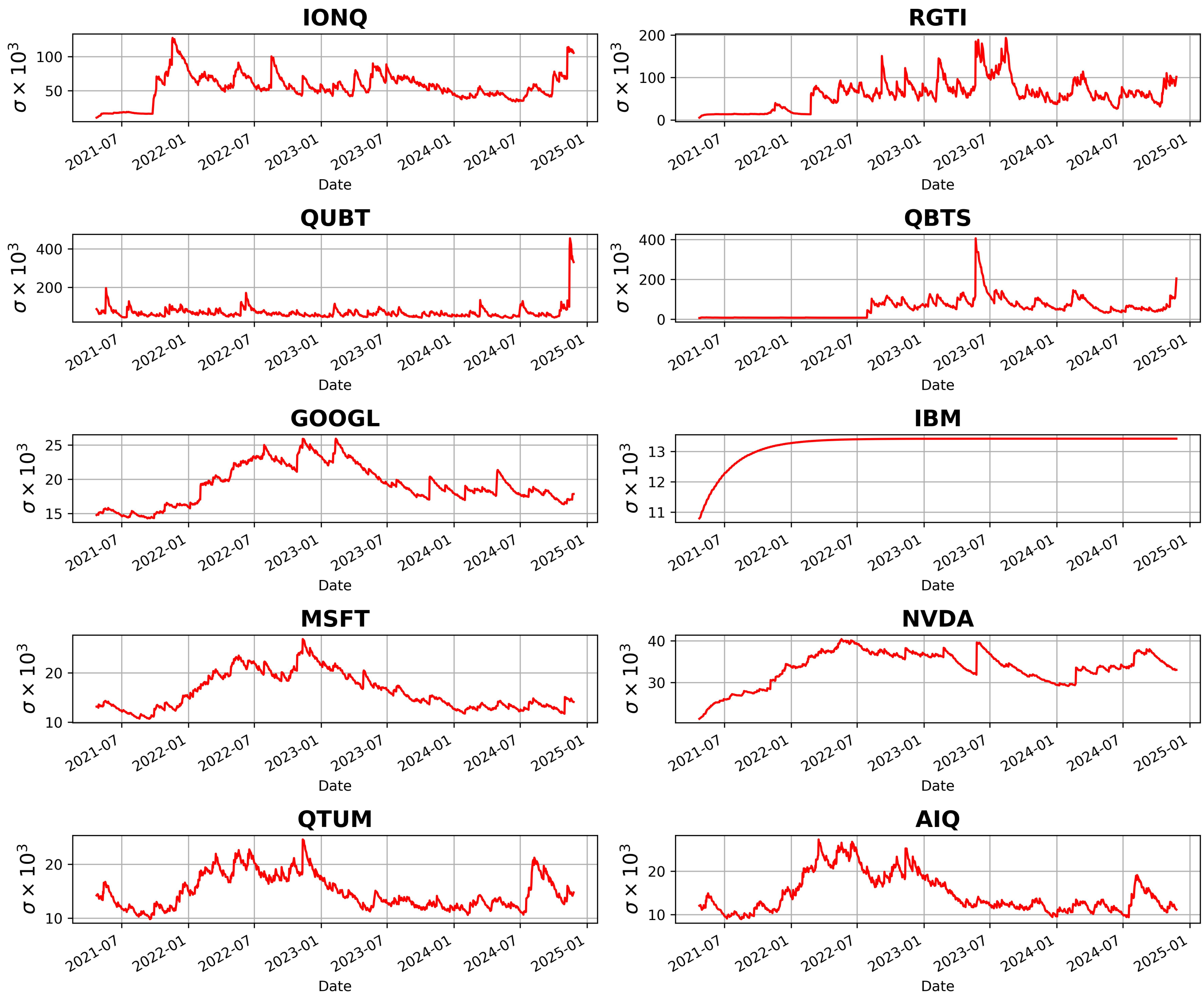

Fig. 3: Numerical results of fitting GARCH(1,1) model for stock's price volatility (standard deviation, σ) computed in Table 3. The standard deviation is scaled by 1000 times for numerical stability

4.2 Foundation of Associated Risks

4.2.1 Risk Identification

Identifying the risks associated with investments in quantum technology requires understanding both the inherent uncertainties of the technology itself and the broader financial environment. The following are key risks associated with investments in quantum technology:

1. Technological Risk

Uncertainty of Development: Quantum technology, particularly in areas such as quantum computing and quantum cryptography, is still in its early stages. There is a high risk that the technology may not mature as expected or that breakthroughs could take longer than anticipated.

Obsolescence Risk: As new developments emerge, existing quantum technologies may become outdated or surpassed by more advanced solutions, making investments in early-stage technologies less valuable.

Example: The Segway personal transporter, launched in 2001, was touted as a groundbreaking innovation in transportation. However, despite significant technological investment, it failed to achieve widespread market adoption. This can be attributed to technological risks such as overestimating the market readiness for the technology and the failure to address practical issues like safety, legal restrictions, and infrastructure requirements[††].

2. Regulatory Risk

- **Uncertain Regulatory Landscape**: Quantum technology is rapidly evolving, and many countries are still developing their regulations for its use, particularly in sensitive areas like data security and encryption. Regulatory changes can impact the viability of certain investments or create additional compliance costs.

[††]https://edition.cnn.com/2018/10/30/tech/segway-history/index.html

TABLE 9: Summary of Direct and Indirect Effects

Risk Type	Direct Effects	Indirect Effects
Technological Risk	Financial losses, underperformance of products	Reputational damage, market confidence drop, competitive disadvantage
Regulatory Risk	Compliance costs, restricted market access	Investment uncertainty, geopolitical tensions, reputational damage
Market Risk	Revenue uncertainty, delayed product adoption	Brand damage, disrupted business plans, long-term market shifts
Operational Risk	Production delays, talent shortages	Innovation slowdown, strategic uncertainty
Financial Risk	High capital expenditure, valuation inaccuracies	Funding reduction, loss of investor confidence
Cybersecurity Risk	Data breaches, security failure in quantum encryption	Reputation damage, regulatory fallout
Geopolitical Risk	Trade restrictions, national security concerns	Market fragmentation, increased political risk
Ethical and Social Risk	Inequitable access, public backlash	Regulatory scrutiny, public perception issues

TABLE 10: Cascading Effects of Risks in QuanTech

Risk Type	Cascading Effects
Technological Risk	Delay in product releases, impact on R&D, loss of competitive advantage, investor pullback, market penetration delays
Regulatory Risk	Increased compliance costs, disrupted market access, cross-border trade barriers, operational overhaul, reputation damage
Market Risk	Revenue shortfalls, downward investment spiral, reduction in product development, increased market fragmentation, consolidation and layoffs
Operational Risk	Production delays, decreased innovation capacity, increased costs, loss of competitive edge, decreased market confidence
Financial Risk	Funding shortages, stock price volatility, inability to scale, delayed product development, investor exits
Cybersecurity Risk	Data breaches, loss of trust, regulatory backlash, liability and legal costs, increased competition
Geopolitical Risk	Supply chain disruptions, investment uncertainty, market fragmentation, increased national investment, strategic shifts
Ethical and Social Risk	Regulatory pressure, public backlash, investor withdrawal, slow adoption, increased social divisions

TABLE 11: Summarized Long-Term Consequences of Risks in Quantum Technology Investments

Risk Type	Long-Term Consequences
Technological Risk	Delayed adoption, loss of market momentum, competitive disadvantage, regulatory bottlenecks.
Regulatory Risk	Shifting regulatory landscapes, increased government control, stifled innovation, market fragmentation.
Market Risk	Slow market adoption, prolonged revenue uncertainty, consolidation of the market, negative public perception.
Operational Risk	Supply chain vulnerabilities, increased operational costs, talent drain, technological stagnation.
Financial Risk	Capital shortages, weakened investment ecosystem, decreased valuations, economic ripple effects.
Cybersecurity, Privacy Risk	Breakdown of cryptographic systems, security vulnerabilities, privacy concerns, need for quantum-resistant encryption.

TABLE 12: Strategies for Managing Quantum Technology Risks based on ARMT Principles

FRM Strategy	Description
Avoid	Steer clear of high-uncertainty investments, such as unproven quantum hardware lacking infrastructure.
Retain	Accept manageable risks for long-term potential, e.g., early-stage quantum research despite technological uncertainty.
Mitigate	Take proactive measures to reduce risk impact: - Invest in research to resolve technological risks. - Build diverse portfolios to avoid over-reliance on quantum tech. - Implement strong cybersecurity measures to protect IP and data.
Transfer	Transfer risks through contracts, insurance, or partnerships, e.g., hedging volatility with derivatives or joint ventures.

- **Government Intervention**: Governments may intervene to control or restrict access to certain quantum technologies for national security reasons, which could negatively affect private sector investments.
- The introduction of autonomous vehicles (AVs), particularly by companies like Uber and Tesla, has been met with a complex regulatory environment. In 2018, Uber's self-driving car was involved in a fatal accident, highlighting the regulatory uncertainty surrounding autonomous technology. Different jurisdictions have varying regulations for AVs, and the lack of a cohesive framework in the U.S. led to Uber halting its self-driving program temporarily[‡‡].

