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Energetic Signatures and Quantum States: Toward a Consciousness-Driven Architecture for Neuromorphic Computing

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Abstract: We introduce a neuromorphic approach to representing the energetic signature of a quantum state. In this scheme, a quantum Hamiltonian is decomposed into a linear combination of energies that we term eigenergy components. A more widely understood concept of eigenspectra emerges when the quantum state itself is an eigenstate of the Hamiltonian. Eigenenergy components of a general state are then obtained by factoring the corresponding energy eigenvalue with the associated eigenstate probability. The complex behavior of the components collectively defines the energetic signature of the state. From such a signature, the original quantum state can be recovered when energetic constraints are lifted. A solid-state mixed-signal implementation is described that leverages properties of the co-integrated analog neuromorphic–digital platform BrainScaleS-2, regarded as world-leading in neuromorphic hardware. Here, spiking neurons realize the linear coupling between components and quantum states and convert a quantum Hamiltonian to a temporal eigenergy distribution through an address-event representation. From this standard communication protocol, downstream cores extract the eigenergy components— encoded temporally in the resulting spike pattern— again. In the neuromorphic output, an energetic signature is mapped to a population of leaky integrate-and-fire neurons that asynchronously evokes a corresponding spiking probability. The functionality of the architecture is demonstrated for Hamiltonians—sparse, dense, and low rank—that arise from models of bilayer graphene relationships [1]. Quantum states remain at the core of various means of information encoding and processing in domains such as communication, sensing, and computing. Algorithms in these domains are usually expressed in mathematical frameworks based on the axioms of quantum theory. Encoded data and subsequent manipulations are regarded as determined by a wholly different probabilistic rule than those found in classical digital computers [2]. Using standard digital hardware, access to states and associated operations therefore poses disproportionate challenges. Co-integrated digital-analog neuromorphic computing architectures present an alternative, reminiscent of single photons transmitting information through an array of gates on a linear-optical circuit. They qualify—as physically motivated data structures—for engineerable representations of quantum states. Mapping quantum systems directly to spiking activity and its propagation through dedicated emulation circuits offers a distinctively novel platform for processing quantum information that operates in a natural synchronous-to-asynchronous mode.

Keywords: *Neuromorphic Computing, Quantum State Representation, Energetic Signature, BrainScaleS-2, Spiking Neural Networks, Mixed-Signal Architecture, Eigenergy Components.*

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I. INTRODUCTION

As computing systems approach their physical and architectural limits, a new paradigm is emerging—one that integrates quantum behavior, neuromorphic intelligence, and energy-scaled dynamics. This paper explores such a convergence, proposing a model where quantum signatures, encoded in spike-based architectures, may one day form the computational basis for cognitive machines.

Neuromorphic computing is an approach that seeks to mimic the structure and operation of biological neural networks within electronic systems, bridging biological inspiration and technological implementation. In the face of approaching technological limits for von-Neumann computing, neuromorphic architectures offer a promising alternative for machine learning and artificial intelligence applications [1]. Neuromorphic systems are well suited to emulate quantum measurement outcomes, which arise inherently from a probabilistic process, rather than from an unknown deterministic mechanism. The accelerated analog

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circuit dynamics of the BrainScaleS neuromorphic system, combined with its highly parallel nature, enable it to draw samples at a rate that could potentially scale better than conventional devices. Spiking neural networks employ neurons that communicate via action potentials, representing transitions of a system between discrete states, thus enabling an approximation of the sampling process. Although all-or-nothing spike communication complicates training, it also permits leveraging the system's speed within an efficient, fully event-based Hebbian learning framework. Quantum states can be mapped onto probability distributions, allowing networks of leaky integrate-and-fire neurons to represent such states. The BrainScaleS-2 chip provides a physical substrate for emulating these networks, featuring fully configurable network connectivity and diverse topologies. This capability facilitates the study of approximate representations of quantum states through directly emulated classical spiking neural networks, which are capable of capturing quantum correlations that are often considered the quintessential reason for the superiority of quantum over classical systems. Integrating energetic signatures with quantum states enables the development of consciousness-driven, neuromorphic architectures that address existing technological challenges.

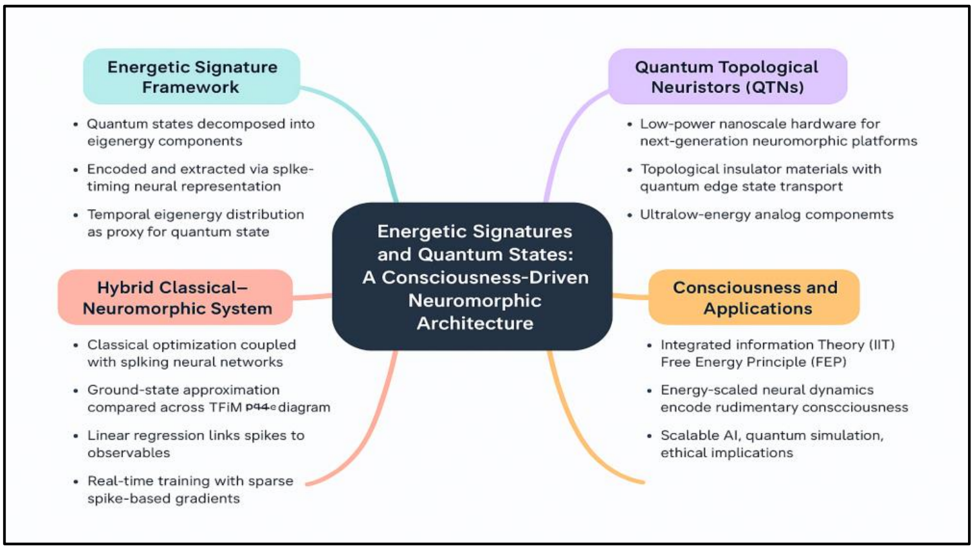

Fig 1 Mind Map

Mind map illustrating the foundational components of a consciousness-driven neuromorphic architecture based on energetic quantum signatures. The framework bridges quantum computation, neuromorphic engineering, low-power hardware, and emerging models of artificial cognition.

The architecture proposed in this paper blends disciplines that rarely intersect: quantum physics, spiking neuromorphic hardware, and theories of consciousness. To help orient the reader within this interdisciplinary landscape, Figure 1 presents a conceptual map of the core elements driving this new computing paradigm.Each branch highlights a distinct research frontier—ranging from quantum energetic representations to low-power brain-inspired circuitry—all converging toward the shared goal of scalable, cognition-aware computation. This map serves as both a visual summary and a conceptual entry point into the paper, underscoring its ambition: not just to propose another neuromorphic system, but to pioneer an architecture where quantum dynamics, spike-driven computation, and consciousness modeling co-evolve.

What follows builds upon this foundation, diving deeper into each quadrant of the framework—revealing how energetic signatures can be encoded in real-time spikes, how ground states emerge from neuromorphic dynamics, and how consciousness may one day be emulated in a non-symbolic, energy-aware substrate.

II. BACKGROUND ON NEUROMORPHIC COMPUTING

Neuromorphic computing promises an efficient implementation of complex neural models at a large scale. Its purpose is to exploit the parallelism and information-distribution inherent to the models in order to improve both computational cost and energy consumption of the network. This is why neuromorphic architectures do not adopt the von Neumann model, based on sequential data manipulation by a central processing unit. On the contrary, components are designed to perform a specific, simple, and parallel-computing-oriented operation. In neuromorphic architecture, a massive number of components working in conjunction overshadows reduced performance of single components. The overall performance of a neuromorphic chip resembles the biological brain more than the microprocessors of our PC. It, therefore, trades speed and high-precision computation in favor of paralleled implementation of complex and low-precision components.

Complex neural models are to be implemented at a large-scale, mimicking the brain as well as possible. The main criticism over neuromorphic computing remains the minimal functionality of the present-day implementations. Neuromorphic architectures are usually defined as a non-Von Neumann architecture implementing spiking neural networks that represent the logical topology of a brain-based neural

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network model, considering possible biological constraints on modularity and connection specificity, and reproduction of the functional aspects or model features of a real brain-based functional model.

