ROTONIUM
MADE OF LIGHT

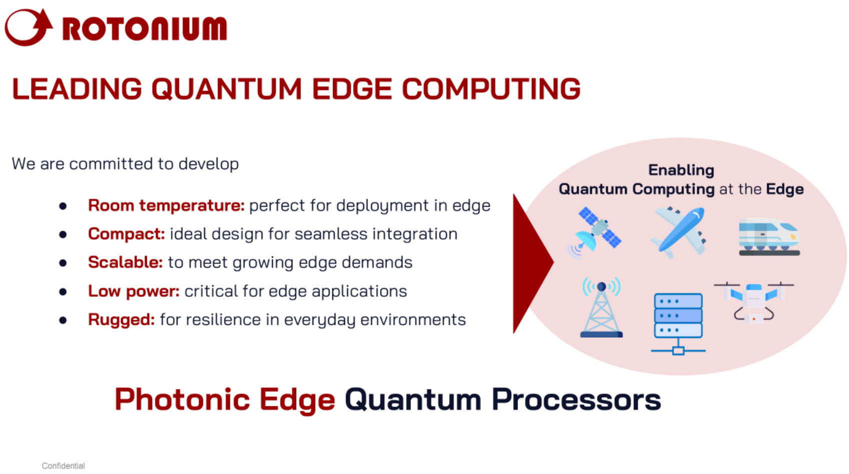
RWP 1G25

White Paper

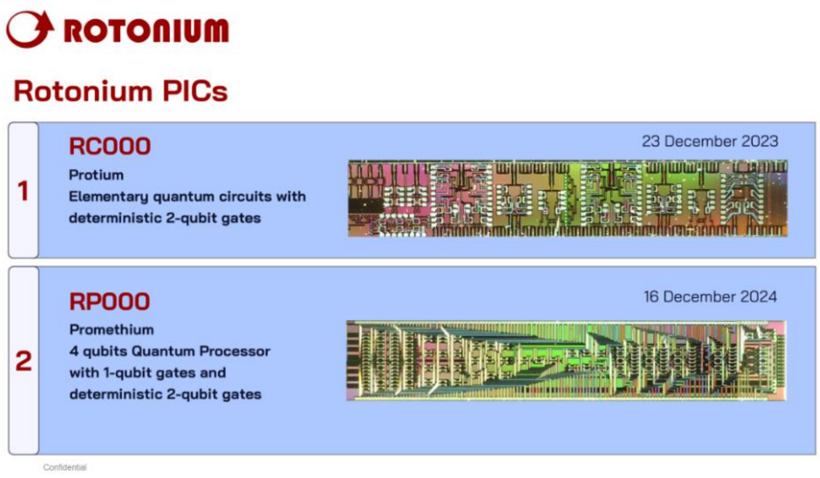
Harnessing Photonic Orbital Angular Momentum for Scalable Quantum Computing

This white paper explores the principles behind photonic orbital angular momentum (OAM), Rotonium's technological advancements, and their application in quantum computing. It outlines our architecture for scalable, room-temperature quantum processors and highlights the path toward edge-compatible quantum acceleration.

Rotonium since 2022 has pioneered a new era in quantum computing by leveraging the Orbital Angular Momentum (OAM) properties of photons. This approach aims to reduce circuit complexity, minimize photon losses, and enhance scalability enabling scalable, room-temperature photonic quantum computers optimized for edge computing applications.



The two basic designs, we have developed, include **Prot-ium** (the name is inspired by Proteus, the mythological master of transformation, an image of flexible, evolving computation), a prototype for OAM-based quantum computers, and **Prometh-ium**, (the name is inspired by Prometheus, who defied the gods to deliver fire, the spark of progress, to mankind) an improved, scalable version implemented on a standard silicon-on-insulator (SOI) platform.



1 Introduction

Quantum computing is evolving rapidly, promising revolutionary advances in computation. Rotonium's photonic quantum computer harnesses photon polarization and orbital angular momentum (OAM) to construct a powerful, scalable quantum computing architecture. This paper details the technical foundations, implementation, advantages, and potential applications of Rotonium's photonic quantum computing platform.

Quantum computing has long promised a revolution in computational power, but existing technologies face challenges such as decoherence, cooling requirements, and scalability. Photonic quantum computing, particularly through OAM, offers a novel alternative. Rotonium aims to develop quantum processors that operate at room temperature while maintaining high coherence and error resistance. By utilizing OAM states, Rotonium aims to significantly enhance the performance and efficiency of quantum systems compared to traditional qubit-based models.

2 Quantum Computing Principles

Quantum computers leverage quantum mechanics, particularly superposition and entanglement, to significantly outperform classical computers on specific computational tasks. Unlike classical bits, quantum bits (qubits) exist in a superposition of states, enabling simultaneous processing of complex computations.