3. Market Risk

- **Lack of Established Market**: The market for quantum technologies is not yet fully developed, which

[‡‡]https://arxiv.org/pdf/2010.15665

TABLE 13: Summary of Statistical Model Parameters

Symbol	ADF Statistic	p-value	AR Parameters	MA Parameters	ARMA Parameters	ARIMA Parameters
IONQ	-4.9026	3.45×10^{-5}	const: 0.00061 IONQ.L1: 0.846 IONQ.L2: 0.070 IONQ.L3: -0.130 IONQ.L4: 0.035 IONQ.L5: -0.108	const: 0.002 ma.L1: 0.965 ma.L2: 0.500 sigma2: 0.392	const: 0.0002 ar.L1: 1.172 ar.L2: -0.575 ma.L1: -0.643 ma.L2: 0.926 sigma2: 0.304	const: 0.0002 ar.L1: 1.172 ar.L2: -0.575 ma.L1: -0.643 ma.L2: 0.926 sigma2: 0.304
RGTI	-4.8855	3.72×10^{-5}	const: 0.0036 RGTI.L1: 0.892 RGTI.L2: 0.008 RGTI.L3: -0.148 RGTI.L4: 0.034 RGTI.L5: -0.114	const: 0.0065 ma.L1: 0.984 ma.L2: 0.506 sigma2: 0.393	const: 0.0124 ar.L1: 1.359 ar.L2: -0.620 ma.L1: -0.559 ma.L2: 0.411 sigma2: 0.331	const: 0.0124 ar.L1: 1.359 ar.L2: -0.620 ma.L1: -0.559 ma.L2: 0.411 sigma2: 0.331
QUBT	-2.8892	0.0466	const: 0.0063 QUBT.L1: 0.951 QUBT.L2: -0.142 QUBT.L3: 0.026 QUBT.L4: 0.024 QUBT.L5: -0.124	const: 0.008 ma.L1: 1.176 ma.L2: 0.631 sigma2: 0.360	const: 0.026 ar.L1: 1.340 ar.L2: -0.482 ma.L1: -0.374 ma.L2: 0.004 sigma2: 0.331	const: 0.026 ar.L1: 1.340 ar.L2: -0.482 ma.L1: -0.374 ma.L2: 0.004 sigma2: 0.331
QBTS	-5.0748	1.57×10^{-5}	const: 0.0027 QBTS.L1: 0.828 QBTS.L2: 0.031 QBTS.L3: -0.027 QBTS.L4: 0.053 QBTS.L5: -0.205	const: 0.0033 ma.L1: 0.990 ma.L2: 0.508 sigma2: 0.400	const: 0.0044 ar.L1: -0.369 ar.L2: 0.309 ma.L1: 1.569 ma.L2: 0.912 sigma2: 0.323	const: 0.0044 ar.L1: -0.369 ar.L2: 0.309 ma.L1: 1.569 ma.L2: 0.912 sigma2: 0.323
GOOGL	-6.3607	2.48×10^{-8}	const: -0.00009 GOOGL.L1: 0.829 GOOGL.L2: -0.028 GOOGL.L3: -0.026 GOOGL.L4: -0.015 GOOGL.L5: -0.149	const: 0.00098 ma.L1: 0.962 ma.L2: 0.475 sigma2: 0.423	const: 0.0012 ar.L1: 1.327 ar.L2: -0.623 ma.L1: -0.615 ma.L2: 0.464 sigma2: 0.369	const: 0.0012 ar.L1: 1.327 ar.L2: -0.623 ma.L1: -0.615 ma.L2: 0.464 sigma2: 0.369
IBM	-5.7263	6.76×10^{-7}	const: 0.00037 IBM.L1: 0.900 IBM.L2: -0.078 IBM.L3: 0.062 IBM.L4: -0.044 IBM.L5: -0.146	const: 0.0042 ma.L1: 1.158 ma.L2: 0.612 sigma2: 0.355	const: 0.0052 ar.L1: 1.406 ar.L2: -0.592 ma.L1: -0.564 ma.L2: 0.254 sigma2: 0.311	const: 0.0052 ar.L1: 1.406 ar.L2: -0.592 ma.L1: -0.564 ma.L2: 0.254 sigma2: 0.311
MSFT	-5.9908	1.75×10^{-7}	const: 0.0026 MSFT.L1: 0.830 MSFT.L2: -0.071 MSFT.L3: 0.068 MSFT.L4: 0.023 MSFT.L5: -0.205	const: 0.0056 ma.L1: 0.970 ma.L2: 0.542 sigma2: 0.379	const: 0.0043 ar.L1: 1.148 ar.L2: -0.522 ma.L1: -0.451 ma.L2: 0.352 sigma2: 0.337	const: 0.0043 ar.L1: 1.148 ar.L2: -0.522 ma.L1: -0.451 ma.L2: 0.352 sigma2: 0.337

means demand for quantum-based products and services is uncertain. This makes forecasting future revenue streams from quantum investments highly speculative.

- **Adoption Delays**: Even if quantum technologies become commercially viable, market adoption may take longer than expected due to the need for industries to integrate the new technology, retrain personnel, and change existing infrastructure.
- Google Glass, launched in 2014, faced significant market risk due to a lack of established demand. Despite being an impressive technological feat, it failed to gain mass adoption. Consumers found the product intrusive, uncomfortable, and costly. Market adoption was delayed as businesses and consumers were not ready to embrace the technology, leading to Google suspending the project.

4. Operational Risk

- **Supply Chain and Scalability Challenges**: Quantum technology requires highly specialized components and sophisticated infrastructure. The risk of supply chain disruptions or challenges in scaling production could delay the realization of returns on investment.
- **Talent Shortage**: The quantum tech field requires highly specialized talent, and there may be a shortage of skilled professionals capable of developing and deploying quantum technologies, which could hinder progress or increase operational costs.

5. Financial Risk

- **High Capital Expenditure**: Quantum technology investments are typically capital intensive, requiring significant funding for research and development (R&D). Investors face the risk of large initial investments with uncertain returns.
- **Valuation Risk**: The absence of clear benchmarks or widely accepted metrics for evaluating quantum technology companies makes it challenging to accurately value potential investments. This could lead to overvaluation or undervaluation.

6. Cybersecurity and Privacy Risk

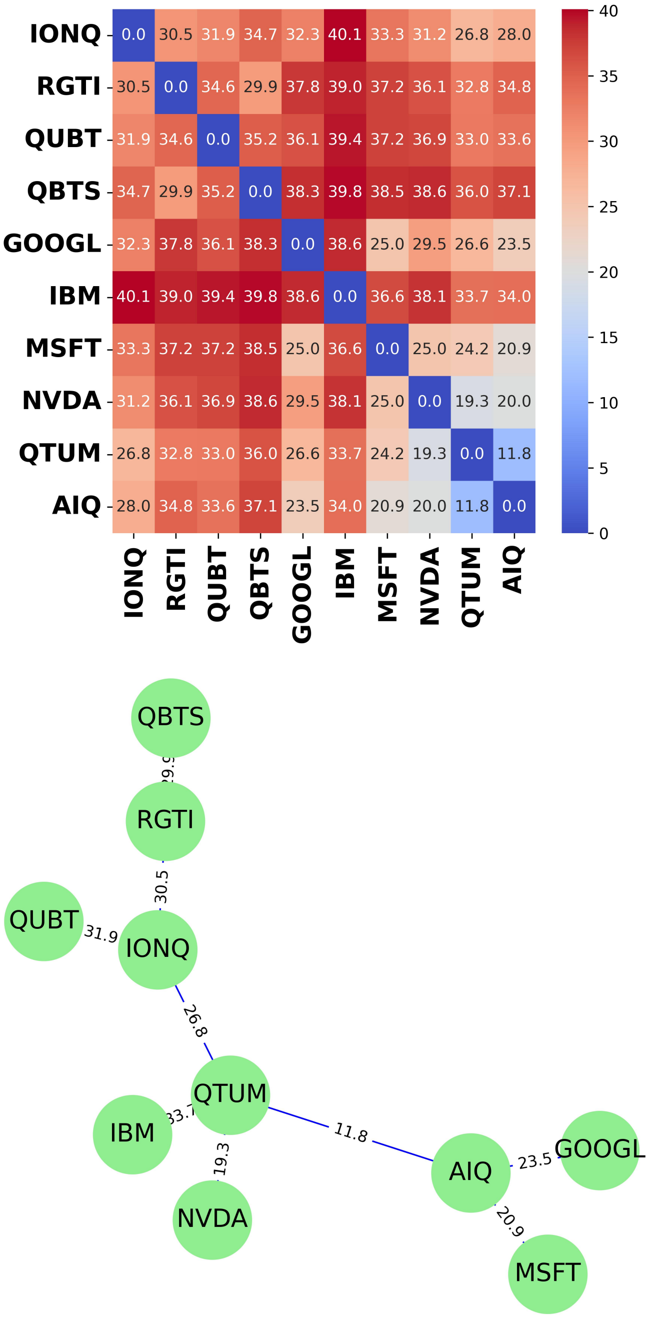

Fig. 4: Pair-wise distance between stock price and the MST based on the measured distance

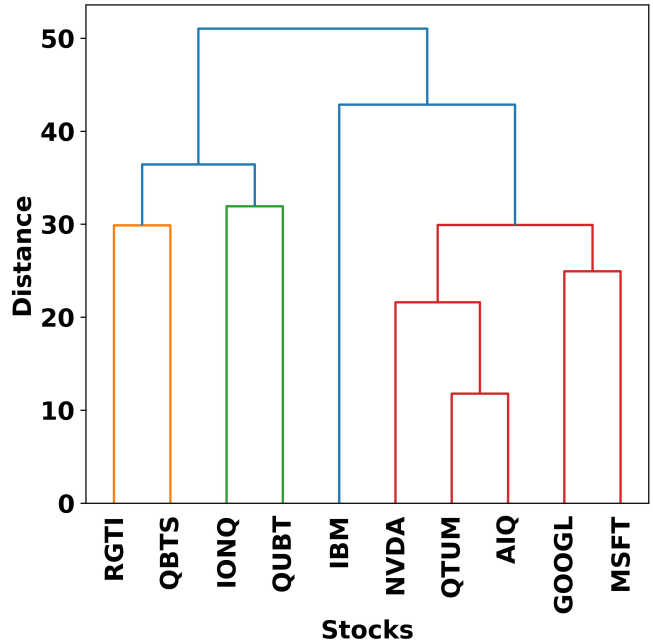

Fig. 5: Dendrogram (a tree-like diagram that shows the relationships between similar objects or entities) of the portfolio. The stock indices in Table 3 are stratified into four clusters based on Euclidean distance illustrated in Figure 4

- **Quantum Cybersecurity**: Quantum computing could eventually break current cryptographic methods, creating new risks related to the security of sensitive financial data. On the other hand, investing in quantum cryptography solutions introduces risks associated with technological adoption and integration into existing cybersecurity frameworks.
- **Privacy Implications**: The use of quantum technology could raise new privacy concerns, especially in relation to how data is stored and transmitted, which might affect the financial value of related investments.
- In 2017, Equifax, one of the largest credit reporting agencies in the U.S., suffered a massive data breach affecting approximately 147 million people. The breach was largely due to vulnerabilities in outdated software. It highlights the cybersecurity risks associated with new technologies like big data analytics and cloud storage. Even though Equifax had the latest technology in data analysis, they failed to secure the data, causing a significant loss of consumer trust and reputational damage[§§].

7. Geopolitical Risk

- **Global Competition and National Security Concerns**: Quantum technologies have significant implications for national security (e.g., in encryption and defense). This could lead to a geopolitical race where countries or corporations might restrict access to certain quantum technologies or even engage in trade wars, affecting investment returns.
- **Technology Export Controls**: As quantum technologies are seen as strategic assets, export controls could limit the ability of investors to benefit from global markets, especially in countries with strict export regulations like the U.S. and China.
- In 2019, the U.S. government placed Huawei on a trade blacklist due to concerns about national security risks. The geopolitical tensions surrounding Huawei's 5G technology raised concerns about the potential consequences for investors. Companies invested in 5G technologies faced uncertainty as a result of trade restrictions and export bans, which affected both the technology and its broader market adoption.