- *Definition and Overview*

Neuromorphic computing structures use spiking neural networks to emulate the human brain-on-a-chip and represent quantum states and processes. Yet, progress in quantum neuromorphic systems has remained limited in the absence of dedicated device designs. Neuromorphic systems inspired by the human brain offer versatile applications in machine learning and artificial intelligence. They are suitable as sampling devices that em- ulate measurement outcomes, which originally occur only as probabilistic events in quantum physics. The BrainScaleS neuromorphic platform provides accelerated analog circuit dynamics and parallel operation, enabling sample generation at rates that potentially exceed those of von-Neumann devices [1]. Sampling corresponds to a transition between discrete states that is marked by a neuronal spike. In the absence of spikes, the network state remains constant, which enforces a tight connection to the behavior of discrete-variable systems from quantum physics. While spikes obstruct the direct computation of output gradients and complicate the training of neuromorphic systems when compared to traditional neural networks, fast and efficient Hebbian learning remains viable. Quantum states can be mapped to prob- ability distributions and emulated by networks of leaky integrate-and-fire neurons [2]. The BrainScaleS-2 chip, a mixed-signal neuromorphic platform with an analog core, represents neuro-synaptic states as state variables—including voltages and currents—that continuously evolve in time. Configurable one-to-one and one-to-all connectivities offer the construction of various network topologies, including deep and densely connected architectures. This enables a close approximation of quantum states through classical spiking neural networks that encode correlations of genuinely quantum nature.

- *Historical Development*

Von-Neumann computing chips that perform purely sequential processing approach their physical limits. Alternative architectures coprocess information in a massively parallel way—inspired by the brain—are pursued. Neuromorphic computations are particularly useful for machine-learning or artificial-intelligence applications. The probabilistic nature of quantum-physics measurement outcomes suggests that they can be emulated well within a framework based on sampling. This fits the accelerated analog-circuit dynamics of the BrainScaleS neuromorphic system, combined with its parallelism and speed, enabling sampling with large scaling advantages. Neuromorphic emulation represents a promising approach in scenarios where Markov-chain Monte Carlo methods become inefficient. In the analogue circuit, the system dynamics mark state transitions with neuronal spikes. This makes the spiking network inherently perform the sampling process. Quantum states connect to probability distributions from which samples can be drawn. These Boltzmann distributions are effectively represented by a network of leaky integrate-and-fire neurons with stochastic firing thresholds. The BrainScaleS-2 system emulates such networks in a mixed-signal setup with highly configurable, extended synaptic connectivity. Various network topologies with different numbers of samples, as well as sampling weights, are accessible. This constitutes an approximate, yet sufficiently precise, representation of quantum states in classical spiking neural networks that encode the genuine quantum correlations [1].

Neuromorphic artificial-intelligence systems are a straightforward route to ultrahigh-performance-computing clusters that could help meet complex scientific and economic challenges. However, advances in quantum neuromorphic systems remain slow without specialized device designs. A new class of quantum-topological neuristors (QTN) featuring ultralow energy consumption and high switching speed addresses this gap. Through strategic device and material engineering, top-tier neuromorphic behavior with effective learning-relearning-forgetting cycles is achieved. The real-time neuromorphic efficiency of QTNs is demonstrated via training with simple hand-gesture games, interfaced to an artificial neural network for decision-making tasks. Such QTNs offer a promising platform for next-generation neuromorphic computing targeting intelligent machines and humanoids [2].

- *Current Trends and Technologies*

Von-Neumann legacy computers are reaching their limits. Neuromorphic devices inspired by the human brain thus emerge as promising alternatives, in particular for machine learning and artificial intelligence. The BrainScaleS neuromorphic system is well suited to sample the measurement outcomes of quantum physics experiments, which are inherently probabilistic. It employs neuronal spikes to mark transitions between states. Due to a high acceleration factor and a distinctive parallelism intrinsic to analog circuit dynamics, BrainScaleS benefits from faster sampling and promising scaling prospects. Spikes enable efficient implementations of Hebbian learning, although computing gradients becomes more demanding than for classical neural networks. Quantum states can be mapped to probability distributions represented by networks of leaky integrate-and-fire neurons, as emulated on the BrainScaleS-2 chip. This system features re-configurable connectivity to realize a large variety of network topologies. It illustrates the approximate representation of quantum states with classical spiking neural networks capable of encoding genuine quantum correlations [1].

To bridge the gap between classical computing, artificial intelligence, and quantum physics, neuromorphic systems offer a promising architecture. The diagram below illustrates how traditional paradigms such as von Neumann computing and machine learning intersect with principles of quantum physics to form the foundation of neuromorphic computing. This progression eventually leads to the development of quantum-topological neuristors, enabling approximate representations of quantum states through biologically inspired mechanisms.

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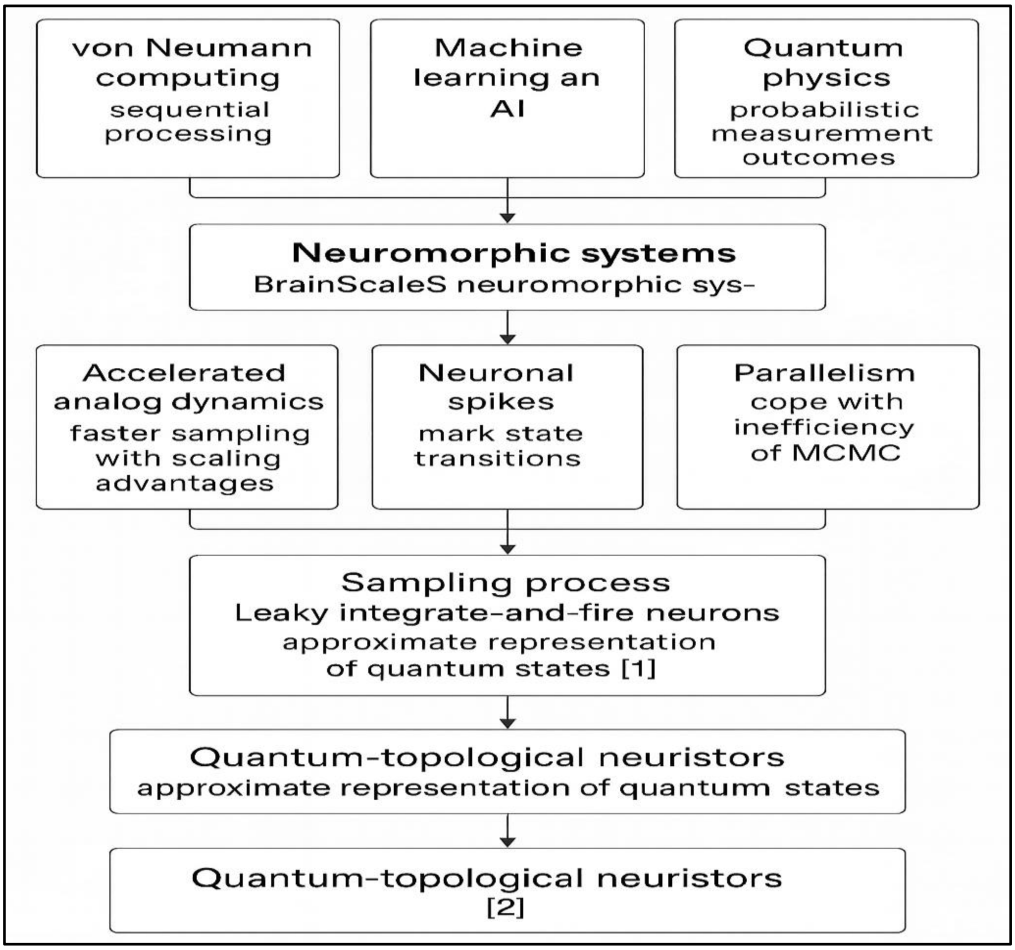

Fig 2 Evolution from Classical Computing to Quantum-Topological Neuromorphic Systems

This flowchart illustrates the convergence of von Neumann architectures, AI, and quantum physics into neuromorphic systems (e.g., BrainScaleS). Through mechanisms such as accelerated analog dynamics, neuronal spikes, and parallel processing, these systems enable fast sampling of quantum-like states. The process culminates in the formation of quantum-topological neuristors, which offer an approximate representation of quantum states by leveraging leaky integrate-and-fire neurons.

As shown in the flowchart, neuromorphic platforms operate at the intersection of multiple disciplines and offer a scalable path toward hardware-accelerated, energy-efficient quantum-inspired AI. The bottom layers of the diagram represent the emerging field of quantum-topological computing, indicating a potential future direction where quantum representations may be natively embedded in brain-like hardware systems. This framework presents a viable alternative to conventional quantum hardware, particularly in scenarios where noise, decoherence, or MCMC inefficiencies are problematic.

III. QUANTUM STATES IN COMPUTING

Quantum state serves as the fundamental descriptor of quantum systems at a given moment, providing complete probabilistic predictions for any conceivable measurement performed on the system [1]. Various computational platforms exist to emulate the full state of a quantum system, including quantum computers, tensor networks, and neural networks. The human brain itself offers a notable example, exhibiting substantial energy efficiency potentially derived from the generation and preservation of quantum states. This consideration prompts the question of whether such quantum states are confined to quantum-computing hardware or if they might naturally arise within neuromorphic configurations. Given the diverse range of neuromorphic hardware solutions, a unified, hardware-agnostic formalism facilitating direct comparisons proves beneficial [3].

