Open Schools Journal for Open Science

Vol 9, No 1 (2026)

Open Schools Journal for Open Science

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doi: [10.12681/osj.44022](https://doi.org/10.12681/osj.44022)

To cite this article:

Giannikopoulos, V. (2026). Anyon qubits and quantum AI beyond interstellar. *Open Schools Journal for Open Science*, *9*(1). https://doi.org/10.12681/osj.44022

Anyon qubits and quantum AI beyond interstellar

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Summary

Interstellar probes must operate for decades with long communication delays and limited opportunities for repair. This study explains why anyon qubits—topological qubits built from non-Abelian anyons—are promising for deep-space autonomy. We describe how braiding encodes information non-locally, providing intrinsic robustness against local noise, and how this can support quantum artificial intelligence (AI) for onboard decision-making. We also discuss why deep space may help: low vibration, high vacuum, and strong passive cooling can reduce decoherence channels. We conclude that anyon qubits combined with quantum AI provide a credible route to secure, autonomous communication beyond the Solar System.

Keywords: Anyon qubits, Interstellar, quantum AI

1. Introduction

Interstellar missions beyond the heliosphere face a simple operational fact: round-trip communication can take many hours or days. That latency breaks the traditional "ground in the loop" model, where teams on Earth diagnose anomalies, plan observations, and uplink decisions. A spacecraft that encounters an unexpected plasma boundary, a transient energetic-particle burst, or a novel dust population cannot wait for Earth to respond; it must prioritize measurements and adapt its own plan.

Autonomy, however, is ultimately an information problem. The vehicle must store data reliably for long periods, resist radiation-induced faults, and maintain trustworthy internal state for decision-making.

Classical spacecraft computers encode information in bits, which take values 0 or 1. Classical fault tolerance is achieved mainly through redundancy (for example, triple-modular voting) and error-correcting codes. These methods work, but they cost mass, power, and complexity—precisely the resources that are most constrained on interstellar missions.

Quantum information introduces qubits, which are described by states in a two-dimensional Hilbert space: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with $|\alpha|^2 + |\beta|^2 = 1$.

Superposition and entanglement can improve certain computations, but the same physics makes most qubit platforms fragile: coupling to the environment leads to decoherence.
This study focuses on a class of qubits designed to be robust by construction—anyon (topological) qubits—and argues that, paired with quantum artificial intelligence, they can

enable secure and autonomous information handling for missions beyond the Solar System.

Figure 1 introduces the braiding concept that underpins topological encoding. Figure 2 connects this concept to deep-space conditions, highlighting how low noise and extreme cooling can stabilize quantum hardware.

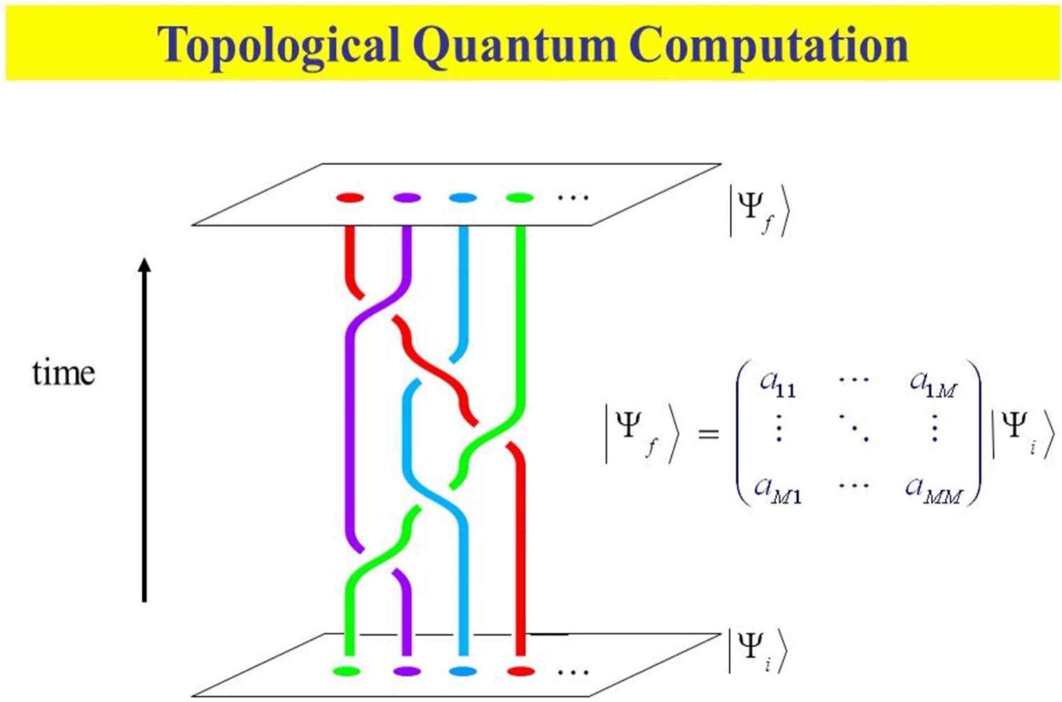

Figure 1. Braiding schematic: logical information depends on the global braid topology (non-local encoding). (Source: Lucas et al. (2023), Nature Communications, 14:3522)