8. Ethical and Social Risk

[§§]https://archive.epic.org/privacy/data-breach/equifax/

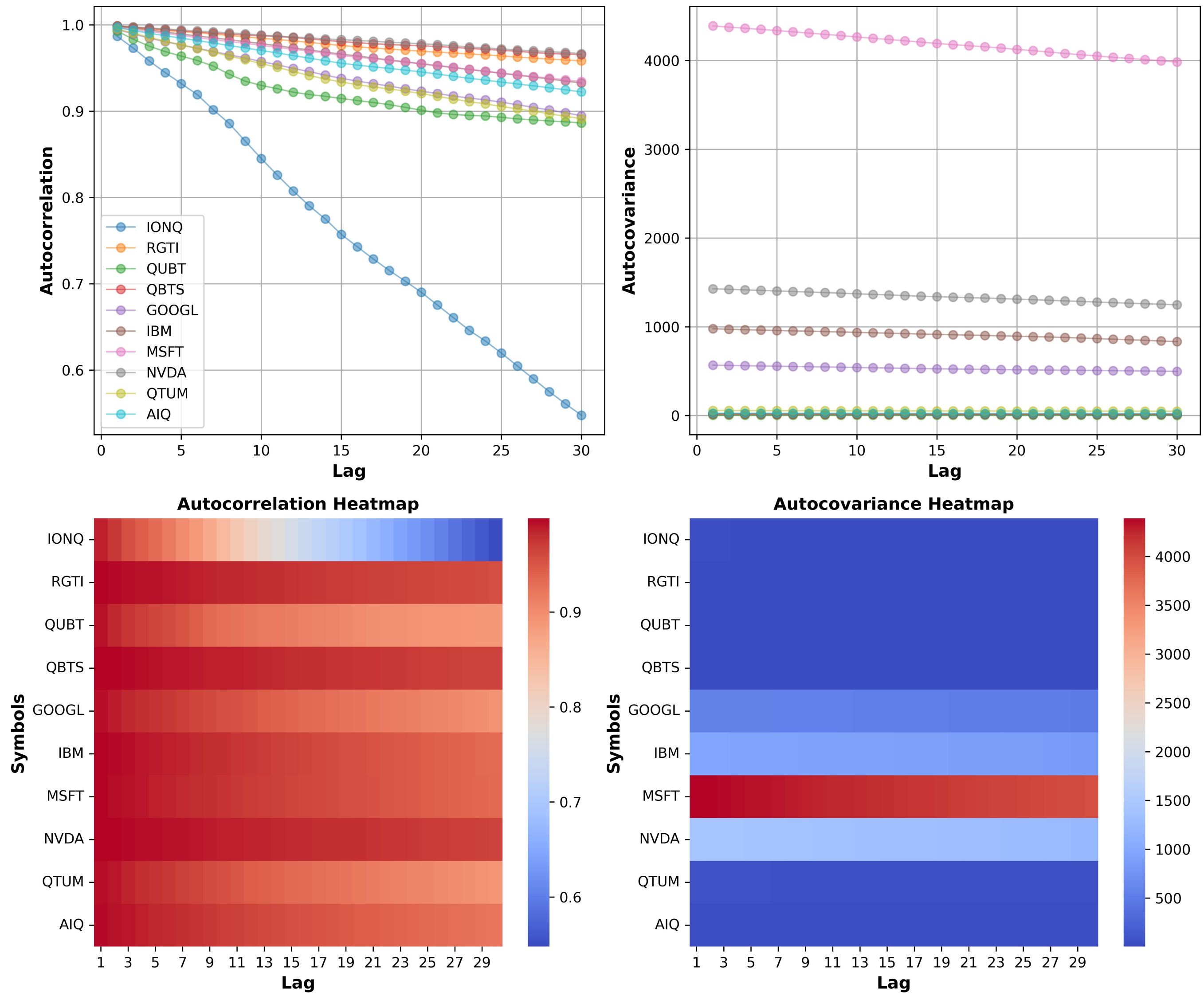

Fig. 6: Autocorrelation and autocovariance of stock prices in Table 3 computed using lag of one to thirty trading days

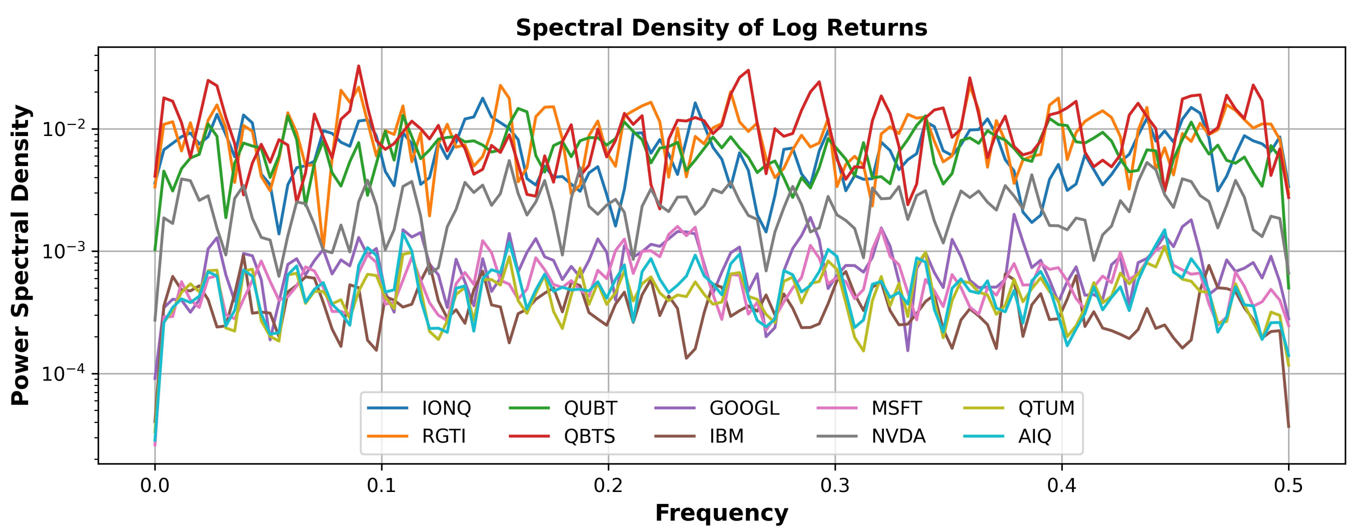

Fig. 7: Power spectral density of stock price in Table 3

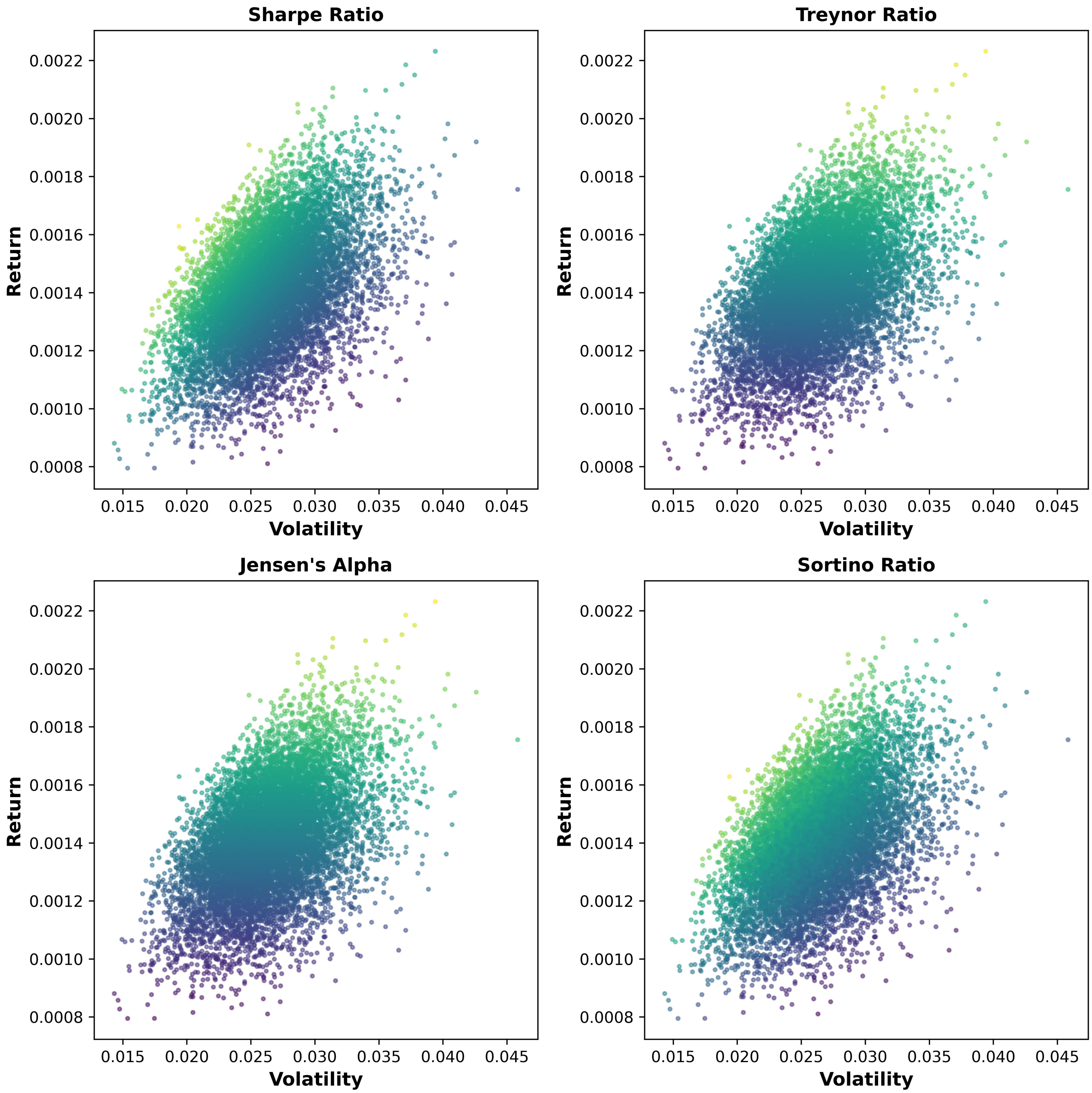

Fig. 8: Efficient frontier of portfolio optimization using indices in Table 3. We use $10,000$ independent runs to simulate the best portfolio based on four metrics: Sharpe, Treynor ratio, Jensen's Alpha and Sortino ratio

- **Inequality in Access**: If quantum technologies are monopolized by a few companies or governments, it could lead to unequal access, causing ethical concerns about fairness and equity. This might influence public perception and affect the long-term success of quantum-based investments.
- The widespread use of facial recognition technology has raised significant ethical concerns about privacy and civil liberties. For instance, in 2020, the city of San Francisco banned the use of facial recognition by city agencies due to concerns about racial profiling and surveillance. This decision underscores the social risks related to emerging technologies that can infringe upon personal freedoms.