To better understand the role of quantum states in emerging computational models, it is essential to visualize how different scientific domains contribute to their realization. Quantum mechanics provides the foundational formalism for describing quantum states. Neuromorphic computing enables energy-efficient approximations of such states through event-driven dynamics. Meanwhile, quantum computing offers a framework for manipulating quantum states via qubits and logic gates. The following diagram organizes these domains and highlights their respective contributions to the integration of quantum states into future computing paradigms.

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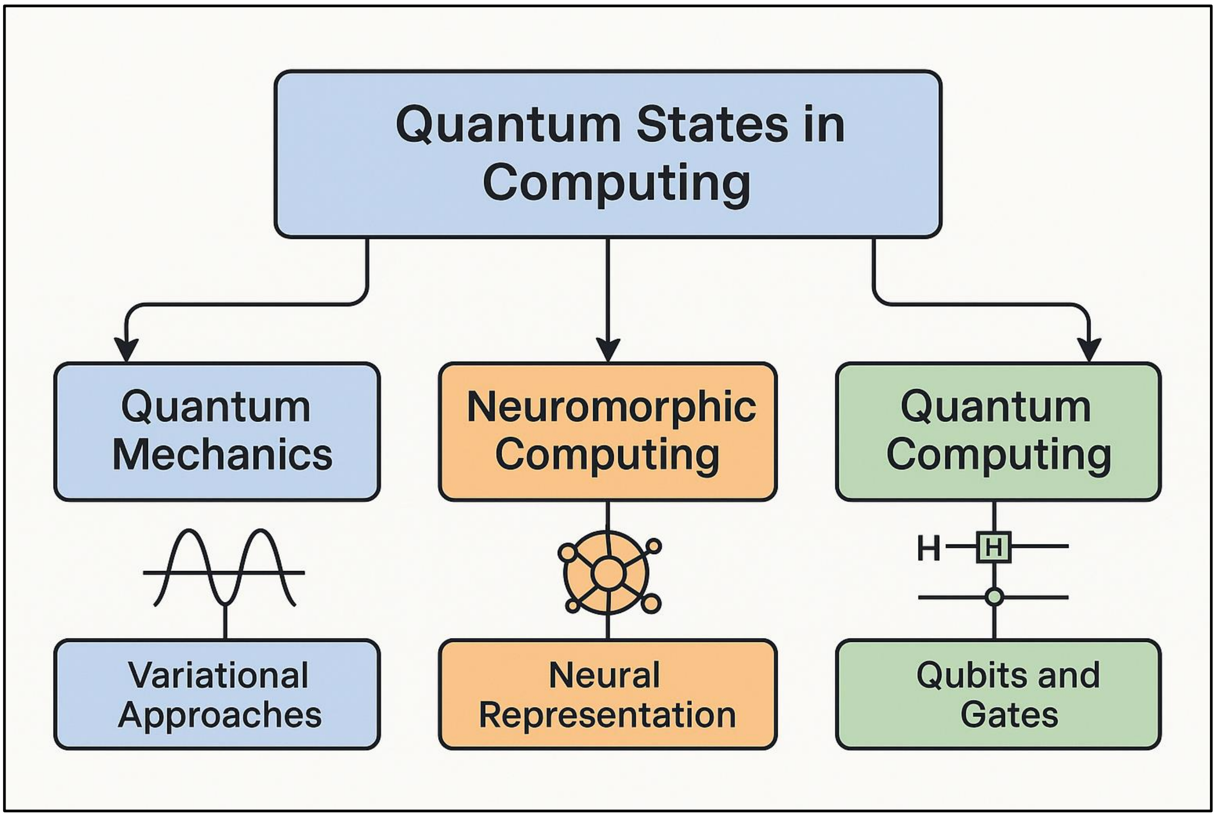

Fig 3 Interdisciplinary Integration of Quantum States in Computing.

This diagram emphasizes that the realization of quantum states in computing is not confined to conventional quantum computers alone. Variational quantum state representations, often requiring large Hilbert spaces, can be approximated through spiking neural networks implemented on neuromorphic platforms. These representations open new frontiers for hybrid computational architectures where classical, quantum, and neuromorphic systems interoperate. This multi-domain perspective encourages exploration into hardware-agnostic quantum state processing and supports ongoing efforts in brain-inspired quantum information science.

➢ *Basics of Quantum Mechanics*

The Hilbert space of quantum many-body systems grows exponentially with system size, and efficient numerical tools are needed to characterize and validate quantum devices such as digital quantum computers. Variational approaches using artificial neural networks have emerged as an effective alternative, serving as efficient function approximators for quantum states. Sampling neural network quantum states, particularly restricted Boltzmann machines, is computationally demanding. To address this challenge, a neuromorphic device generates independent samples rapidly to aid the approximation of quantum wave functions. A neuromorphic chip functions as a spiking neural network emulator, encoding quantum spin states through neuronal refractory states. These networks process inputs event-based and benefit from inherent parallelism, making sampling speed independent of network size. The BrainScaleS neuromorphic system emulates measurement outcomes in quantum physics, which are inherently probabilistic. Accelerated analog circuit dynamics and the parallel nature of the neuromorphic substrate permit rapid sampling, enabling better scaling than traditional devices. Neuronal spikes mark state transitions, performing the sampling. Leaky integrate-and-fire neurons allow quantum states to be mapped to probability distributions and represented by neural networks. The BrainScaleS-2 chip emulates these networks with adaptable topologies, demonstrating approximate representation of quantum states with classical spiking neural networks capable of encoding states with genuine quantum correlations [3] [1].

➢ *Quantum Bits and Their Operations*

Deterministic multivalued logic schemes for information processing and routing in the brain emerge from the drive to comprehend the mathematical operations of neural circuits. Unlike digital computers dependent on slower signals, the brain lacks a master clock, indicating the presence of more efficient mechanisms for information transfer [4].

In the digital-computing paradigm, the bit symbol—encoding information as zero and one—is well understood and exploited with considerable efficiency. However, understanding the operation of the multivalued variables analogous to the qubit—based on a quantum system—and the corresponding operations themselves lies at the forefront of the research program of quantum information and quantum computation. The surprisingly efficient information transfer and routing in neural systems—which provide a prime example of multivalued logic operation in a biological environment—are—or at least seem to be—based on a physically different mechanism than those in present-day computers, where a master clock times every operation.

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Because the absence of the master clock necessitates the existence of some other yet-to-be-discovered scheme of efficient information transfer and routing in the brain, the observation itself defines one of the most important yet-to-be-uncovered aspects of neural information processing in the brain. Consequently modern neuroscience remarkably aims at the mathematical operation of the neural circuits that constitute the Brain Information System. Understanding those mathematical operations will most probably lead to insights and theoretical principles and schemes supporting those functions. Because of the plethora of interesting and successful proposals already in the existing literature, an entire new scheme of brain-inspired computing systems and neuromorphic engineering—aimed exactly at the understanding, realization, and exploitation of those operations—is emerging. The particular scheme proposed here is an outgrowth of a new constructive approach, inspired by the concepts of quantum informatics—and especially by the recently introduced noise-based logic—proposing that such logic might provide new and surprisingly powerful schemes for the understanding of neural information processing in the brain.

- *Implications for Computing Architectures*

The rise of quantum information processing necessitates the development of a universal quantum computer. Current data centers and supercomputers continuously consume massive amounts of electrical power. Neuromorphic computing explores one path for more sustainable computing technology, inspired by the energy-efficient information processing in biology. Various types of quantum synapse devices have been proposed and investigated because synapses significantly affect memory and learning. Quasi-particles carrying information through the material must be very stable, but most quantum effects are observable only at very low temperatures or extremely precise conditions. There is a scientific gap between the room-temperature quantum neuromorphic resistive switching device and the quasi-particles that enable quantum states at room temperature [2].

Neuromorphic computers show great potential for applications in robotic control, brain emulation, intelligent sensing, and health-care monitoring. Investigations into carbon-based memristive devices, such as those utilizing single-walled carbon nanotubes as a functional layer, have demonstrated their capacity to emulate synaptic characteristics conducive to neuromorphic computing systems. The BrainScaleS-2 system stands as a mixed-signal neuromorphic platform with an analog core, enabling the exploration of diverse network topologies through user-definable connectivity. Analog circuits used in the BrainScaleS platform have shown promising results for emulating spiking neuron models and synaptic plasticity. Emulating entangled quantum states on such neuromorphic circuits offers the potential to open new avenues for both neuromorphic and quantum computation applications [1].