What are quantum computers?
Quantum computers are computing machines based on the principles of quantum physics.

Quantum computers vs. Classical computers
Quantum computers leverage **superposition** and **entanglement** to solve problems exponentially faster than classical systems.
They offer immediate advantages on some classes of computational problems as they operate faster than classical computers in solving some specific classes of complex optimization and combinatorics problems, obtaining the so-called **Quantum Supremacy** as their processing time is reduced from exponential to polynomial. Their computational power overwhelms that of classical computers. The basis of **quantum supremacy** over classical computers is the qubit, the quantum bit. Quantum computers, instead of operating on sets and sequences of

classical bits, which can have either the value 0 and the value 1, but never the two values at the same time, operate with qubits that in the simplest case are quantities not represented by numbers but represented by the continuous superposition of the two vector states that constitute a basis of space and therefore mutually orthogonal[1].

Today, optical quantum computers, together with those based on confined ions and with qubits based on superconductors, seem to be the technologies capable of meeting the five criteria required for quantum computing (QC), defined by quantum computing pioneer Di Vincenzo:

Criteria	**To realize quantum computing, it is necessary to have**
1.	A scalable physics system with well-defined and characterized qubits;
2.	The ability to initialize the state of qubits into a simple fiducial state;
3.	Long and significant decoherence times; **typical of the quantum photonic computers**
4.	A universal set of quantum gates;
5.	A specific measurement capability for each qubit state

3 The Photonic Revolution

The main advantage of quantum optical computers lies in the fact that they should be much faster, do not require a complete cryogenic approach and the possibility of realizing many qubit registers using entanglement or multi-path correlations or multi-state correlations. The best advantage is that the device can be installed in mobile platforms and can be better shielded against external disturbances such as accelerations, electromagnetic shocks up to EMP, the electromagnetic pulses triggered by nuclear explosions. The disadvantage of optical quantum computers is in their circuit complexity, which grows exponentially as it is designed to solve increasingly complex calculations.

Why photonic quantum computing?

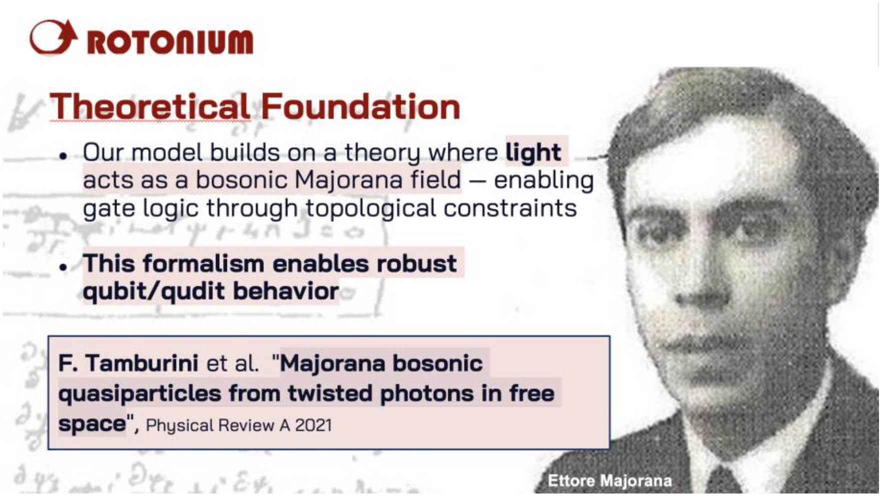
- Does not require cryogenic cooling, unlike superconducting qubits.
- Uses photonic qubits encoded in OAM states, increasing computational power.
- Minimizes photon loss and circuit complexity, ensuring efficient quantum operations.

The Approach to Reducing Circuit Complexity

It involves using topological photonics and in our case, through the use of the Orbital angular momentum (OAM) of the photon. With this approach, a single photon can carry a large set of quantum data encoded only in its orbital angular momentum that can be manipulated with ad hoc optical elements in order to perform quantum computing on single, multiple, or entangled photons. In this way, the complexity of the circuit can be reduced by two or more orders of magnitude. By using OAM states, instead of two-state qubits, it is possible to create n-state qudits and therefore operate in dimensionally larger vector spaces (Hilbert spaces) with a significant increase in computing power due to the increase in the information that can be stored on each individual photon. It is therefore the increase in states on each individual photon that mitigates the complexity of the circuit as the qudits increase, i.e. the circuit to handle a qudit does not have the same complexity as an optical circuit that handles a qubit.