4.2.2 Risk Management Process

We construct a process to manage the identified risks by the *first principle approach*, which breaks down complex issues into their most fundamental parts and then rebuilding them from the ground up.

1. **Identify:** The first step in risk management involves identifying the specific risks associated with investing

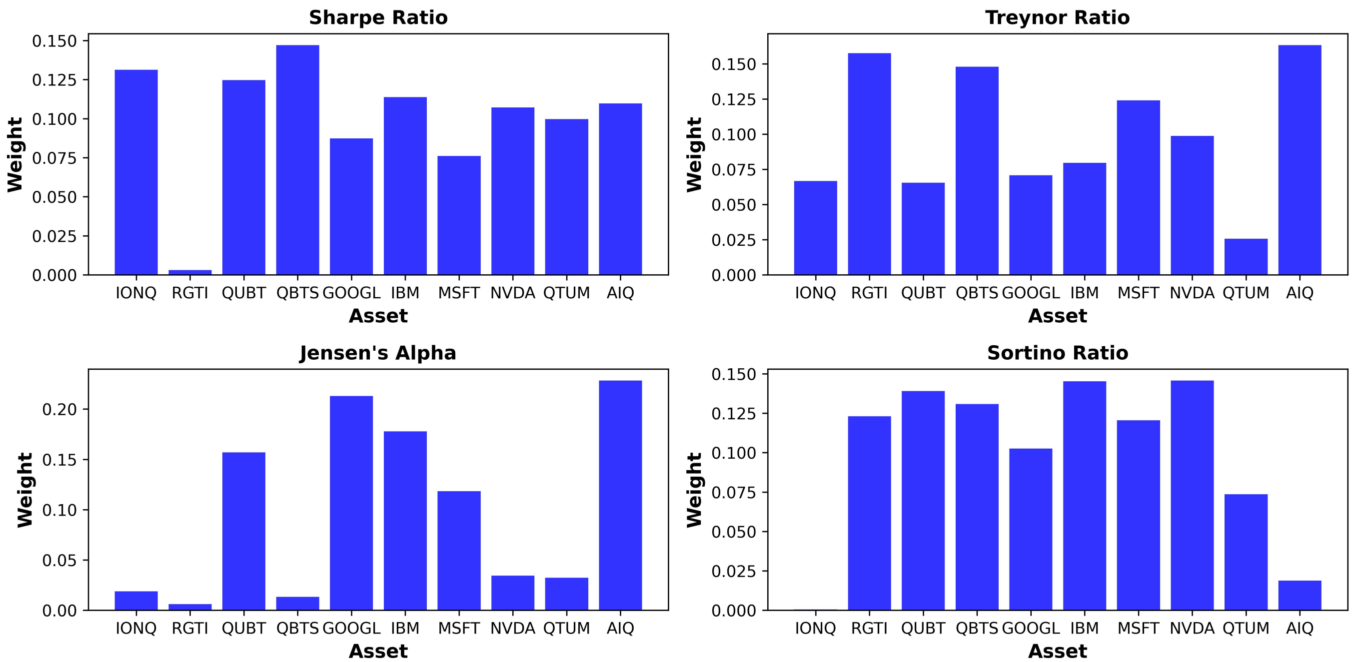

Fig. 9: The weight of best portfolio found using the same simulation in Figure 8

in quantum technologies. These risks may come from multiple sources, such as technological uncertainty, market volatility, regulatory changes, or potential security breaches. We have discussed the potential risks in Section 4.2.1. There are eight types of risks in our proposed taxonomy. For each category of risks, we give detailed discussions of their causes. Besides, we also refer to incidents with similar risk category, which could provide merit insight for how to further manage these risks.

2. Analyze: **Rank** the identified risks based on their potential severity and likelihood. This could be done using a risk matrix that helps to prioritize which risks need immediate attention. We summarize the risk severity and likelihood in Table 4 and the associated risk matrix in Table 5. Quantifying risks with **scores** can help to track their relative importance. For instance, using a scale from 1 (low risk) to 5 (high risk), assign each risk a score based on its likelihood of occurring and its potential impact (Table 6). A risk with a 4 or 5 score should be addressed immediately.

- Risks with a **total score of 25** are critical and require **immediate attention** (e.g., Regulatory, Market, and Cybersecurity Risks).
- Risks with scores between **15 and 20** are **high-priority** but may be addressed after critical risks (e.g., Geopolitical Risk).
- Risks with scores between **10 and 15** can be **monitored proactively** and addressed in due time (e.g., Technological, Operational, and Financial Risks).
- Risks with scores below **10** can follow a **long-term strategy** (e.g., Ethical and Social Risk).

To **measure** the potential exposure to each risk for quantum technologies, we can adopt a structured approach using three main dimensions: Investment Amounts, Cost of Failure, and Probability of Occurrence (Table 7).

1) **Investment Amounts**
   - **Definition:** The total financial resources allocated to the risk area.
   - **Example:** Investments in quantum R&D, quantum startups, or cybersecurity frameworks.
   - **Measurement:** Use actual investment data or budgeted amounts.
2) **Cost of Failure**
   - **Definition:** The financial impact if the risk materializes.
   - **Example:** Loss of investment in a failed quantum startup, compliance costs due to new regulations, or market loss due to cybersecurity breaches.
   - **Measurement:** Estimate potential costs through scenario analysis or industry benchmarks.
3) **Probability of Occurrence**
   - **Definition:** The likelihood of the risk event occurring.
   - **Example:** Regulatory intervention in quantum applications, cybersecurity threats, or technological obsolescence.
   - **Measurement:** Assign probabilities based on historical data, expert judgment, or predictive models.

Insights: From Table 7, the highest potential exposure is from market risk and regulatory risk, indicating the need for immediate strategies to mitigate these risks. Technological risk has significant exposure, reflecting the high R&D investments required for quantum advancements. Cybersecurity risk remains a critical

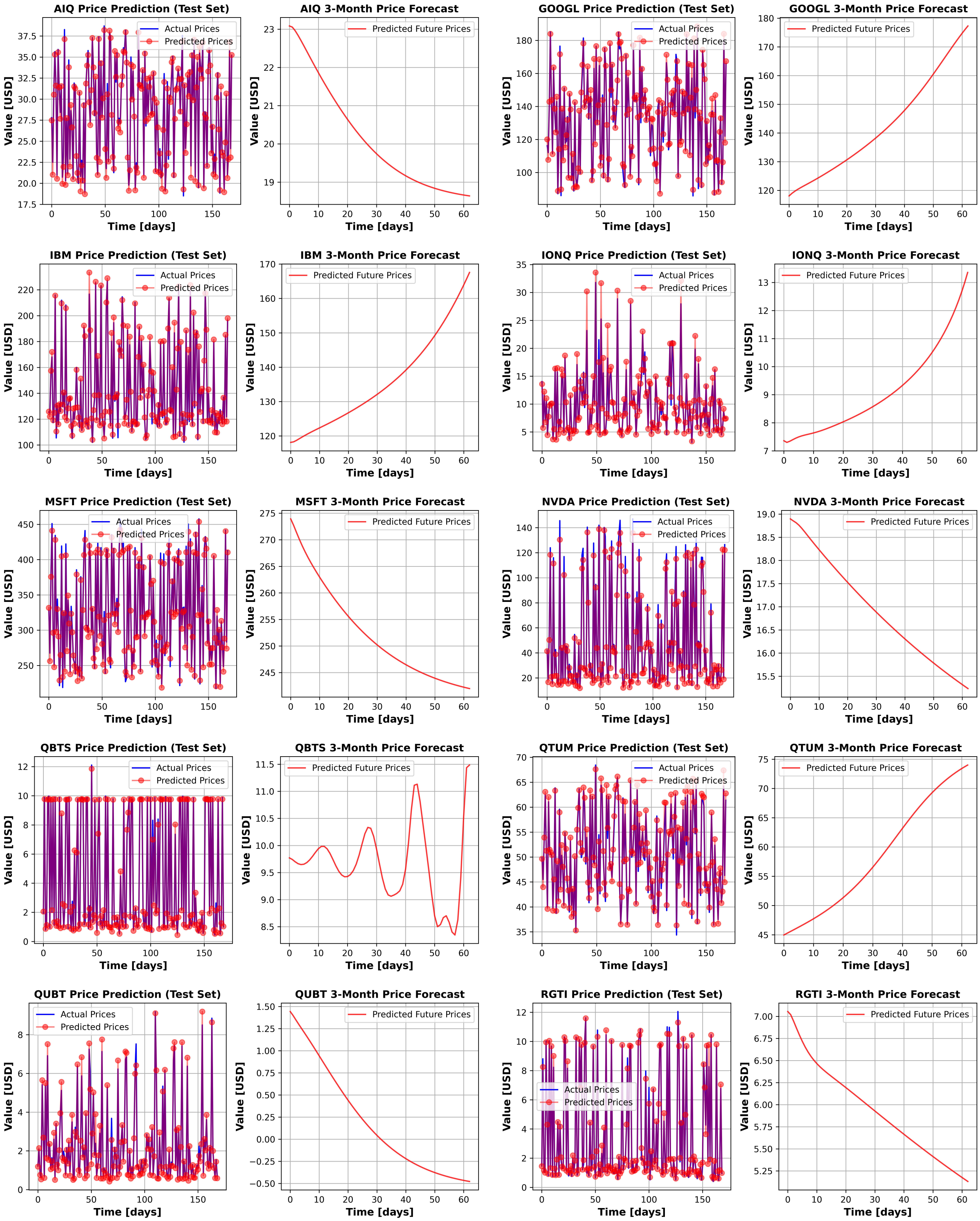

Fig. 10: The stock price predicitons using RNNs. Left panels show the prediction on test set, while right panels show the forecast in the next 3 months (Q1-2025, 63 days)