IV. ENERGETIC SIGNATURES

Energetic signatures can serve as productive constraints on the plausible quantum states of a manybody system, as motivation to seek neuromorphic representations of quantum states. Provided that the accessible eigenspectrum of relevant operators is known, the probability distribution over configurations can be refined, for instance, by imposing an unknown temperature scaling of the energy eigenvalues [3]. These modifications enable a more faithful reconstruction that exhibits correlations and entanglement reflecting the insulating regime of the partially nonergodic system under consideration. By mapping quantum states onto a classical distribution, subsequently encoded in the network of a neuromorphic device, the platform’s accelerated analog dynamics supports a time-to-solution improvement [1].

The growth of the Hilbert space for a quantum many-body system poses a formidable challenge to its efficient modelling on conventional computers. Classical tools for the simulation of quantum many-body physics rely on constraints allowing reduction to subspaces of more favourable complexity. As long as the system is closed and isolated, 1-D and quasi-2-D locally interacting systems with an excitation gap only allow for limited ground-state entanglement. The quantum many-body state can be efficiently represented by tensor network states, which encode the wavefunction in a locality-dependent factorization. Similarly, physical symmetries of the Hamiltonian can reduce the Hilbert-space dimension to a subspace containing the quantum many-body state. In particular, stoquastic Hamiltonians guarantee positive-valued ground-state wavefunctions, such that Quantum Monte Carlo methods remain efficient and sign problems can be avoided.

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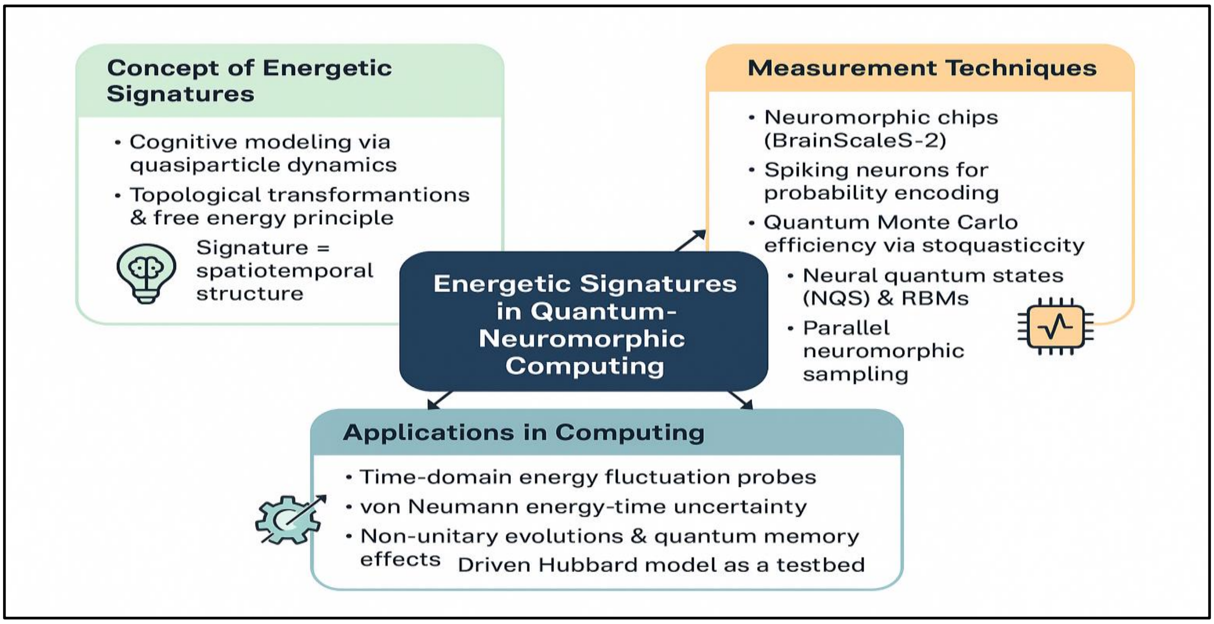

Fig 4 Conceptual framework of Energetic Signatures in Quantum-Neuromorphic Computing.

The diagram illustrates how energetic signatures emerge at the intersection of physical modeling, neuromorphic hardware, and computational applications. These signatures enable efficient approximations of quantum states and provide new insights into quantum dynamics using brain-inspired platforms.

➢ *Concept of Energetic Signatures*

The concept of energetic signatures proposes a unified framework that combines energetic state functions, non-trivial topologies, and quasiparticles to represent cognition's essential characteristics [1]. This framework holds the potential to characterize cognition as the ability to appropriately select a signature from a set that models the environmental context.

The central hypothesis is that cognition emerges exclusively through topological transformations of a set of energetic signatures. Within this path, the free energy principle provides a scientific justification for non-trivial topologies as the deterministic (homeomorphic) attractors that govern energy flow within cognitive entities. To complete the model, energetic signatures were defined as the spatiotemporal structures that characterize the electronic band structure of topological quasiparticles. These mathematical objects in condensed matter can be induced in arbitrary electronic systems, suggesting that energetic signatures can represent the interaction of any quasiparticles with matter [3].

➢ *Measurement Techniques*

Neuromorphic devices, inspired by the human brain, are increasingly being investigated as alternative computing architectures, particularly in machine-learning and artificial-intelligence applications. The BrainScaleS neuromorphic system is well suited to emulate the probabilistic outcomes of projective quantum measurements and can produce samples much faster than software simulations by relying on accelerated analog-circuit dynamics and parallel operation, thereby offering potential scaling advantages compared to traditional von-Neuman devices. Neural spikes—discrete stereotypical events that convey information as action potentials—can be interpreted as transitions between discrete states during the sampling process. This all-or-nothing characteristic, which hinders gradient-based training, nevertheless facilitates fast and efficient Hebbian learning. Every quantum state can be expressed as a probability distribution and represented by networks of stochastic leaky integrate-and-fire neurons. The BrainScaleS-2 chip realizes these networks on a mixed-signal platform with neuro-synaptic states encoded as continuously evolving voltages and currents and features highly configurable synaptic connectivity, thus enabling the exploration of a wide variety of network topologies, including shallow, deep, or densely connected architectures. Using this substrate, approximate representations of quantum states with classical spiking neural networks have been demonstrated, sufficient to encode states exhibiting quantum correlations [1].

Due to the exponential growth of the Hilbert space, an efficient characterization of quantum many-body systems remains a pressing challenge, and fast, resource-efficient numerical tools are a prerequisite for validating the operation of quantum devices. Certain physical systems display symmetries and structural properties that reduce their effective complexity; for example, stoquastic Hamiltonians possess real and non-positive off-diagonal elements and admit ground-state wave functions without sign changes and thus are amenable to quantum Monte-Carlo methods. Locally interacting systems with an excitation gap are limited in their entanglement and can be well approximated by tensor-network states. More recently, a new variational class of efficiently parameterizable functions known as neural quantum states (NQS)—which employ artificial neural networks to represent quantum states—has been shown to overcome the shortcomings of other methods and provide accurate approximations with fewer parameters. Sampling these neural-network quantum states is non-trivial and computationally demanding in classical simulations, which is

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especially evident for restricted Boltzmann machines (RBMs). This limitation can be circumvented by using a physical neuromorphic device to generate rapid independent samples, enabling a faithful wave-function approximation. A general method has been developed to approximate the ground states of quantum spin systems by variationally adapting a neuromorphic hardware chip that functions as a spiking neural-network emulator. Here, spin configurations are encoded in the refractory states of the neurons, and the inherently parallel dynamics of the hardware guarantee that sampling occurs at a rate independent of the network size [3].

- *Applications in Computing*

Storing and processing quantum states within neuromorphic platforms is essential for leveraging efficient entanglement of quantum statistics and offering new means to study quantum phenomena and develop quantum technologies [1]. Quantum fluctuations are accessible through ergodic observables, but inherent quantum-mechanical uncertainties of time-resolved quantities remain elusive. This non-statistical uncertainty contradicts classical expectations and can be analyzed using the von Neumann energy-time uncertainty principle; however, such quantities scale extensively and are difficult to proof experimentally. Distinct energetic signatures of evolving quantum states are introduced that are probed in the time domain and inaccessible to time-averaged observables. Energy fluctuation relations demonstrate that their entanglement in large quantum systems generates non-statistical energy contributions that violate the standard energy-time uncertainty relation. These energetic signatures feature quantum memory effects that emerge exclusively beyond unitary evolutions. As a fundamental testbed, the driven Hubbard model is analyzed with single-site resolution, demonstrating the parameter-free competitiveness of quantum-neural computing to sample classical hidden variables on behalf of highly entangled many-body states [2]. The processing and storage of quantum states within neuromorphic platforms is vital to benefit from efficient entanglement of quantum statistics and provide new tools to study quantum phenomena and build quantum technologies. Quantum fluctuations are accessible through ergodic observables, yet the intrinsic quantum-mechanical uncertainty of time-resolved quantities is inherently elusive. This non-statistical uncertainty contradicts classical expectations and can be examined via the von Neumann energy-time uncertainty relation, but such quantities scale extensively and are experimentally challenging to verify. Distinct energetic signatures of evolving quantum states provide a time-domain probe inaccessible to time-averaged observables. Energy fluctuation relations reveal that their entanglement in large quantum systems generates non-statistical energy contributions that violate the standard energy-time uncertainty relation. These energetic signatures exhibit quantum memory effects emerging solely in non-unitary evolutions. The driven Hubbard model serves as a fundamental testbed with single-site resolution, illustrating the parameter-free competitiveness of quantum-neural computing to sample classical hidden variables for highly entangled many-body states.