Topological qubits are, with the exception of special cases, qudits. These states are constructed with photons endowed with OAM and can be described in terms of Majorana quasiparticles. It is this quantum property of orbital angular momentum that allows it to be used in the construction of this type of quantum computer.

In our theoretical framework, every photon carrying OAM can be described analogously to Majorana bosonic quasiparticle. This analogy arises from the structured, topological nature of OAM modes, which resemble certain infinite-component field representations introduced in Majorana's theory. The spatial encoding of information in the azimuthal phase of its electromagnetic field allows us to treat OAM photonic states as quasiparticles—entities with defined algebraic properties and symmetry behaviors relevant for quantum information processing. Since each photon can have a large number of OAM states, each photon used in the computation can carry much more information that grows exponentially with the number of states.



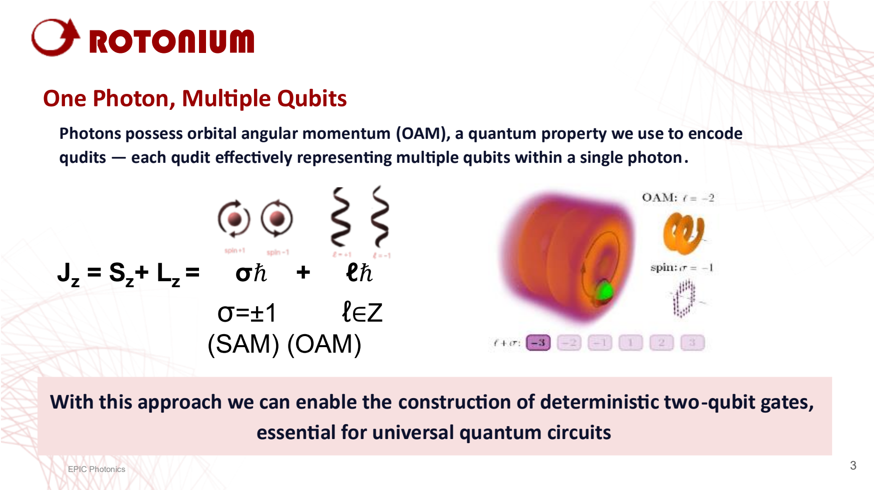
There is no theoretical limit to the amount of this 'information' since the number of OAM states for each individual photon is ideally infinite. That said, the limit reached today in the laboratory is of the order of 10,000 states. It is therefore a piece of information spatially encoded in the phase of the field, described by Majorana's theory as a quasiparticle state and which therefore offers all the properties that make it usable in quantum computing. The simple table below illustrates how increasing from bits to qubits, and from qubits to qudits, exponentially expands the information density and parallelism available in quantum computing. Continuing to do this calculation, ideally 100 qudits with d=16 would correspond to 400 qubits, Each 16-dimensional qudit corresponds to **4 qubits**. Considering that we believe it is possible to create and manage a 128-state qudit, we understand the potential of OAM for the reduction of circuit complexity, understood as the number of optical elements. In fact, It takes only about 57 qudits with dimension 128 to represent the equivalent quantum information of 400 qubits.

2-state bit or qubit	
1 bit	2 states that can only be traded on one at a time
1 qubit	2 states on which you can operate on both at the same time
4-bit	16 states that can only be traded on one at a time
4 qubits	16 states that can be operated on all 16 at the same time
8-bit	256 states that can only be traded on one at a time
8 qubits	256 states that can be operated on all 256 at the same time
4-state qudit	
1 qudit	16 states that can be operated on all 16 at the same time
4 qudit	65,356 states on which you can operate on all 65,356 at the same time
8 qudit	4,294,967,296 states that can be operated on all 4,294,967,296 at the same time

However, it should be remembered that the reduction in complexity in putting many parts together has as a counterpart the development of increasingly increasing construction processes for optical components. Process complexity that, however, is easier to manage over time than circuit complexity.

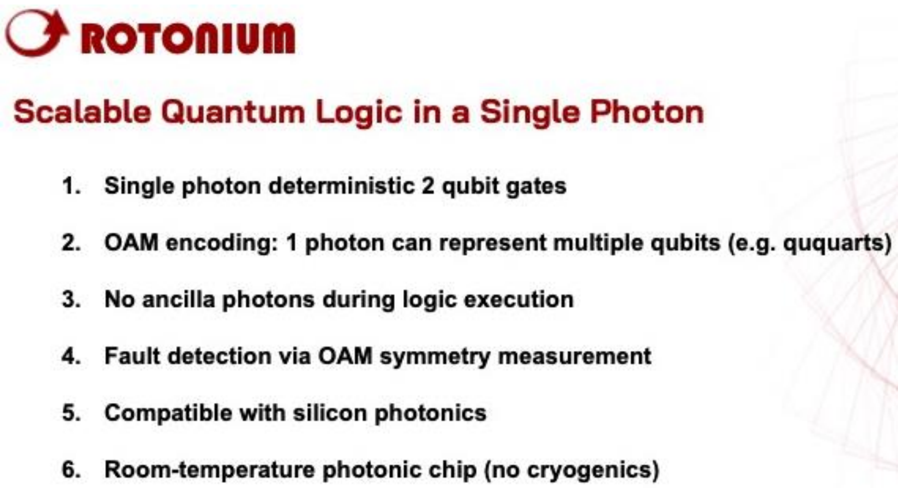
3.1 Understanding Spin and Orbital Angular Momentum (SAM and OAM)