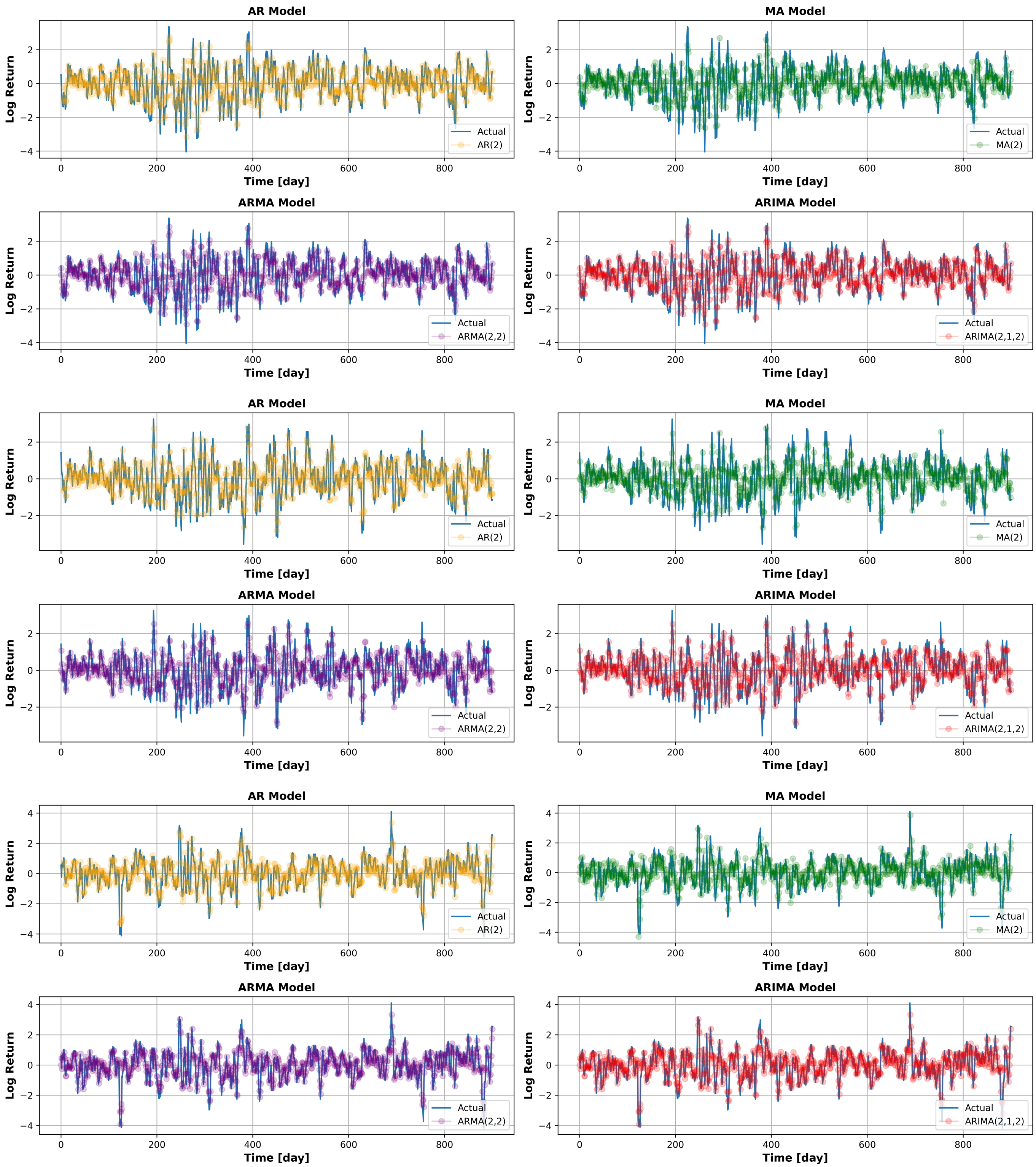

Fig. 11: The numerical results using AR, MA, ARMA and ARIMA to model the log return of AIQ and IBM

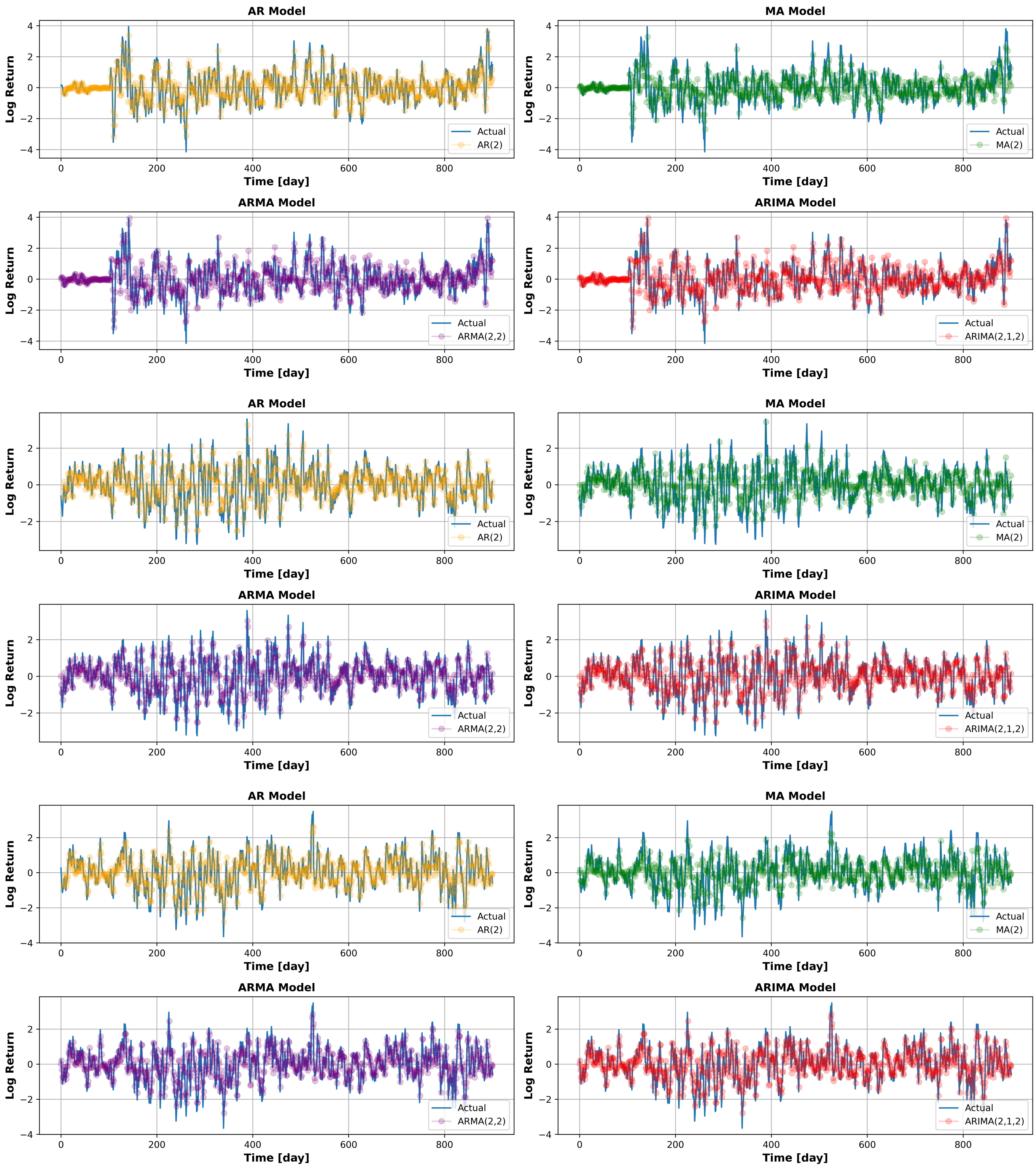

Fig. 12: The numerical results using AR, MA, ARMA and ARIMA to model the log return of IONQ, MSFT and NVDA

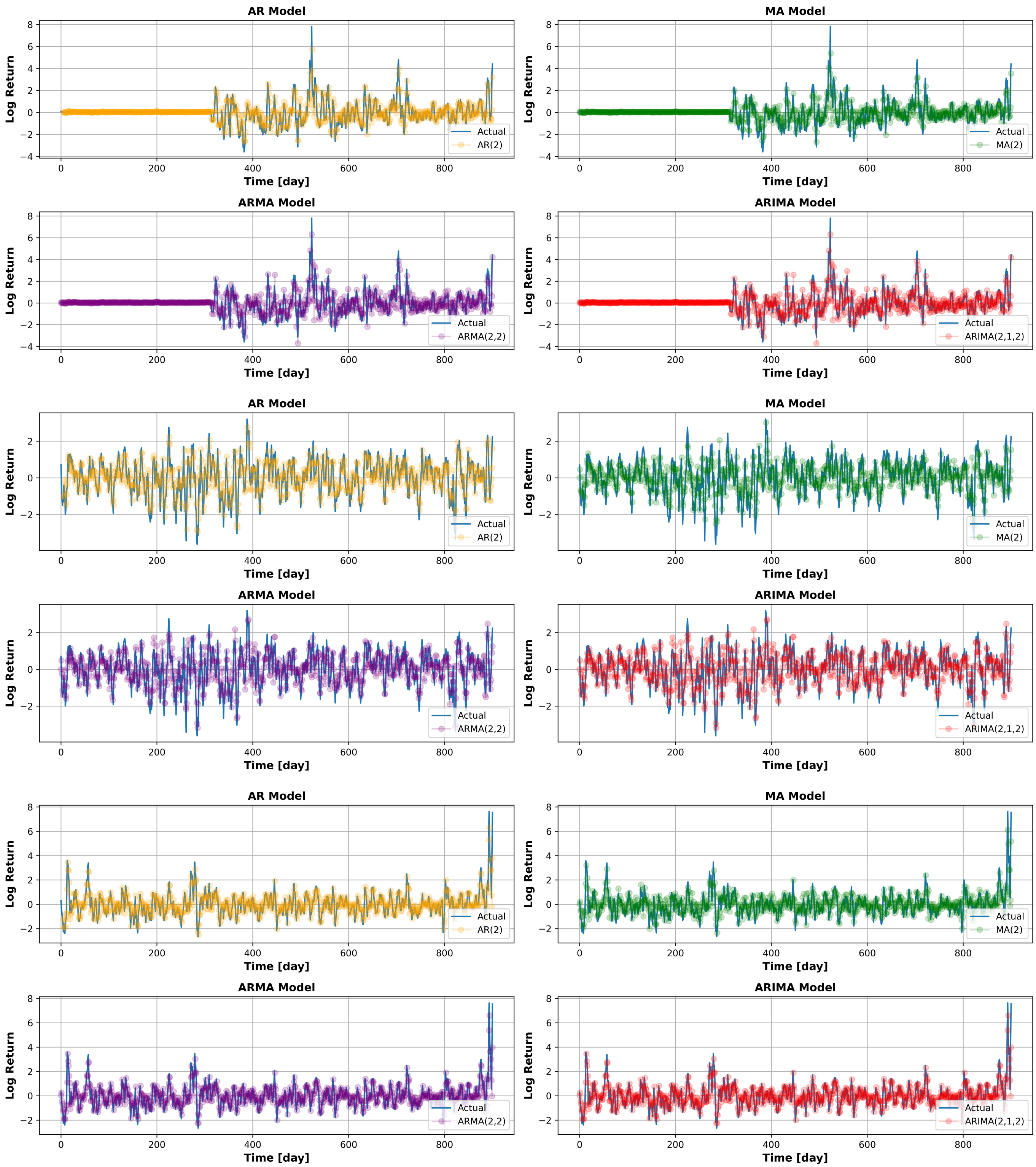

Fig. 13: The numerical results using AR, MA, ARMA and ARIMA to model the log return of QBTS, QTUM and QUBT