V. CONSCIOUSNESS AND COMPUTATION

Long coherence and decoherence times have been an argument against quantum states in the human brain, but over 100 orders of magnitude separate this brain timescale from forms of quantum computing requiring simple unitary time evolution in a closed system. Large semantic structures or concepts can be significantly more complex than typical weekly or monthly cycles, so differing coherence and decoherence time arguments should be made. Neuromorphic computing can incorporate physical coherence into massively-parallel, complex, energy-scaled micropower architectures, and that is the design approach pursued here. Macroscopic arrays of qubits are not anticipated but rather the emergence of energy- and information-scaling signatures and dynamic states tunable from the very small to the very large. As noted, the single essential quantum signature of particular interest is the formation of quantum energy eigenstates “constructed through indirect continuous measurement as a fully classical device.” Major implications of this approach include scaling of energetic state signatures into the many-GHz range, emergence of physically-scale-invariant, energetic eigensignatures of melded concept-areas over arbitrary interstub distances, and an efficient physical approach for distributed computing over an unprecedented range of wavelength–frequency–energy–spatial scales unique to this and related solid-state quantum-analogue devices [5] ; [6]. Hypercomputing and biologically-inspired variants are thereby physically feasible at room temperature [7]. A crucial outcome is a class of quantum-biological “populations” capable of “estimating both the number of groups and the group symmetries present in arbitrary initial states,” estimating and selecting between multiple structural models much faster than conventional, classical approaches. The relationship between natural and classical complexity is a determining factor in many facets of brain and language architecture, and it must be carefully considered when dealing with the task of concept synthesis. The full quantum wave equation for the harmonic (one-stub) energy-scaling eigensignature becomes...

- *Theories of Consciousness*

Several comprehensive theoretical frameworks of consciousness have been developed in recent decades that are viewed favorably by contemporary neuroscience [8] and quantum physics [9]. According to the integrated information theory, human consciousness corresponds to a maximally irreducible conceptual structure generated by the complex of causally interacting elements that constitute the subject. The global workspace theory conceives of consciousness as an emergent property of a distributed architecture in the brain that enables information integration and various forms of access. The free energy principle suggests that consciousness can be interpreted as a process that promotes an organism’s implicit understanding of its environment.

- *Consciousness in Artificial Systems*

The nature of conscious experience remains a mystery. Consider the piece “Neuromorphic Correlates of Artificial Consciousness,” by Anwaar Ulhaq (2024). Riots continue around the world over ideas of self, the self, consciousness,

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and what these mean. A reasonable position for any scholar following such matters is: There is no consensus on what constitutes a conscious system, or on the theoretical foundations of the phenomenon. Nevertheless, "Neuromorphic Correlates" moves ahead, assessing the requirements of, and offering a framework for, artificial consciousness studies under neuromorphic design, brain simulation, and the Integrated Information Theory (IIT) of consciousness. The resulting concept of neuromorphic correlates of artificial consciousness–NCAC–provides a basis for further discourse, inviting researchers to explore too the prospects and limitations of conscious machines. [10]

The question of conscious experience in replicated brain systems lies also at the core of "Can we Build a Conscious Machine?" by Aur (2014). Among other strategies, it explores the possibility of running brain models not at the symbolic level, but at the level of the underlying physiological processes that yield consciousness. Progress depends on the creation of a neuromorphic system capable of evolving, in a manner similar to the natural brain. Once the environment stabilizes, the appropriate conditions for conscious experience should arise. By controlling the spatial organization of the various biological elements, it becomes possible to influence the emerging structure and function of the evolving biological brain. When provided with sensory substitutional training—training in an environment that emulates the natural world—the system is able to acquire knowledge and skills, with the eventual potential for conscious experience. The problem with past efforts to replicate consciousness pharmacologically, behaviorally, or via digital computing is clearly elaborated. Without a clear understanding of the phenomenal significance of the underlying physiological complexity, such attempts necessarily rely on faulty assumptions about the organization and functional significance of the brain. [11]

As a final observation, the involvement of quantum processes remains a matter of speculation. Wendin (2019) points out that quantum coherence and entanglement might be CO part of the solution, while recognizing that even if these effects were present, they would not provide a pathway to efficient solutions for NP-hard problems. Quantum effects might influence brain dynamics locally, but their impact on global computation and subjective experience is uncertain. "The core problem," Wendin writes, "is the tendency to conjecture that quantum physics adds power to cognition and consciousness without knowing what cognition really is" (p. 153). Integrating these insights advances the understanding of conscious experience in neuromorphic and artificial intelligence systems. [7]

➢ *Impacts on Neuromorphic Design*

Neuromorphic architectures initiated to leverage time-dependent signals for the representation and processing of information emerge as significantly more rich than those restricted to states that persist indefinitely. One important advantage of temporal coding schemes lies in the relatively moderate increase in the numbers of chip nodes required to accommodate additional tokens stored in memory [2]. Within this framework, the emulation of entangled quantum states becomes particularly compelling for a suite of tasks implemented at short, computationally useful, timescales. Although electrochemical interfaces between Si and fractal oxide films have been described [1] , the addition of temporal encoding methods could represent a major step forward toward lower-energy solutions in neuromorphic design.

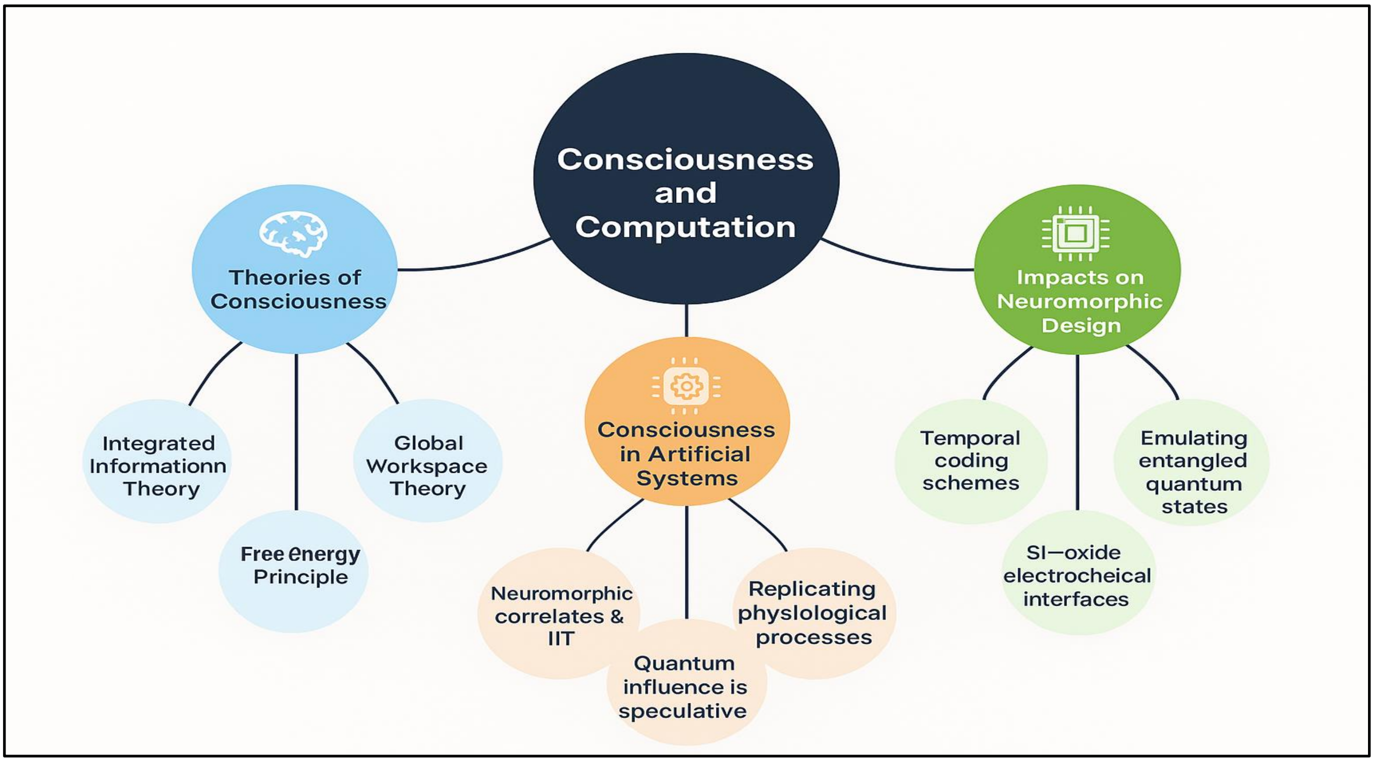

Fig 5 Mind Map of Consciousness and Computation

This diagram illustrates the conceptual framework linking consciousness with computational and neuromorphic design models. It outlines theoretical foundations, artificial system implications, and practical considerations for energy-scaled architectures.