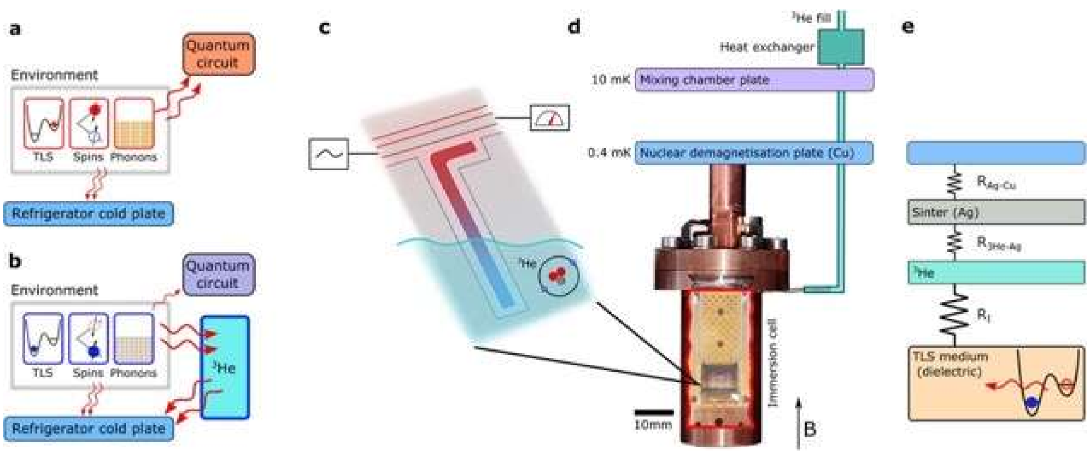

Figure 2. Deep-space context: low environmental noise and strong passive cooling reduce decoherence channels (Source: Lucas et al. (2023), Nature Communications, 14:3522)

1.1 Bits, qubits, and why robustness is hard

A classical bit is local: it is implemented by a voltage level, a magnetic domain, or a charge state at a specific place in hardware. As a result, many deep-space hazards act locally—single-event upsets from energetic particles, latch-up events, and gradual displacement damage—and directly map onto bit errors. Classical mitigation is effective, but it scales by adding redundancy and continuously checking that local states are correct.

A qubit is different. It is a vector, and its relative phase carries information. In practice, the environment "measures" the system: random interactions wash out phase information and turn a pure state into a mixed state.

A common open-system model is the Lindblad master equation:
$d\rho/dt = -i[H,\rho] + \Sigma_k (L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k,\rho\})$.

Here ρ is the density matrix, H is the system Hamiltonian, and L_k represent decoherence channels. The engineering goal is to suppress the effective couplings encoded in L_k.

Conventional quantum error correction can tolerate noise but requires many physical qubits to encode a single logical qubit. For deep-space use, a more attractive approach is to encode information so that typical local noise has little effect in the first place.
That is the central motivation for topological quantum computation.

2. Anyon qubits and topological quantum computation

Topological quantum computation uses non-Abelian anyons —emergent quasiparticles in certain two-dimensional quantum phases— to store and process information non-locally. In the simplest picture, multiple anyons share a degenerate ground-state manifold. A "logical qubit" is encoded in that global manifold rather than in any single local degree of freedom.

Computation is implemented by braiding: moving anyons around one another so that their worldlines form a braid in space–time. The key fact is that the resulting unitary transformation depends only on the topology of the braid, not on the precise path details.
This makes gate operations inherently tolerant to small control errors and many classes of local noise, because local perturbations cannot change the global topological class of the braid.

Theoretical foundations of this approach were developed in the context of non-Abelian statistics and fault-tolerant computation [1,2]. More recent overviews explain how braiding operations can be compiled into logical gates and how measurements complete a computational protocol [3,4].

2.1 Mathematical description of braiding

Let B_n be the braid group on n strands. In a non-Abelian anyon system, elementary exchanges correspond to unitary operators that represent generators of B_n on the degenerate Hilbert space. If σ_i denotes the exchange of neighbouring anyons i and i+1, then a braid word $\sigma_i \sigma_j \ldots$ maps to a unitary $U = \rho(\sigma_i) \rho(\sigma_j) \ldots$, where ρ is a unitary representation.

A logical state $|\psi_L\rangle$ transforms as $|\psi_L'\rangle = U|\psi_L\rangle$.

Topological protection can be expressed informally as a separation of scales: local errors correspond to operators with support in a bounded region, whereas the logical information is stored in a global sector. Unless an error process creates or moves anyons in a way that changes the braid's topological class, it cannot implement a logical error. In many models, logical error rates fall exponentially with the relevant energy gap and with spatial separation of anyons, making the architecture naturally robust to small disturbances.