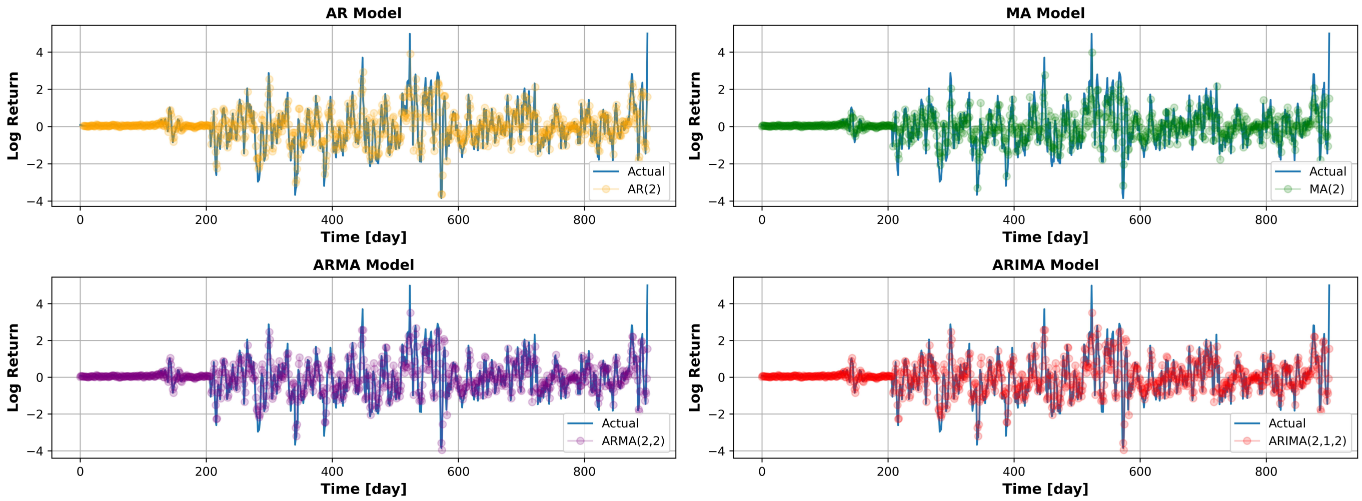

Fig. 14: The numerical results using AR, MA, ARMA and ARIMA to model the log return of RGTI

concern due to its high probability and potential costs.

3. **Assess Impact:** Each of the identified risks in quantum technology has both direct and indirect effects that can impact investors, companies, and the broader industry. These effects can range from immediate financial losses to long-term reputational damage and market shifts, summarized in Table 9. Each of the identified risks has cascading effects that can escalate from a single incident into a broader set of challenges for a company or the industry as a whole (Table 10). These secondary effects can lead to delayed product releases, financial losses, loss of market leadership, and even reputational damage. For investors and companies, understanding these cascading risks is crucial to developing risk mitigation strategies that include contingency planning, diversified investment portfolios, and a strong focus on regulatory compliance to minimize negative outcomes. The quantum industry must remain agile, prepared for the possibility that risks will compound and require rapid responses. The long-term consequences of risks associated with quantum technology investments can be profound, extending far beyond immediate financial losses (Table 11). These consequences often manifest in industry-wide setbacks, shifts in public perception, regulatory overhauls, and strategic realignments. Let's evaluate the long-term repercussions of each identified risk, considering how they could shape the quantum technology ecosystem over the next decade or more.
4. **Manage:** The discussed risks could be managed by the ARMT principles: Avoid, Retain, Mitigate and Transfer, with is summarized in Table 12. Investors should avoid high-uncertainty investments, particularly those involving unproven quantum hardware that lacks the necessary infrastructure. These ventures carry significant risk and may not yield returns in the short term. Besides, retaining manageable risks offers potential for long-term rewards. For example, investing in early-stage quantum research can be risky due to technological uncertainty but presents opportunities for substantial advancements in the future. Investors can also mitigate risks by taking proactive measures to reduce their potential impact. This includes investing in research to address technological challenges, building diversified portfolios to avoid over-dependence on any single technology (like quantum computing), and implementing robust cybersecurity practices to safeguard intellectual property and sensitive data. Finally, transferring risks involved in quantum technology's investment is similar to other fields, which is through mechanisms such as contracts, insurance, or strategic partnerships. For instance, risks related to market volatility can be hedged through financial derivatives, or technological and operational risks can be shared via joint ventures. By combining these approaches, investors can effectively manage risks while positioning themselves to benefit from the emerging quantum technology sector.
5. **Construct Reliable and Efficient Derivatives Market:** A derivatives market for quantum technologies could allow investors to hedge their exposure to risks associated with price fluctuations in quantum technology stocks or the market for quantum computing services. To mitigate the risks outlined in the Table 4, a range of financial derivatives can be designed to hedge against specific types of risks. Below are some proposed derivative instruments tailored for each risk type:

   1. Technological Risk:
   - **Technology Futures Contracts**: These contracts could be based on indices representing the market performance of technology firms or specific technologies (e.g., AI, blockchain). Investors can use these futures to hedge against the risk of technological obsolescence or failure to develop new products.
   - **R&D Cost Insurance**: A derivative where firms insure against unexpected increases in R&D expenses, which could help mitigate the financial risk arising from technology development.

   2. Regulatory Risk:

- **Regulatory Risk Swaps**: Similar to credit default swaps, these could allow firms to exchange cash flows based on the likelihood of a regulatory change or compliance cost increases. This can provide firms with a buffer against regulatory uncertainty.
- **Compliance Cost Options**: These options would provide financial protection for firms if their compliance costs exceed a predetermined threshold due to new or changing regulations.

3. **Market Risk:**
   - **Demand-Driven Futures**: Futures contracts that are tied to specific market demand indices or adoption rates of a product or technology. Firms could use these instruments to hedge against the risk of delayed market adoption or lack of demand.
   - **Market Volatility Options**: These would allow firms to profit from or hedge against volatility in adoption rates or market conditions surrounding the product or technology.
4. **Operational Risk:**
   - **Supply Chain Derivatives**: A form of insurance or futures contract based on the performance of key suppliers or logistic providers. These could help companies hedge against supply chain disruptions or talent shortages.
   - **Human Capital Derivatives**: These could be based on labor market indices or specific skill sets, providing firms with financial protection if they cannot access the required talent or experience shortages.
5. **Financial risk:**
   - **R&D Expense Derivatives**: These could be designed to hedge against unexpectedly high R&D costs. They would be based on the volatility or certainty of projected R&D expenditure and valuations.
   - **Investment Risk Swaps**: These swaps would allow firms to exchange the risk of high R&D costs or poor valuation against a stable, pre-agreed payout.
6. **Cybersecurity and Privacy Risk:**
   - **Cybersecurity Risk Futures**: Futures based on cybersecurity events or indices tracking cyberattack frequency and severity. Companies could use these to hedge against data breaches or cryptographic vulnerabilities.
   - **Data Breach Insurance Derivatives**: A form of derivative that provides financial protection to firms in the event of a major data breach, based on the scale and impact of the breach.
7. **Geopolitical Risk:**
   - **Geopolitical Risk Swaps**: Similar to currency swaps, these would be based on geopolitical stability indices, allowing firms to hedge against risks like trade restrictions, tariffs, and national security concerns.
   - **Geopolitical Event-Linked Bonds**: These bonds would be linked to specific geopolitical events, and payouts could vary depending on the occurrence of trade wars, conflicts, or other geopolitical disruptions.
8. **Ethical and Social Risk:**
   - **Social Responsibility Options**: Options that allow firms to hedge against the risk of public backlash related to social responsibility issues. This could be tied to the company's CSR (Corporate Social Responsibility) performance or a broader social sentiment index.
   - **Public Opinion Hedging Contracts**: These contracts could be tied to sentiment indices or social media analytics, providing firms with financial protection if public backlash results in financial losses.

4.3 Scenario Analysis

Scenario 1: High growth and early adoption

Assumptions:

1) Breakthroughs in quantum computing lead to practical applications in logistics, pharmaceuticals, and finance within the next five years.
2) Regulatory frameworks adapt swiftly to enable growth while addressing ethical and cybersecurity concerns.
3) Market demand for quantum-based encryption solutions surges as companies prepare for post-quantum cybersecurity threats.

Risk Assessment:

- Technological Risk: Reduced due to successful advancements, but obsolescence remains a threat as newer quantum architectures emerge.
- Regulatory Risk: Favorable regulations encourage investment, but minor delays could arise in global standardization.
- Market Risk: Initial adoption by industries like finance and healthcare provides momentum, mitigating demand uncertainties.
- Operational Risk: Supply chain bottlenecks could slow scalability, but partnerships with major technology providers reduce this impact.
- Financial Risk: Early investors experience high returns, but later-stage entrants face steep capital requirements.
- Cybersecurity and Privacy Risk: Increased spending on quantum-safe encryption technologies balances potential risks of cryptographic vulnerabilities.
- Geopolitical Risk: Countries collaborate on shared research initiatives, easing geopolitical tensions.
- Ethical and Social Risk: Early discussions on equitable access and ethical use reduce societal pushback.

Outcome: High returns for early investors, but continued vigilance on obsolescence and operational challenges is required.

Scenario 2: Regulatory hurdles and delayed adoption

Assumptions:

1) Regulatory bodies implement stringent policies for quantum technologies due to privacy and national security concerns.
2) Industry adoption lags as companies struggle to integrate quantum solutions into existing workflows.
3) A major cybersecurity breach linked to quantum computing raises alarm among stakeholders.

Risk Assessment:

- Technological Risk: Delays in commercial readiness due to regulatory scrutiny slow innovation.
- Regulatory Risk: Uncertain and fragmented regulations across jurisdictions create compliance challenges and increase costs.
- Market Risk: Slow market adoption exacerbates uncertainties, limiting immediate revenue potential.
- Operational Risk: Shortages of skilled talent and specialized infrastructure persist, driving up operational costs.
- Financial Risk: Investors face prolonged timelines for returns, causing overvaluation concerns for startups.
- Cybersecurities and Privacy Risk: Increased focus on mitigating quantum-enabled breaches, diverting resources from other innovations.
- Geopolitical Risk: Trade restrictions and export controls limit global market opportunities.
- Ethical and Social Risk: Public concerns over privacy and inequality heighten resistance to widespread deployment.