Photons possess both spin and orbital angular momentum. Unlike polarization, which provides a binary state, OAM enables a theoretically infinite-dimensional Hilbert space, allowing for more complex quantum operations. This property offers immense potential for increasing the data-carrying capacity of quantum systems and improving information security. OAM introduces additional states beyond binary polarization, significantly increasing information density per photon. OAM states are characterized by an azimuthal phase factor $e^{il\phi}$, where l denotes the topological charge, enhancing quantum processing capabilities. Polarization provides an efficient two-level system (horizontal and vertical polarization states). Polarization (SAM) qubits are easy to generate, manipulate, and measure, making them ideal for quantum computing.



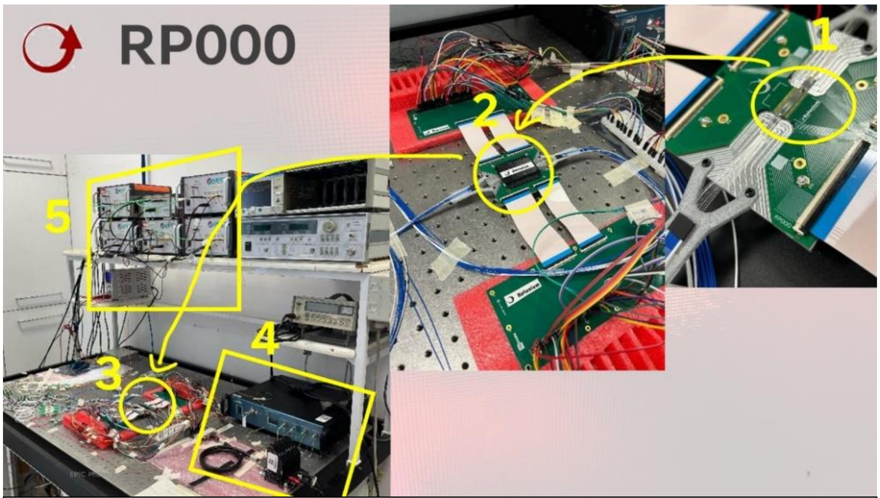
4 Rotonium's Quantum Computing Approach

Rotonium encodes quantum information in two intrinsic photon properties: polarization (spin angular momentum, SAM) and orbital angular momentum (OAM). Rotonium utilizes multidimensional quantum states known as *qudits*. Unlike binary qubits, qudits can occupy multiple discrete states, exponentially increasing computational capacity. They are realized encoding SAM and OAM states on each single photon.



What we do: OAM-based Optical Quantum Computers, which is essentially simplifying circuits using qudits to build any quantum logic gate (i.e. quantum unit operators that are mathematically representable with matrices) using beamsplitters, phase shifters, holograms, Mach-Zehnder interferometers just to name the most well-known components. This is regarding the calculation that once performed, i.e. at the end of each path of the photons in the circuit, the result must be extracted. It is therefore necessary to build a measurement system to perform the so-called "quantum interrogation", i.e. to collapse the wave function and read in which of the states the photonic qudits are located, thus providing the desired result expected by the calculation. For this purpose, it is very important to maintain the consistency of OAM states during the calculation, which can also be achieved by constructing a set of states that are easier to handle without losing the "squeezed" state.

Our architecture: Rotonium's basic idea for the construction of an optical quantum computer involves the creation of a modular structure in which each of the modules processes quantum information carried by qudits that correspond to that of the states obtained using 16 - 32 qubits. Each module can be connected with other modules through quantum entanglement or the sharing of quantum properties of photons by creating a parallel computing network. The advantage is that we will be able to get a 32 or 64-qubit calculator by entanglement on just two modules and at room temperature.