3. Why deep space can help: temperature, noise, and mission constraints

Anyon-based platforms generally require cryogenic operation because the topological phase and the gap protecting it must dominate over thermal excitations. On Earth, dilution refrigerators and careful vibration isolation provide the needed environment, but they are power-hungry and sensitive to mechanical noise.

Deep space changes the boundary conditions. Far from planets, the environment provides ultra-high vacuum and very low mechanical vibration. Thermal loads can be reduced with passive radiators and sunshields. While the cosmic microwave background temperature (~2.7K) is not sufficient by itself for millikelvin operation, it reduces heat-rejection demands compared with terrestrial lab settings, and it removes whole categories of terrestrial noise sources. In terms of the Lindblad model, deep space can reduce the magnitude of certain L_k channels (for example, vibration-induced fluctuations and electromagnetic interference), complementing topological protection.

The engineering implication is not that "space is automatically cold enough," but that the spacecraft can, in principle, achieve a lower-noise environment with fewer external disturbances. This makes topological hardware more plausible for long-duration operation, provided that cryocoolers, shielding, and thermal design are integrated from the start of the mission concept.

4. Quantum artificial intelligence: using robust quantum memory for autonomy

Quantum artificial intelligence (AI) is best understood here as a hybrid autonomy stack: classical flight software handles safety-critical control loops, while quantum resources support selected tasks such as optimization, probabilistic inference, and secure state storage. The value of anyon qubits in this stack is their potential to act as a long-lived, fault-tolerant quantum memory that remains reliable across radiation events and long mission times.

A practical architecture can be framed as three layers. First, instruments produce raw measurements. Second, onboard models summarize those measurements and estimate scientific value under uncertainty. Third, a protected memory stores critical "decision state": model parameters, encryption keys, and high-value compressed data products.

If the protected memory is stable, the spacecraft can make consistent decisions even after transient faults, because its internal state is not silently corrupted.

For interstellar missions, this matters because decisions are long-horizon: the system must preserve not only data but also the context needed to interpret it. Robust memory is therefore not an accessory; it is a prerequisite for trustworthy autonomy.

5. Secure interstellar communication with topological storage

Secure communication beyond the Solar System must handle three constraints at once: extreme latency, intermittent contact windows, and limited bandwidth. Classical cryptography can secure data, but it depends on protecting keys and on maintaining integrity of stored states over long periods. If keys are corrupted by radiation or silent bit flips, the mission can lose the ability to authenticate commands or verify science data.

Anyon qubits offer a complementary approach: store key material and authentication state in a topologically protected form, reducing the probability of silent corruption. In addition, a quantum-capable probe could support quantum-secure primitives when hardware permits (for example, preparing and verifying quantum states for key establishment). Even if full quantum networking is not available over interstellar distances in the near term, the ability to protect internal cryptographic state and to manage security policies autonomously is valuable.

Quantum artificial intelligence strengthens this further by continuously monitoring communication integrity, adapting coding and compression strategies to link conditions, and prioritising which data to transmit. The resulting system is not just "encrypted"; it is resilient: it preserves trust under uncertainty and long delay.

6. Current research ecosystem relevant to anyon qubits

Topological quantum computation is an active research area across academia and industry. Core theoretical work on non-Abelian anyons and topological computation established the principles of braiding and fault tolerance [1,2].

Review articles and lecture notes provide accessible summaries of the field and its device-level challenges [5,6]. Experimental programs focus on candidate platforms, including Majorana zero modes in engineered semiconductor–superconductor structures and fractional quantum Hall states.

In practice, mission-relevant technology maturation will require collaboration between quantum laboratories and space-systems engineers. The main point for this study is not to claim that a flight-ready topological quantum computer exists today, but to show that the underlying physics offers a robustness property aligned with deep-space needs and that the research ecosystem is actively pushing toward scalable implementations.

7. Conclusion

This work argues that anyon qubits provide robustness fundamentally different from classical redundancy and conventional quantum error correction, because information is stored non-locally in a topological sector and remains insensitive to many local disturbances. Deep-space conditions—high vacuum, low vibration, and strong passive cooling—suppress dominant decoherence mechanisms, complementing this intrinsic protection, as illustrated in Figure 2. When combined with quantum artificial intelligence, protected quantum memory enables a credible autonomy architecture in which decision state, cryptographic material, and high-value scientific data remain reliable over long mission durations.

From a system-design perspective, anyon qubits are treated as a specialized subsystem rather than a full quantum computer. A minimal set of braiding operations supports verification, refresh, and controlled interaction with classical avionics, addressing silent state drift during communication blackouts. Consequently, anyon qubits emerge as a reliability component for interstellar autonomy, secure communications, and verification beyond the Solar System.

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Footnotes

1.NASA Interstellar Probe Mission Concept Report:
https://interstellarprobe.jhuapl.edu/Interstellar-Probe-MCR.pdf

2. NASA JPL Voyager Program: https://voyager.jpl.nasa.gov/

3. NASA Quantum Development Roadmap portal: https://quantum.gov