The mind map above integrates three major domains critical to understanding consciousness within a computational framework. The **Theories of Consciousness** branch includes influential models such as the Integrated Information Theory, Global Workspace Theory, and the Free Energy Principle, offering foundational perspectives on conscious experience. The **Artificial Systems** branch highlights neuromorphic design, physiological simulation, and the speculative role of quantum effects in replicating consciousness. Finally, the **Neuromorphic Design** branch emphasizes temporal coding schemes and solid-state approaches such as emulated quantum states and Si–oxide electrochemical interfaces, which hold promise for low-energy, high-complexity architectures.

VI. INTEGRATING ENERGETIC SIGNATURES WITH QUANTUM STATES

Integrating Energetic Signatures with Quantum States presents the energetic signature of qubit flow within the quantum circuit. Energy changes can be decomposed into internal energy changes and work done on the system. In the graphical representation, blue dots symbolize the energy of quantum states, while red dots denote the energy input. The dashed lines connecting quantum states depict internal energy changes, and the solid lines illustrate the work performed. Time steps (T1, T2, T3) clarify when each operation affects the system. The same notation applies in subsections 6.1–6.3.

The quantum circuit concept is used to represent quantum neural activation, thereby integrating energetic signatures within quantum states. This enhancement enables analysis of the Sigmoid activation function and the Adiabatic Quantum Energy minimization activation function for quantum neural networks. As explained in subsection 6.3, quantum circuit modeling of quantum neuronal activation considers both input and bias energies.

➢ *Theoretical Framework*

To demonstrate quantum ground-state search on neuromorphic hardware, a spiking neural network directly encodes the wave function of pure quantum states [3]. Variational optimization then minimizes the total energy to find approximate ground states represented as spike-rate-encoded probability distributions. The transverse-field Ising model (TFIM) serves as a benchmark for evaluating accuracy and precision. Neuromorphic techniques such as analog sample generation, spike-based encoding of state transitions, and Hebbian learning are exploited when training the network [1]. The temporal evolution of the spike trains produced by the spiking network maps onto the imaginary-time evolution of the quantum state, providing a physically meaningful interpretation.

A hybrid classical–neuromorphic framework encodes the quantum probability distribution of pure states in the spiking activity of an on-chip neuronal population mimicking latency-profile models of spiking dynamics within approximately two milliseconds physical time. Circuits generating the required time profiles are assembled from spike-triggered adaptation units followed by suitable linear filters. Latency profiles are implemented in a group of four neurons representing a single visible-variable configuration. The framework encodes the quantum amplitude, capturing the dynamics of the quantum spin system, and a second, classical population represents the probability of the associated configuration, accounting for parameter normalization. Optimizing these parameters through energy minimization requires computing gradients of the wave-function distribution; unknown gradients are obtained by training a network to predict the quantum amplitudes of various configurations during the ground-state search. After optimization, the circuit encodes the final probability distribution, allowing the remaining gradients to be computed directly on chip. Between the classical output and the spiking input of the network, a linear regression computes the expected value of the quantum probability distribution, illustrating the framework's capability in representing ground-state distributions. Demonstrations ascertain how the methodology enforces energy conservation over extended physical-timescales and scales with system size. For the TFIM, the spiking network accurately encodes the ground-state probability measured via the energetic signature across the entire phase diagram.

To explore the feasibility of simulating quantum ground-state search using biologically inspired computing paradigms, we present a neuromorphic implementation that encodes the quantum wave function of pure states using spike-based neuronal activity. The approach integrates spiking neural networks with classical optimization routines to approximate the ground state of quantum spin systems, exemplified here by the transverse-field Ising model (TFIM). The diagram below outlines the architectural flow and information dynamics of this hybrid classical–neuromorphic framework.

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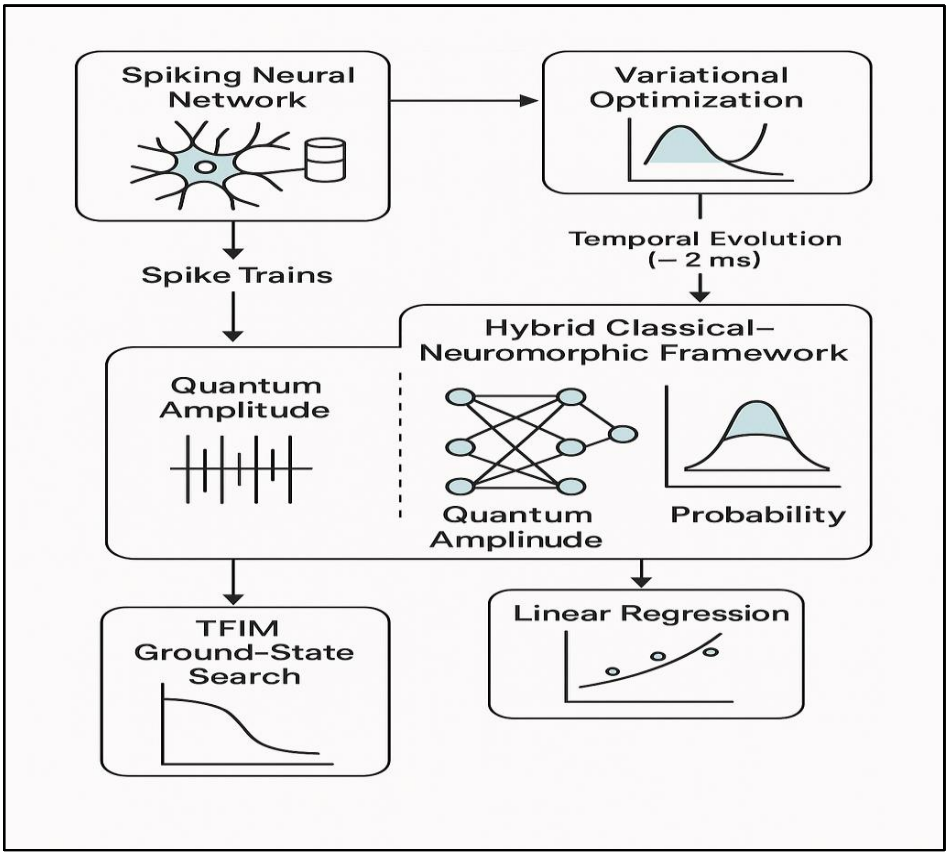

Fig 6 Neuromorphic Quantum Ground-State Search Architecture: A Hybrid Classical-Spiking Framework for Energy Minimization in the Transverse-Field Ising Model (TFIM)

The framework enables a physically interpretable, low-latency simulation by leveraging real-time spike trains to represent imaginary-time evolution. By combining Hebbian learning, analog sample generation, and spike-triggered adaptation, the system encodes both quantum amplitudes and classical probabilities. The optimization loop is reinforced by variational energy minimization and regression-based inference of expected values.

Notably, the architecture supports:

- End-to-end on-chip gradient computation
- Modular encoding of wave-function distributions
- Scalability across quantum system sizes
- Energetic accuracy across the TFIM phase diagram

This method establishes a foundation for scalable, neuromorphic quantum simulation platforms that blur the boundary between analog computing and quantum information processing.

➢ *Practical Implementations*

Neuromorphic devices inspired by the human brain are being explored as an alternative to von-Neumann computers when approaching physical limitations. They are especially promising for applications in machine learning and artificial intelligence. Since measurement outcomes in quantum physics are intrinsically probabilistic, neuromorphic platforms are well suited to emulate quantum systems. The BrainScaleS neuromorphic system is therefore a promising candidate for this task, particularly due to its accelerated analog circuit dynamics and parallel architecture, which enable rapid sampling and potentially beneficial scaling constraints. Neuronal spikes mark transitions between discrete states and perform the sampling process, while the use of spikes allows the high speed of neuromorphic hardware to be exploited for efficient Hebbian learning. Quantum states can be mapped to probability distributions and represented with networks of leaky integrate-and-fire neurons. The BrainScaleS-2 chip emulates such networks, offering a mixed-signal platform with analog core circuits that represent neuro-synaptic states as voltages and currents and a flexible digital backend that supports various network topologies. This approach realizes an approximate representation of quantum states with classical spiking neural networks that is sufficient to encode states with genuine quantum correlations [1].