Outcome: Moderate to low returns, with significant financial strain on smaller players. Strategic alliances and regulatory lobbying are critical.

Scenario 3: Technological stagnation and market disruption

Assumptions:

1) Key technological challenges, such as error correction in quantum computing, remain unresolved for over a decade.
2) Competing technologies (e.g., advanced AI or classical computing enhancements) provide comparable solutions at lower costs.
3) Political tensions over quantum technology escalate, disrupting global supply chains.

Risk Assessment:

- Technological Risk: Prolonged stagnation increases the likelihood of obsolescence and diverts investments to alternative innovations.
- Regulatory Risk: Governments impose restrictive measures to curb speculative investments in unproven technologies.
- Market Risk: Market demand declines as industries lose confidence in the viability of quantum solutions.
- Operational Risk: Supply chain disruptions and talent shortages exacerbate delays, reducing investor confidence.
- Financial Risk: Significant capital outlays result in sunk costs, with limited exit options for investors.
- Cybersecurity and Privacy Risk: Limited progress in quantum-safe technologies leaves industries vulnerable to long-term risks.
- Geopolitical Risk: Intensified trade wars and national security concerns prevent international collaboration.
- Ethical and Social Risk: Public skepticism about the viability and ethics of quantum technologies further deters investments.

Outcome: Low or negative returns, with widespread consolidation among firms. Only well-diversified investors avoid significant losses.

Scenario 4: Balanced development and strategic growth

Assumptions:

1) Steady progress in quantum technology allows gradual commercialization without overpromising capabilities.
2) Public-private partnerships foster innovation while mitigating risks.
3) Ethical, social, and regulatory frameworks evolve in tandem with technological advances.

Risk Assessment:

- Technological Risk: Managed through incremental advancements and industry collaboration.
- Regulatory Risk: Proactive engagement with policymakers ensures favorable conditions for growth.
- Market Risk: Slow but steady adoption across industries aligns with realistic forecasts.
- Operational Risk: Investments in talent development and supply chain resilience reduce delays.
- Financial Risk: Balanced R&D spending and realistic valuations attract sustainable investments.
- Cybersecurities and Privacy Risk: Focused development of quantum-safe technologies enhances confidence.
- Geopolitical Risk: Collaborative research initiatives mitigate tensions, encouraging global market access.
- Ethical and Social Risk: Transparent practices and equitable access reduce societal resistance.

Outcome: Moderate returns with lower risk exposure. Long-term investors benefit from gradual market maturity.

Investing in quantum technology presents a high-risk, high-reward landscape influenced by technological progress, regulatory dynamics, and market readiness. Risk mitigation strategies include diversifying investments, engaging in public-private partnerships, and monitoring regulatory developments. For a balanced portfolio, investors should combine quantum investments with less speculative sectors to offset potential losses.

5 A Quantitative Risk Assessment

5.1 Exploratory Data Analysis

We report the preliminary data analysis of stock prices of Table 3 in Figure 1. In the diagonal plots, the time-series of stock prices from $04/22/2021$ to $11/25/2024$ of the ten indices are shown, including 906 observations. We observe a significant increase in all assets, except RGTI and QBTS. The off-diagonal panels show the scatter plots of stock prices. Notably, the AIQ (ETF) is positively correlated with GOOGL, IBM, MSFT, NVDA and QTUM but negatively correlated with IONQ, RGTI, QUBT and QBTS. Besides, giant tech's stocks GOOGL, IBM and NVDA are also positively correlated. In Figure 2, RGTI, QUBT and QBTS are highly correlated (with ρ from 0.76 to 0.91) but these assets have negative correlation with other index, except IONQ with very minimal correlation. On the other hand, GOOGL, IBM, MSFT, NVDA, QTUM and AIQ stocks are highly correlated, indicates a double sword-ed effects on investors:

Advantage: When an asset in the portfolio constructed from GOOGL, IBM, MSFT, NVDA, QTUM and AIQ stocks increase, the other might increase as the shown positive correlation.

Disadvantage: Investors might expose with systematic risk (market risk or undiversifiable risk) when invests on to "too big to fail" (TBTF) companies such as GOOGLE, IBM, MSFT and NVDA. It could be a ripple effect when the stock price of a tech giant falls, the other will significantly decrease.

5.2 Stationary Analysis

A *stationary process* has properties (mean, variance, and autocovariance) that do not change over time. Stock prices are usually non-stationary (due to trends and volatility changes), but we can analyze returns or transform the data to make it stationary. With the portfolio of quantum technology, we pre-processing the time-series of close price using the following steps:

1) We convert stock prices P_t to log returns:
$$r_t = \ln(P_t) - \ln(P_{t-1}) \tag{1}$$
Log returns are often stationary because they remove trends and scale effects.
2) We use Augmented Dickey-Fuller (ADF) to assess stationarity.

The analysis of the ADF test results (Table 13) indicates the quantified stocks (Table 3) exhibit stationarity. These stock prices are stationary, meaning their time series are stable and do not exhibit a unit root or persistent trends over time[¶¶], which is essential for certain time series models and forecasting techniques. We show that classical models such as AR, MA, ARMA and ARIMA models can effectively model the log return of these stocks, depicted in Figure 11. The corresponding parameters of these models is given in Table 13.

5.3 Modeling Volatility with GARCH Process

GARCH (Generalized Autoregressive Conditional Heteroskedasticity) is a statistical model used to analyze and forecast time-series data with time-varying volatility, commonly observed in financial markets []. The numerical results of fitting GARCHC(1,1) model for assets in Table 3 are depicted in Figure 3. Use use python package `arch` for the evaluation. The actual standard deviation (volatility) is scalded by $1,000$ times for numerical stability; thus, the y-axis show the values of $10^3\sigma$, where σ is the actual volatility computed from the stock prices. QUBT and QBTS expose to a high volatility in Q4-2025 and Q3-2024, respectively. However, such quantities are saturated below 0.2 over the observing horizon, similar to IONQ and RGTI. Giant tech's stock prices (GOOGL, IBM, MSFT and NVDA) have a significantly small risk compared to QUBT, QBTS, IONQ and RGTI. Of note, IBM's stock price not only has small volatility (just under 0.015), but the risk is nealy unchanged since Q1-2022 to the present. Besides, MSFT, QTUM and AIQ stock's volatility also reduce since Q1-2023 to the present.

[¶¶]A unit root refers to a property of a time series where past shocks have a lasting impact, causing the series to wander or exhibit random walks without returning to a mean. A persistent trend describes a time series that consistently moves in one direction over time, often due to long-term forces or shocks.

5.4 Distance between Stocks

The distance between stocks is defined as the Euclidean distance between the normalized quantity r_t in Equation 1. In Figure 4, we show the heatmap of pair-wise distance between stock prices, followed by the minimum spanning tree (MST) derived by Kruskal's algorithm []. The MST reflects the most significant relationships between stocks based on minimal total pairwise distances. Clearly, NVDA, QTUM and AIQ forms a cluster, for which the distance is below 30, depicted in Figure 5. GOOGL and MSFT is also in this cluster (the red brach in Figure 5) but in another branch from QTUM and AIQ.

The hierarchical clustering dendrogram in Figure 5 complements the MST by stratifying stocks into clearly defined clusters. The yellow branch (QBTS and RGTI) and green branch (IONQ and QUBT) reflect isolated but tight-knit stock behavior. These branches likely correspond to niche or emerging industries. The red branch reveals broader interconnections, splitting into two groups:

Group 1 NVDA, QTUM, and AIQ — stocks that may share strong market or sectoral influences.

Group 2 GOOGL and MSFT — part of the technology sector, yet differing slightly in dynamics compared to the NVDA-QTUM-AIQ cluster.

From these above evidence, we have three investment implications:

Cluster analysis for portfolio diversification: To reduce risk, investors should consider stocks from different clusters. For instance, pairing stocks like QBTS/RGTI with NVDA/QTUM/AIQ may balance portfolio exposure.

Sector correlations: The clustering of GOOGL and MSFT suggests shared market drivers, making them suitable for thematic investment strategies, e.g., focusing on big tech.

Emerging trends: The tight correlation between stocks like IONQ and QUBT may indicate emerging trends, possibly in quantum computing or related sectors. Investors may want to monitor these for high-growth opportunities.

5.5 Correlation Analysis

In this analysis, we highlights the temporal dynamics of different stocks, offering insights into their behavior over time (Figure 6). Stocks with high and consistent autocorrelation/autocovariance are ideal for long-term positions, while those with weaker metrics might be leveraged for tactical trading. These findings can guide portfolio allocation, balancing risk, and opportunity.

Autocorrelation analysis: IONQ exhibits the steepest decline in autocorrelation with lag, suggesting a low persistence of price movements over time. This behavior might indicate higher volatility or lack of strong trends in its returns. Other assets show slower declines, implying higher momentum or smoother trends in their price movements. RGTI, QBTS and NVDA maintain consistently high autocorrelation across all lags, reflecting strong temporal dependencies, possibly due to sector-specific influences or predictable trading patterns.

Autocovariance analysis: MSFT stock is significantly higher compared to other stocks, indicating larger variances in their absolute price levels while still maintaining some degree of dependency over time. IONQ, RGTI, QUBT, QBTS, QTUM and AIQ have relatively low autocovariance values, reflecting smaller absolute price movements or less pronounced trends.

Investors seeking momentum strategies might focus on stocks like NVDA, MSFT, and GOOGL, as their high autocorrelation suggests persistence in trends over time. Conversely, all other stocks might be better suited for short-term trading strategies given their low persistence and high variability. Low autocovariance stocks (IONQ, RGTI, QUBT, QBTS, QTUM and AIQ) could signify higher risks but also higher potential returns, appealing to risk-tolerant investors. Stable autocovariance in MSFT, GOOGL, NVDA and IBM implies they may serve as more reliable components of a portfolio focused on stable returns. Investors should be cautious about stocks with declining autocorrelation and low autocovariance (e.g., IONQ) as these may not offer predictable returns, increasing the need for diversification.

5.6 Spectral Density Analysis

The spectral density analysis underscores the varying characteristics of these stocks in terms of their volatility, stability, and cyclical behavior. Stable, large-cap stocks offer predictability and lower risk, whereas speculative stocks present opportunities for higher, albeit riskier, returns.