1.Promethium PIC use standard CMOS-compatible technology, ensuring economical manufacturing and compatibility with existing silicon fabrication processes. The waveguides, polarization rotators, and trench modulators integrate seamlessly onto silicon chips. 2. PIC with package 3. Promethium in operation 4. Single photon source and programmable PSU. 5. SPAD detector and Time Tagger

4.1 Photonic Qubits and State Manipulation

Ququarts

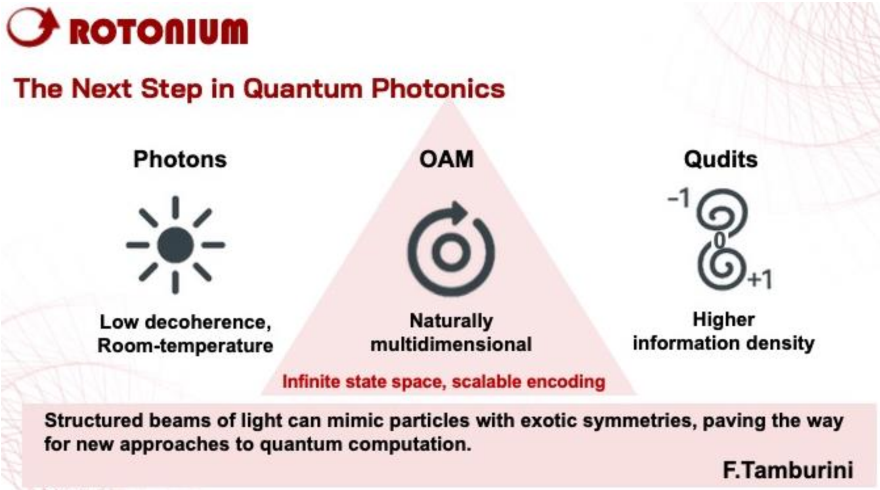
Instead of qubits, Rotonium encodes quantum information in ququarts (4-level systems), equivalent to two qubits. This multi-level encoding is particularly natural in photonic systems, where structured light can support multiple degrees of freedom.

Hybrid Encoding (OAM + Polarization)

• Photons possess two intrinsic and independent degrees of freedom: polarization, corresponding to spin angular momentum (SAM), and spatial structure, corresponding to orbital angular momentum (OAM).
• By coupling SAM and OAM on the same photon, Rotonium creates high-dimensional quantum states (qudits or ququarts) without requiring additional photons.
• This hybrid encoding enables each photon to carry more information, improving computational density while leveraging the natural scalability and speed of photonic systems.
• The combination is particularly suited for integrated photonic platforms, where both SAM and OAM can be manipulated using waveguides, interferometers, and mode converters

5 Rotonium's Technological Approach for a gate-based photonic quantum computer

The key innovations in Rotonium's approach are to build and exploit topological photonic qudits and better exploit deterministic 2-qubit gates with single photons without the need of nonlinear photon couplings.



Quantum Logic Gates Implementation

Rotonium's modules implement essential quantum gates, such as CNOT and Toffoli (CCNOT), using photon polarization and OAM and building hybrid quantum circuits with

- Photon state encoding via waveguide design minimizes noise and maximizes signal integrity.
- Programmable waveguides enable quantum gates (CNOT, Toffoli, Hadamard, Pauli-Z, and CZ gates).
- Utilization of programmable switchers and Mach-Zehnder interferometers (MZI) improves computational accuracy.

Rotonium employs hybrid entanglement between polarization and OAM states to optimize qubit encoding. This technique ensures high coherence while minimizing environmental decoherence, providing a robust solution for practical quantum computing applications.

5.1 CNOT Gate

The Controlled-NOT gate operates with polarization as the control and OAM as the target state. Polarization beam splitters (PBS) and trench waveguides enable deterministic two-qubit logic operations.

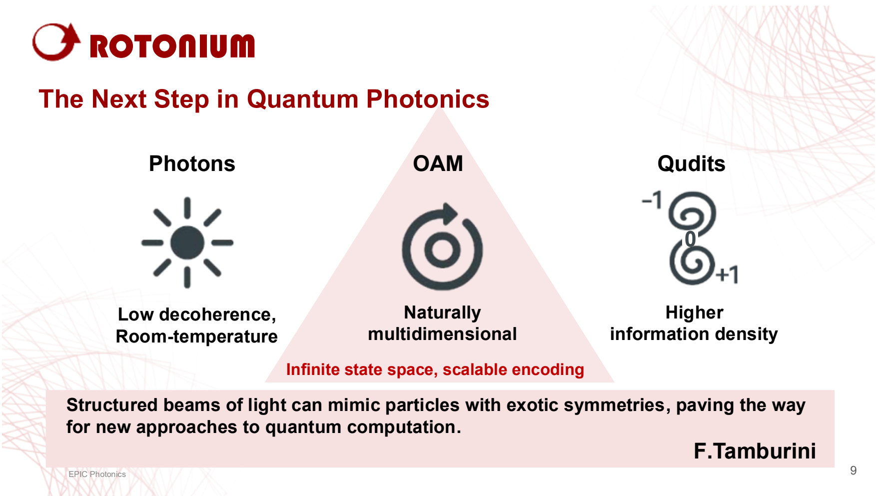
5.2 CCNOT (Toffoli) Gate

Rotonium's CCNOT gate extends the CNOT architecture by integrating additional degrees of freedom (momentum or spatial paths). It utilizes controlled polarization rotations and mode conversions, resulting in efficient, scalable logic gates.