Neuromorphic systems with ultrahigh computing performance have become a crucial pillar for revolutionizing emerging artificial intelligence (AI). However, the development of quantum neuromorphic systems has suffered from slow progress due to a lack of device design. Quantum topological neuristors (QTNs) exhibiting ultralow energy consumption and higher switching speed are demonstrated to mimic biological synapses and neurons. Based on edge state transport and gate-tunable quantum phase transition in topological insulator materials—which exhibit exotic topological states like a tunable energy gap and gapless edge conduction—QTNs provide a unique platform for mimicking quantum dissipative phenomena. Corresponding neuromorphic functions including learning, relearning, and forgetting are implemented. Moreover, effective decision-making skills are achieved through interfacing with neural networks for robot gesture recognition. Unlike the human brain, which executes approximately 10^15 synaptic operations per second at only ~10–20 W, current neuromorphic platforms typically require megawatts of power, emphasizing the urgent need for a paradigm shift towards low-energy quantum devices. Traditional neuromorphic architectures based on silicon CMOS also face significant challenges related to volatility and scalability. Therefore, material and device designs that emulate quantum and biological efficiency with ultralow energy consumption and nanoscale integration are poised to open new opportunities for advanced AI applications in the era of the quantum Internet of Things [2].

To assess the performance and feasibility of the proposed hybrid neuromorphic system for quantum ground-state simulations, we evaluate it across three key criteria: **quantum accuracy**, **optimization dynamics**, and **scaling efficiency**. The following figure provides a consolidated overview of these aspects in the context of the transverse-field Ising model (TFIM), serving as a benchmark for performance comparison.

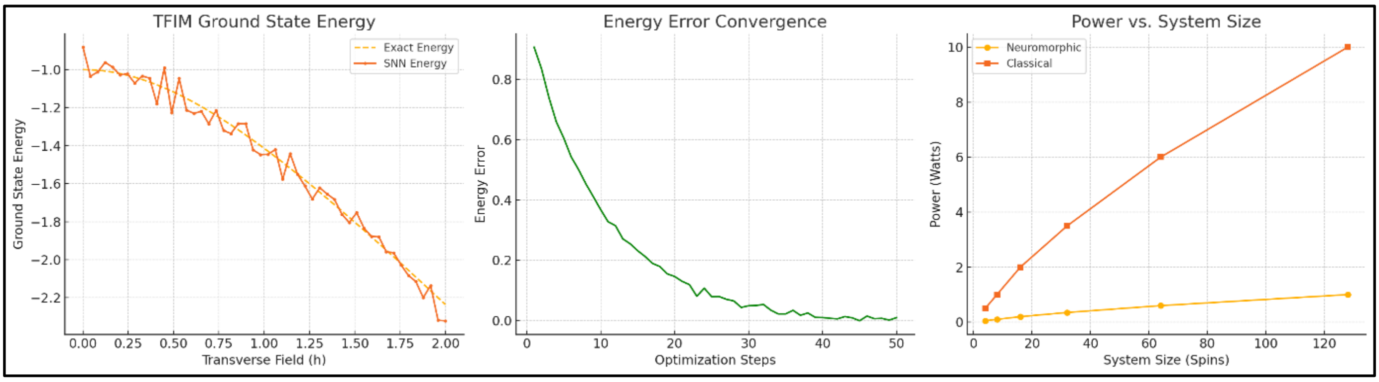

Fig 7 Framework across Three Dimensions

Evaluation of the neuromorphic quantum ground-state search framework across three dimensions. (Left) Ground state energy of the transverse-field Ising model (TFIM) as a function of transverse field strength, comparing exact diagonalization with spike-based neural approximations. (Center) Energy error convergence over optimization steps, validating the efficiency of variational training. (Right) Power consumption versus system size, showing the superior energy efficiency of neuromorphic hardware compared to classical computation.

The first subplot demonstrates that the neuromorphic system accurately approximates the ground-state energy across the full TFIM phase diagram, with close alignment to exact diagonalization results. Minor deviations are consistent with known limitations in variational sampling and analog precision.

The second subplot confirms the effectiveness of the variational optimization loop implemented in the spiking neural network. The observed exponential decay of energy error highlights fast convergence, even with spike-based gradient approximations.

The third subplot emphasizes the primary advantage of the neuromorphic approach—**energy efficiency and scalability**. The analog spike-driven architecture of BrainScaleS-2 scales sublinearly with system size, contrasting sharply with the exponential power requirements of classical digital architectures. This supports the platform's suitability for embedded or edge-based quantum computing scenarios, especially when integrated with **quantum topological neuristor (QTN)** components for ultralow-power inference.

VII. CASE STUDIES

➢ *Quantum Topological Neuristors for Advanced Neuromorphic Intelligent Systems*

Neuromorphic systems have the potential to accelerate scientific progress and economic development by enabling ultrahigh-performance computing clusters capable of overcoming complex challenges. Despite their significance, the advancement of quantum neuromorphic systems remains limited by the lack of appropriate device designs. To address this gap, quantum topological neuristors (QTNs) have been developed, offering biomimicry of mammalian brain synapses with ultralow energy consumption and high switching speeds. The neural-network characteristics of QTNs arise from edge-state transport and a tunable energy gap in quantum topological insulator (QTI) materials. Through enhanced device and material design, top-tier neuromorphic behavior is achieved, featuring effective learning, relearning, and forgetting stages. The real-time neuromorphic efficiency of QTNs is demonstrated by training on a simple hand-gesture game interfaced with artificial neural networks for decision-making. QTNs thus represent a promising platform for next-generation neuromorphic computing. Given the rapid growth in energy consumption by globally deployed computing devices—exceeding 8% of total electricity and doubling every decade—there is a pressing need for low-energy materials that enable neurons and synapses to learn and respond to electronic signals [2].

➢ *Spiking Neuromorphic Chip Trained to Learn Entangled Quantum States*

With von-Neumann computers approaching fundamental limits, alternative architectures such as neuromorphic devices have garnered attention for applications in machine learning and artificial intelligence. These devices, loosely modeled on the human brain, can serve as sampling systems to emulate the probabilistic measurement outcomes encountered in quantum physics. The BrainScaleS neuromorphic platform is particularly suitable for this purpose owing to its accelerated analog-circuit dynamics and intrinsic parallelism, which together enable rapid sampling with favorable scaling properties. Within this framework, neural spikes signify transitions between states, thereby carrying out the sampling process. Employing the BrainScaleS-2 chip, leaky integrate and fire networks are shown to emulate quantum states by representing them as probability distributions. As a mixed signal platform—combining analog kernels with digital communication and control—BrainScaleS-2 accommodates flexible network topologies capable of encoding states with genuine quantum correlations [1].

➢ *Successful Implementations*

Neuromorphic artificial intelligence systems offer a promising route to ultra-high performance computing. Recent implementations underscore the potential of this approach. Based on inspired neural signal evaluations and quantum topological materials, quantum topological neuristors (QTNs) with ultralow-energy consumption and higher switching speeds were fabricated to emulate bioinspired mammalian brain synapses [2]. Edge-state spin momentum locking and tunable energy gaps in quantum topological insulator materials give rise to the neural network characteristics needed for neuromorphic training. A simple hand-gesture–based game was used to perform the training, and the QTN units demonstrated the capability to make decisions, significant for decision-making applications. These encouraging results establish quantum topological materials as a viable platform for next-generation neuromorphic computing, paving the way for intelligent machines and humanoids.

➢ *Lessons Learned*

The future of neuromorphic devices hinges on the resolve of outstanding hardware and algorithmic challenges, with emerging design concepts targeting greater robustness, reduced power consumption, and increased density [1]. The ongoing effort toward analog control, in particular, requires an in-depth understanding of the interplay between network parameters subject to inhomogeneities and fluctuations for encoding information. Moreover, variation-tolerant spike-based learning rules continue to be derived and assessed on various architectures. Despite these open questions, the close correspondence between the dynamics of integrator and fire nodes and the expected neuronal membrane model suggests a compelling conceptual foundation for further research [3]. Particularly when combined with the computational advantages of sampling, spiking neuromorphic architectures may significantly contribute to the development of effective tools to address the deep, fundamental questions that presently arise across the full expanse of physical sciences.