IBM stock (dominant frequency (df) of 0390625) exhibits slow-moving trends, meaning price changes are dominated by long-term fluctuations. This could indicate stability or less frequent oscillations in the stock's returns. IONQ (df: 0.14453125), RGTI (df: 0.15234375), QUBT (df: 0.16015625) stocks exhibit moderate oscillations, suggesting a balance between short- and long-term fluctuations. This may indicate stocks with medium volatility cycles, where neither trend nor noise is overwhelmingly dominant. QTUM and AIQ have higher dominant frequencies, implying more rapid price changes or higher short-term volatility. These stocks are likely influenced by short-term market dynamics or external shocks. GOOGL (df: 0.37890625) and MSFT (df: 0.23046875) exhibit relatively high dominant frequencies, indicating that their returns are subject to faster oscillations. This could reflect the high sensitivity of tech stocks to news, innovation cycles, or market sentiment. The frequencies provided are fractions of the sampling frequency (assumed to be 1 cycle per day if daily data). For example, $0.14453125 \approx \frac{1}{7}$, suggesting a periodic component with a cycle of approximately 7 days in IONQ returns. From this analysis, we can recognize two marker behaviors:

Low-frequency dominance The observation on IBM reflects long-term investor behavior, potentially driven by fundamentals.

High-frequency dominance The analysis on QTUM, AIQ, GOOGL and MSFT stock reveals speculative behavior, algorithmic trading, or sensitivity to high-frequency external signals.

Then, we have three recommendations for investors:

1) *Low-frequency stocks* (IBM) is suitable for long-term investors focusing on stability and their risk is generally tied to market trends and macroeconomic conditions.
2) *Moderate-frequency stocks* (e.g., IONQ, RGTI, QUBT) are Likely to exhibit balanced risk profiles and they are Ideal for medium-term strategies, capturing oscillations without excessive noise.
3) *High-frequency stocks* (e.g., QTUM, AIQ, GOOGL and MSFT) are Riskier due to rapid price oscillations and they are the best suited for day trading or high-frequency trading strategies.

5.7 Portfolio Analysis

We perform portfolio analysis in this section, reported in Figure 8 and 9. Figure 8 depicts a visualization of portfolio optimization results, showing scatter-plots of portfolio returns versus volatility, evaluated using four different metrics: Sharpe Ratio, Treynor Ratio, Jensen's Alpha, and Sortino Ratio. Each point represents the outcome of a portfolio simulation, and the data is based on $10,000$ independent runs. We use the annual risk-free rate of 5%, which is equivalent to approximately 0.02% daily risk-free rate.

The top left plot of Figure 8 suggests a generally positive relationship between return and volatility, with higher Sharpe and Sortino rations likely clustered in regions where volatility is less than $\sigma = 0.03$ and returns are above 0.0014. Unlike the Sharpe Ratio, portfolios with higher Treynor Ratios and Jensen's Alpha likely exhibit a higher returns (above 0.0016) with higher exposure to market risk (above $\sigma = 0.03$). Hence, we recommend that risk-averse investors may prioritize the Sortino Ratio to minimize downside risks, while market-risk-sensitive investors may focus on Treynor Ratio or Jensen's Alpha.

The portfolio optimized for the Sharpe Ratio achieved the highest risk-adjusted returns, with an expected annualized return of 38.89% and a corresponding annualized volatility of 41.17%. This reflects a well-balanced portfolio that maximizes excess return relative to total portfolio risk (volatility). It is ideal for investors seeking overall efficiency in balancing returns and risks across the entire portfolio. The Treynor Ratio optimization resulted in a portfolio with an expected annualized return of 32.73% and annualized volatility of 44.64%. While the return is slightly lower than the Sharpe-based portfolio, this metric focuses on systematic risk (beta). As such, it highlights the performance of the portfolio relative to the market. This portfolio is particularly suited for investors who prioritize returns while being mindful of market risk exposure. The Jensen's Alpha portfolio produced an expected annualized return of 28.03% and an annualized volatility of 30.43%. This portfolio emphasizes excess returns above the Capital Asset Pricing Model (CAPM) benchmark. It demonstrates the potential for active management strategies to deliver alpha. Investors seeking to outperform market expectations, while tolerating moderate volatility, may favor this portfolio. The portfolio optimized for the Sortino Ratio achieved an expected annualized return of 36.28% with an annualized volatility of 42.65%. By focusing solely on downside risk, the Sortino Ratio provides a clearer picture of risk-adjusted returns when avoiding negative performance is a priority. This portfolio is ideal for risk-averse investors seeking strong returns while minimizing exposure to downside volatility.

Figure 9 depicts the asset weights of the optimal portfolios derived from the simulations in Figure 8. The Sharpe, Treynor and Sortino ratio portfolio is highly diversified, for which diversification is present but favors assets with higher contributions to risk-adjusted returns. These allocations suggest a focus on assets that provide a strong balance of return relative to total volatility. The emphasis on systematic risk (beta) in the Treynor Ratio leads to a similar, yet distinct allocation compared to the Sharpe Ratio portfolio. The high weights for AIQ, RGTI and QBTS imply their superior performance in relation to market risk. In contrast, the portfolio derived from Jensen's Alpha has low diversification, which features a heavy allocation to AIQ, GOOGL, IBM, QUBT and MSFT, with smaller contributions from other stocks.

Certain assets, like MSFT and QBTS, consistently receive substantial weights across all portfolios. This suggests these assets are strong contributors to overall portfolio performance, irrespective of the evaluation metric. IONQ stock is consistently assigned minimal weights, except in the portfolio using Sharpe ratio. We would like to give two suggestions for further analysis:

Metric selection: Investors should select portfolio metrics aligning with their risk-return preferences. For example, Risk-averse investors might favor the Sharpe, Treynor or Sortino Ratio to limit downside risk. Growth-oriented investors may prioritize Jensen's Alpha for capturing excess returns.

Diversification: While some metrics favor concentrated allocations, incorporating a blend of metrics in the optimization process could provide a more balanced and robust portfolio.

5.8 AI-enabled Stock Price Prediction

Figure 10 illustrates the performance of Recurrent Neural Networks (RNNs) in predicting stock prices. The analysis is divided into two main aspects: (1) the model's performance on the test set (left panels) and (2) the 3-month price forecasts for the first quarter of 2025 (right panels).

For each stock, the RNN model's predictions closely follow the actual price movements, as evidenced by the overlapping red (predicted) and blue (actual) lines. The model demonstrates the ability to capture short-term fluctuations in prices for most stocks, such as GOOGL, IBM, and MSFT, suggesting it can effectively model high-frequency volatility. Certain stocks, such as RGTI and QUBT, exhibit larger deviations between actual and predicted prices, implying potential challenges in modeling their high volatility or limited predictability due to external factors. The overall trends are well-aligned for many stocks, but occasional spikes or dips in the test data are not fully captured, indicating limitations in capturing extreme events.

The 3-month forecasts provide insights into the expected stock price trajectories for Q1-2025, showed in Figure 10. Stocks such as GOOGL, IBM, IONQ, and QTUM are predicted to experience steady growth over the 63-day forecast period. This suggests the RNN model expects a bullish market trend for these assets. Stocks like AIQ, MSFT, QUBT and RGTI show consistent downward price forecasts, reflecting a bearish outlook for these assets in Q1-2025. QBTS stock shows mixed forecasts, with relatively major variations over the prediction period. This implies uncertainty or expected consolidation in price movements. Nevertheless, we find that AI fails to predict NVDA, IONQ and MSFT stocks because the projection is highly deviate from the current price (from above \$100 to just \$19 in NVDA stock).

6 Discussion

6.1 Recommendations for Financial Risk Management of Quantum Technology

In this section, we recommends six principles to construct a *risk management* framework for investments in quantum technology. These principles include understanding risk sources, measuring potential impacts, and aligning with strategic objectives. The following pillar outline a systematic guide for risk management of quantum technology:

1. **Understand the nature of the technologies:** Quantum technology is an emerging field with high potential returns but significant uncertainties, including technological feasibility, market adoption, and regulatory risks. Breakthroughs and commercialization in quantum computing, cryptography, and sensors often require long-term commitment. Quantum projects often intersect with advanced material science, artificial intelligence, and cybersecurity, increasing complexity.
2. **Define risk appetite based on organizational goals:** Investors should establish how quantum technology investments fit within broader organizational goals (e.g., competitive advantage, diversification). Then, deciding on acceptable levels of risk in relation to potential returns is crucial, considering the speculative nature of quantum technologies. Finally, we should align risk appetite with stakeholders' willingness to accept uncertainty in pursuit of innovation and growth.
3. **Implement a dynamic monitoring framework:** We propose to use three main strategies for dynamics monitoring of the risks, which are
   - **Key Risk Indicators (KRIs):** Track technological milestones, market trends, and regulatory changes.
   - **Stress Testing:** Simulate adverse scenarios to assess the resilience of investment portfolios.
   - **Continuous Review:** Adjust risk appetite based on evolving insights, competitive landscape, and emerging opportunities.
4. **Build a risk governance structure:** To managing the risk, we suggest to adopt the following risk governance structure:
   - **Risk Committees:** Form a cross-functional team to oversee quantum investments.
   - **Risk Reporting:** Establish transparent mechanisms for reporting risk exposures and performance to stakeholders.
   - **Ethics and Compliance:** Ensure investments adhere to ethical standards, particularly in areas like quantum cryptography and national security.

6. **Foster a learning organization** To construct a sustainable framework, given the novelty and advancement of quantum technology, we suggest to
   - Encourage ongoing education about quantum advancements.
   - Develop in-house expertise or collaborate with specialists to refine risk assessments.
   - Adapt risk appetite as more empirical data becomes available from quantum technology ventures.

6.2 Recommendations for Using AI to Predict Stock Prices

The RNN-based stock price predictions offer valuable insights into short-term price trends and medium-term forecasts. However, while the model demonstrates strong predictive capabilities for stable and moderately volatile stocks, it requires refinement to improve performance under high-volatility conditions and account for unexpected market shocks. For practical application, we suggest to use predictions as supplementary tools alongside traditional financial analysis. Besides, practitioners can enhance the model by integrating external factors such as macroeconomic indicators or sentiment analysis to improve robustness. Finally, benchmarking neural architectures other from RNNs is a good direction for future research.

7 Conclusion

To this end, we have review the historical developments current trends of quantum technologies in Section 2.1. A risk assessment of the technology is given qualitatively in Section 4 and quantitatively in Section 5. We humbly find that there are substantial number of aspects has not been addressed in this article. Nevertheless, our research provides comprehensive risk assessments with significantly statistical evidence, which is a first good step for future studies. Besides, we also gave the recommendation for practitioners in Section 6, which focuses on a sustainable and reliable risk management framework and the suggestion to adopt frontier technology, i.e. AI for further analysis.