5.3 Waveguide-Based OAM Multiplexing

- Uses active trench waveguides for OAM mode conversion.
- Converts linear polarization states into OAM modes, increasing computational density.
- Mitigates photon loss in folded circuits, improving fidelity.

6 Advantages of Rotonium's Approach



6.1 Increased Information Density

Encoding quantum information in polarization and OAM significantly increases computational density per photon, reducing circuit complexity and photon loss.

6.2 Room Temperature Operation

Photonic quantum computing operates at room temperature, avoiding cryogenic environments and enabling easier deployment and integration.

6.3 Reduced Energy Consumption

Low photon losses and compact waveguide architectures ensure highly efficient operations with minimal energy consumption, making Rotonium's quantum computer eco-friendly and cost-effective.

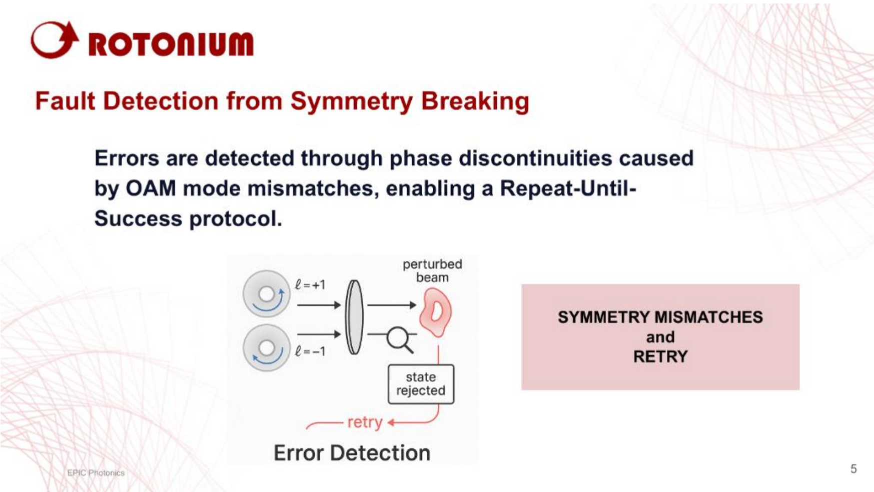
6.4 New Error Correction all Qubits can be Logical

Error correction is a fundamental challenge in quantum computing, essential for protecting quantum information from decoherence and operational errors. The graded paraparticle algebra based on Majorana fields and -graded Lie superalgebras presents a new route for novel error correction mechanisms as written in one of our patents.
This method is currently theoretical, but it provides a well-defined algebraic foundation for designing fault-tolerant quantum gates. Its components—such as SAM–OAM hybrid encoding and algebraic projections—are compatible with current photonic technologies under experimental validation.To clarify the mechanism, we provide a simplified example using a logical ququart encoded with SAM and OAM states:

	logical state	SAM	OAM
1	0	H	$\ell = +1$
2	1	V	$\ell = +1$
3	2	H	$\ell = -1$
4	3	V	$\ell = -1$

A logical error (e.g., an X gate acting on SAM) may move the state into a different $Z_2 \times Z_2$ graded sector. This violation can be detected by the **graded parity projector** Pg, which returns zero (Pg|ψ⟩=0) when the state is no longer in the allowed subspace. This allows for **error detection without collapsing the wavefunction**.

We now provide a technical summary of how the algebraic structure supports error correction. This section introduces the theoretical framework underlying paraparticle-based encoding and its robustness against quantum errors, based on graded algebra and trilinear relations.



How it works: Paraparticles, extending beyond traditional bosonic and fermionic statistics, are described using -graded Lie algebras. This algebraic structure assigns a graded label to each mode, dictating their symmetry properties under exchange and interactions. The crucial characteristic of paraparticles, such as parabosons and parafermions, is encapsulated in trilinear commutation and anticommutation relations, ensuring the algebraic consistency needed for error-correcting operations.

The Majorana Tower further enriches this structure, embedding infinite-component wavefunctions into paraparticle frameworks. Each component of the Majorana Tower, defined by spin-dependent masses, naturally corresponds to graded sectors. Such sectors can encode quantum information robustly due to their inherent algebraic redundancy and statistical constraints.