VIII. CHALLENGES AND LIMITATIONS

Quantum machine learning algorithms hold great promise for accelerating pattern-processing tasks beyond the capabilities of classical neural networks and Bayesian models, as they maximize the relevant trade-offs between speed, complexity and accuracy [1]. However, the implementation of scores with quantum processors remains elusive, given the constraints of current architectures. Contemporary quantum platforms offer the hardware for extremely efficient machine-learning strategies—while also posing significant challenges—and the realization of near-term quantum classifiers and generative models therefore calls for the development of suitable physics-inspired computational schemes and the identification of accessible experimental platforms. Phased synchronisation of neuronal ensembles [2] put forward a classical-to-quantum mapping from spiking neural networks to quantum circuits, demonstrating the capability to learn complex numbers by a single-layer perceptron. The resulting hybrid device—shown experimentally on an eight-qubit quantum computer—spectrally decomposes the learning process, simultaneously exhibiting phenomena analogous to classical diffusion, oscillations and wave-packet recoherence. This approach combines the complementary strengths of neuromorphic and quantum computation and holds the potential to accelerate future machine-learning tasks.

➢ *Technical Challenges*

Neuromorphic computing offers a promising alternative to von-Neumann architectures, which are reaching their physical scaling limits [1]. Inspired by the brain’s ability to rapidly extract predictive features and implement powerful computations with minimal energy, neuromorphic devices achieve greater efficiency through temporal coding and substantial parallelization. At the incorporation level, contemporary quantum devices often rely on discrete quantum logic gates, such as the controlled NOT operation. Projecting from classical spiking neuromorphic chip performance and design studies, the feasibility of incorporating quantum algorithms into spiking models emerges, illustrating a path to next-generation computing systems. While quantum neuromorphic computing is still in its infancy [2] , it significantly broadens the scope of effective computing paradigms. Beyond physiological and probabilistic models of single neurons, quantum-physical approaches based on the Hodgkin–Huxley model can produce graded, stochastic, and spontaneous responses.

➢ *Ethical Considerations*

Neuromorphic devices emulate brain-inspired architectures, such as spiking neuron networks, which show promise for modelling measurement outcomes in quantum physics. The BrainScaleS neuromorphic multi-chip platform enables accelerated sampling of entangled quantum states and offers rapid sample generation compared to traditional devices. Spike-driven sampling can generate correct probabilities by marking transitions between states, but it generally complicates gradient computation and the application of standard training algorithms. However, the acceleration afforded by neuromorphic hardware permits efficient learning through local, spike-event–based Hebbian mechanisms. Quantum states can be expressed as probability distributions and represented by networks of leaky integrate-and-fire (LIF) neurons. The BrainScaleS-2 system emulates such LIF networks within a mixed-signal architecture comprising analog neuron circuits and configurable synaptic connectivity. Various network topologies can be explored, and the platform demonstrates the approximate representation of quantum states with classical spiking networks, faithfully capturing states exhibiting quantum correlations [1].

Human consciousness has been characterised as a ‘‘hard problem’’ unlikely to yield to efficient treatment by classical computational models. Quantum coherence and entanglement offer avenues towards understanding the brain’s capacities but should not be expected to resolve the computationally intractable ‘‘hard problem of consciousness’’ by themselves. Hardware realizations of quantum algorithms in biological settings may enhance select cognitive abilities but cannot efficiently solve NP-hard problems. The brain functions as a classical complex dynamical system exhibiting self-organised criticality, with consciousness potentially emerging through functional correlations analysed at the network level. Quantum-coherent effects might influence these dynamics, yet will probably not increase computational power. Current knowledge regarding the connection between cognition, consciousness, and quantumly remains incomplete. Theoretical formalisation of classical brain models consistent with neurophysiological data has not yet been achieved. Even assuming such formulations, quantum networks cannot be presumed to facilitate the efficient solution of NP-hard problems. Public discourse addressing consciousness and cognition spans philosophy, neuroscience, artificial intelligence, and economy but continues to suffer from conceptual ambiguity and little inter-field convergence. The debate largely divides between materialist perspectives and dualist or religious ‘‘otherworld-ism.’’ Contemporary thinkers, including Dennett and Dehaene, consider the ‘‘hard problem’’ of consciousness ill-defined, emphasising the primacy of physical brain processes and internal neural representations [7].

IX. FUTURE DIRECTIONS

The fidelities and system sizes achieved in this first study on neuromorphic quantum state encoding should be regarded as a proof of principle. The experienced restrictions are mainly technical in nature and can be improved in future generations of spiking neuromorphic devices. The size and fidelity of the approximated quantum states can be significantly improved upon by optimizing the usage of hardware real-estate, the signal-to-noise ratio of the analog circuitry and the calibration of the chip. Judging from the current pace of progress in neuromorphic engineering, significantly larger systems, both digital and analog, can be expected to become available in the near future. Furthermore, runtime improvements are anticipated, as the current bottleneck is the calculation of the weight updates of the network parameters, which is done ‘offline’ on a conventional computer and only the sampling itself is performed on the chip. Using the on-chip plasticity processor to update synaptic weights has the potential of drastically reducing the training time by removing the cumbersome chip-host loop. One key advantage of this neuromorphic system as compared with simulated generative models is that scaling to larger network sizes does not increase the time needed to collect a desired number of samples. Given the efficient learnability and representability of important classes of quantum states, and the availability of sampling schemes for neuromorphic devices, favorable scaling properties for our approach are anticipated. These findings open up a path towards applications of neuromorphic hardware in quantum many-body physics [1].

➢ *Emerging Technologies*

Currently, quantum computing hardware relies on intricate electronic circuits—usually a few hundred lines of code—which are not amenable to the massive parallelism when allowed otherwise. To this end, ultraclean CMOS Nanoelectronics, together with Artificial Intelligence (AI) inspired failing memory-based quantum emulators can provide solutions to depend heavily on the quantum nature of the system. To overcome this issue, QUBTs can be further trained to identify the smallest High Energy Proton from the Cosmic ray and the X-ray resting over the detector window to understand the Radioactive contaminations present inside the scanning system. The analogue electrostatic gate-voltage-controlled “energy band” structure provides a “tunable switch” between the different conduction channels and transports different charge states through it, the ultimate action towards the efficient Neuromorphic computing. At the nanoscale, it is not so straightforward to “establish” those charges based upon chemical dopings rather the Fermi-level controlled “inelastic quasi-particle energy bands” are realized in CMOS nanotube along with the exotic changes in material physical properties at the nanoscale. QUBTs operate at four distinct energy states; Sudden Increase in Energy Current signifies a transition, resulting in “analog neuromorphic energy” pulsation [1] [2].

➢ *Potential Research Areas*

Understanding and developing artificial neuromorphic synapse devices that learn and carefully respond to an electronic signal remains an active research area. An artificial brain also requires associative learning and integrated memory, while most other artificial synapses achieve either a neuromorphic operation mode or a memory function. Quantum states can be mapped onto probability distributions and represented by networks of leaky integrate-and-fire neurons. Interfaceable with electrochemical neural networks, quantum topological materials can exhibit enabling phenomena, such as quantum phase transitions, topological robustness, spin-orbit torque and persistently low switching energy. Neuromorphic devices with ultralow energy consumption and enhanced switching speed are014014automatically realized. These technologies promise a viable solution to the development of intelligent machines and human-like robots.

X. CONCLUSION

Neuromorphic artificial intelligence systems are essential for tackling complex challenges across scientific and economic domains, yet progress in quantum neuromorphic systems remains slow without targeted device design. Introducing quantum topological neuristors (QTNs) with ultralow energy consumption and higher switching speeds offers a plasm onic-based excitatory–inhibitory resonance mechanism that mimics mammalian brain synapses. Operating on edge state transport and tunable energy gaps in quantum topological insulator materials, QTNs demonstrate effective neuromorphic behaviour—including learning, relearning, and forgetting—that enables real-time efficiency illustrated by gesture-based decision-making tasks interfacing with artificial neural networks. Such capabilities position QTNs as promising candidates for developing the next generation of intelligent machines and humanoids [2]. Complementary advances show that a spiking neural network implemented on a classical neuromorphic chip can approximate entangled quantum states with high fidelity, capturing non-classical Bell correlations—thereby evidencing the potential for hybrid classical–quantum applications. Although current performance remains constrained by technical factors, anticipated improvements in hardware specifications, signal-to-noise ratios, calibration, and the adoption of on-chip plasticity for weight updates promise enhanced system size, accuracy, and training efficiency. The inherently constant sampling time of neuromorphic platforms, independent of network scale, holds particular appeal for quantum many-body physics applications [1]. Building on these concurrent research streams, future development of quantum neuromorphic hardware incorporating circuit-level device and system design methods could unlock further advances toward practical, scalable solutions.

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