Paraparticle Algebra for Quantum Error Correction

The core of this error-correcting approach relies on the robust algebraic properties of paraparticles:

- **Graded Commutation Relations:**

  $$\psi^{\pm}_{(a,b)}\psi^{\pm}_{(a',b')} = (-1)^{(a,b)\cdot(a',b')}\psi^{\pm}_{(a',b')}\psi^{\pm}_{(a,b)} + \theta_{(a,b),(a',b')}$$

  These relations intrinsically forbid certain error processes and restrict transitions among states, providing natural protection against common quantum errors.

- **Braided Coproducts:** The algebra employs braided coproducts

  $$\Delta_B(\hat{\psi}_{(a,b)}) = \hat{\psi}_{(a,b)} \otimes I + \sum_{(c,d)} R^{(c,d)}_{(a,b)}(I \otimes \hat{\psi}_{(c,d)})$$

  ensuring that multi-particle states maintain symmetry under exchange, a feature crucial for identifying and correcting errors.

Implementation with Majorana Photonic Quasiparticles

Photonic platforms, particularly structured light modes like orbital angular momentum (OAM) coupled with spin angular momentum (SAM), offer practical realizations. Photons carrying these degrees of freedom can directly represent paraparticle modes, facilitating error correction at a fundamental quantum optical level:

- **Quantum Encoding in Photonic Modes:** Each photon mode, (l,) maps uniquely to a Z_2XZ_2-graded sector, forming a robust ququart structure. For instance, ququart encoding can be achieved by assigning:

  $$|0\rangle \to (0,0), \quad |1\rangle \to (0,1), \quad |+\rangle \to (1,0), \quad |-\rangle \to (1,1)$$

- **Logical Operations for Error Detection:** Error detection and correction operations become logical gate implementations based on graded symmetry rules. Logical X, Z, and controlled-Z (CZ) gates, derived from graded algebraic operations, inherently perform error syndrome measurements without disturbing quantum coherence.

Practical Error Correction Strategies

To practically implement error correction, we exploit graded projectors and exchange matrices:

- **Graded Projectors:** Projectors isolate graded sectors, enabling efficient syndrome extraction:

$$P_{(a,b)}\Psi = \sum_{s:(a,b)_s=(a,b)} \Psi_s$$

- **Exchange Matrices:** Exchange operators control interactions between different graded sectors, permitting deterministic syndrome correction by enforcing the algebraic structure:

$$X_{(a,b),(a',b')}\Psi_{(a,b)} \otimes \Psi_{(a',b')} = (-1)^{(a,b)\cdot(a',b')}\Psi_{(a',b')} \otimes \Psi_{(a,b)}$$

Error Correction Procedure

1. **Initialization:** Quantum states are prepared in Majorana graded sectors.
2. **Error Syndrome Extraction:** Errors manifest as transitions violating the graded algebraic relations, detectable via projective measurements.
3. **Syndrome Decoding:** The algebraic structure itself provides immediate error syndrome interpretation, identifying error locations without ancillary qubits.
4. **Correction:** Exchange and grading operations deterministically restore original states, facilitated by algebraically guaranteed exclusion rules.

Advantages of Majorana and Graded Algebra Codes

- **Robustness:** The algebraic constraints inherently limit permissible errors, simplifying syndrome detection.
- **Efficiency:** Reduced overhead in error detection, due to built-in algebraic redundancies.
- **Scalability:** Easily extended to higher dimensions and complex quantum information tasks due to the inherent flexibility of graded algebraic encoding.

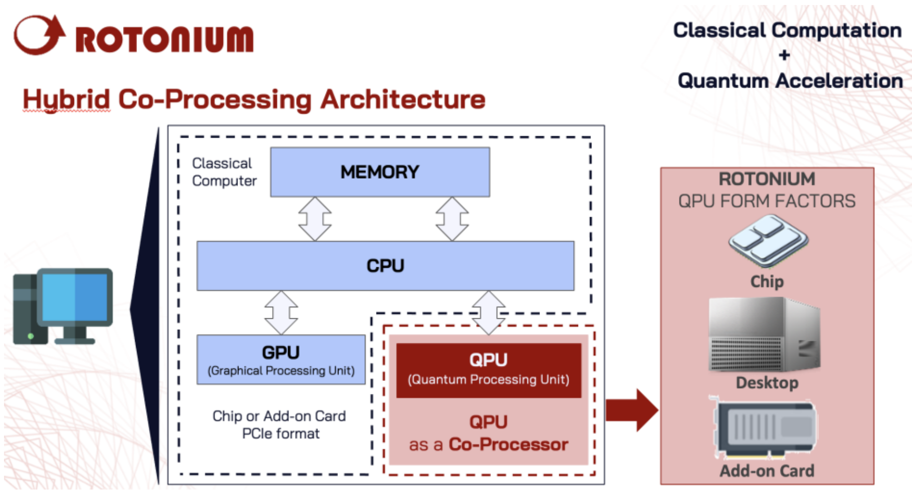
Integrating Majorana quasiparticles with Z_2xZ_2-graded algebra offers a powerful paradigm for error correction in quantum computing. The inherent algebraic redundancy and restricted error pathways provide a natural resilience to decoherence and operational faults. As photonic and other quantum platforms mature, this paraparticle-based algebraic error correction will significantly advance robust and practical quantum information processing.

7 Development Roadmap

Development Milestones

- **2023:** 1st batch of PIC quantum chips manufactured to testing the 2-qubit gates.
- **2024:** 2nd batch of PIC quantum chips manufactured to testing a 4-qubit processor
- **2025:** Demonstration of hybrid entanglement between OAM and polarization.
- **2025:** 3rd batch of PIC quantum chips processor with integrated single photon source
- **2026:** 4th batch of PIC quantum chips: 1st gen. Edge-deployable quantum processors
- **2027:** 5th batch of PIC quantum chips: commercial-scale rollout of photonic quantum processors.

This roadmap is intentionally aggressive, yet feasible given current capabilities and the team's deep expertise in quantum photonic integration.



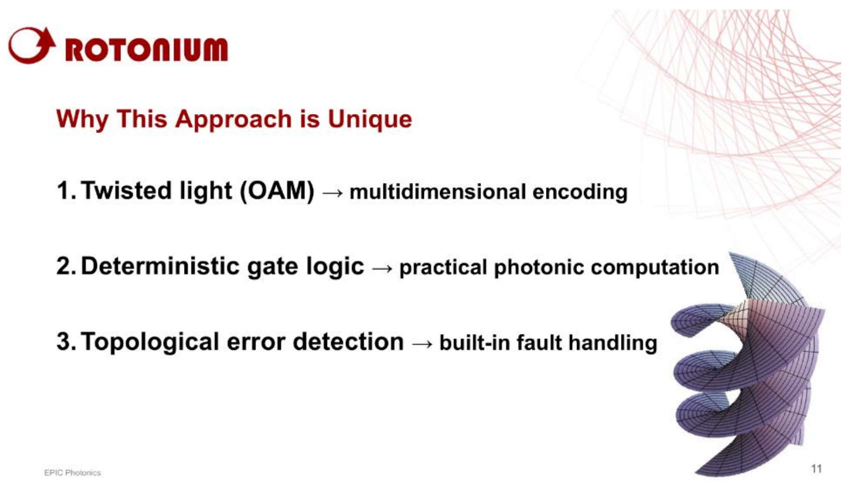
8 Partnerships and Collaborations

Rotonium is collaborating with research institutions and industry leaders to accelerate quantum photonic developments. Key partners include:

- **University Research Labs:** Advancing quantum information science through experimental validation and theoretical exploration with CNIT, Pisa, and University of Trento.
- **Tech Industry Leaders:** Integrating quantum solutions into commercial applications for quantum enhanced computational efficiency.

8.1 Applications of OAM in Quantum Computing

- **High-Dimensional Quantum Computing:** expands computational capabilities beyond traditional qubits, enabling more efficient and more powerful quantum algorithms.
- **Quantum Key Distribution (QKD):** OAM-based photonic states enhance security protocols by providing high-dimensional encoding for cryptographic applications.
- **Quantum Random Number Generation (QRNG):** a quantum processor can be used as a random number generator. QRNG improves data integrity and security in cryptographic applications. It can also enhance neural network models such as GANs by providing entropy-rich input noise for the initialization of weight.



9 Conclusions

Rotonium's unique approach to quantum computing, based on photonic qudits encoded in orbital angular momentum (OAM) and polarization, represents a significant step toward scalable, energy-efficient, and secure quantum technologies.

By leveraging hybrid entanglement and waveguide-based multiplexing, Rotonium achieves high computational density and robustness without the need for cryogenic cooling. This enables room-temperature operation, reduced energy consumption, and simpler system integration.

The architecture is fully compatible with semiconductor processes, allowing for practical deployment and future scaling. Combined with an edge-centric strategy, Rotonium opens new avenues for quantum acceleration in real-world, mobile, and embedded environments.

With its focus on miniaturization, photonic integration, and logical error correction via paraparticle algebra, Rotonium is not only pushing the frontiers of what is possible in quantum hardware, but also making high-performance quantum computing more accessible and commercially viable.

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