

# Research Papers on 'Quantum'

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## Paper 1:

### **Ultrahigh free-electron Kerr nonlinearity in all-semiconductor waveguides for all-optical nonlinear modulation of mid-infrared light**

Date: 2025-03-06

Time: 18:57:25

Authors:

Gonzalo Álvarez-Pérez, Huatian Hu, Fangcheng Huang, Tadele Orbula Otomalo, Michele Ortolani, Cristian Ciraci

#### Summary:

- Nonlinear optical waveguides, particularly those harnessing the optical Kerr effect, are promising for advancing next-generation photonic technologies. Despite the Kerr effect's ultrafast response, its inherently weak nonlinearity has hindered practical applications. Here, we explore free-electron-induced Kerr nonlinearities in all-semiconductor waveguides, revealing that longitudinal bulk plasmons (inherently nonlocal excitations) can generate exceptionally strong Kerr nonlinearities. We specifically develop a nonlinear eigenmode analysis integrated with semiclassical hydrodynamic theory to compute the linear and nonlinear optical responses originating from the quantum behavior of free electrons in heavily doped semiconductors. These waveguides achieve ultrahigh nonlinear coefficients exceeding  $10^7 \text{ W}^{-1} \text{ km}^{-1}$  and support long-propagating modes with propagation distances over  $100 \text{ }\mu\text{m}$ . Additionally, we confirm the robustness of the nonlinear response under realistic conditions by considering viscoelastic and nonlinear damping mechanisms. Finally, we implement our all-semiconductor waveguides in a Mach-Zehnder interferometer, demonstrating efficient nonlinear modulation of the transmittance spectrum via the free-electron Kerr effect. This work evidences the transformative potential of free-electron nonlinearities in heavily doped semiconductors for photonic integrated circuits, paving the way for scalable on-chip nonlinear nanophotonic systems.

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## **Paper 2:**

### **Scalable and Site-Specific Frequency Tuning of Two-Level System Defects in Superconducting Qubit Arrays**

Date: 2025-03-06

Time: 18:49:46

Authors:

Larry Chen, Kan-Heng Lee, Chuan-Hong Liu, Brian Marinelli, Ravi K. Naik, Ziqi Kang, Noah Goss, Hyunseong Kim, David I. Santiago, Irfan Siddiqi

Summary:

- State-of-the-art superconducting quantum processors containing tens to hundreds of qubits have demonstrated the building blocks for realizing fault-tolerant quantum computation. Nonetheless, a fundamental barrier to scaling further is the prevalence of fluctuating quantum two-level system (TLS) defects that can couple resonantly to qubits, causing excess decoherence and enhanced gate errors. Here we introduce a scalable architecture for site-specific and in-situ manipulation of TLS frequencies out of the spectral vicinity of our qubits. Our method is resource efficient, combining TLS frequency tuning and universal single qubit control into a single on-chip control line per qubit. We independently control each qubit's dissipative environment to dynamically improve both qubit coherence times and single qubit gate fidelities -- with a constant time overhead that does not scale with the device size. Over a period of 40 hours across 6 qubits, we demonstrate a 36% improvement in average single qubit error rates and a 17% improvement in average energy relaxation times. Critically, we realize a 4-fold suppression in the occurrence of TLS-induced performance outliers, and a complete reduction of simultaneous outlier events. These results mark a significant step toward overcoming the challenges that TLS defects pose to scaling superconducting quantum processors.

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## **Paper 3:**

### **Anyon Theory and Topological Frustration of High-Efficiency Quantum LDPC Codes**

Date: 2025-03-06

Time: 18:46:14

Authors:

Keyang Chen, Yuanting Liu, Yiming Zhang, Zijian Liang, Yu-An Chen, Ke

Liu, Hao Song

Summary:

- Quantum low-density parity-check (QLDPC) codes present a promising route to low-overhead fault-tolerant quantum computation, yet systematic strategies for their exploration remain underdeveloped. In this work, we establish a topological framework for studying the bivariate-bicycle codes, a prominent class of QLDPC codes tailored for real-world quantum hardware. Our framework enables the investigation of these codes through universal properties of topological orders. Besides providing efficient characterizations for demonstrations using Gröbner bases, we also introduce a novel algebraic-geometric approach based on the Bernstein--Khovanskii--Kushnirenko theorem, allowing us to analytically determine how the topological order varies with the generic choice of bivariate-bicycle codes under toric layouts. Novel phenomena are unveiled, including topological frustration, where ground-state degeneracy on a torus deviates from the total anyon number, and quasi-fractonic mobility, where anyon movement violates energy conservation. We demonstrate their inherent link to symmetry-enriched topological orders and offer an efficient method for searching for finite-size codes. Furthermore, we extend the connection between anyons and logical operators using Koszul complex theory. Our work provides a rigorous theoretical basis for exploring the fault tolerance of QLDPC codes and deepens the interplay among topological order, quantum error correction, and advanced mathematical structures.

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## **Paper 4:**

### **Origin and emergent features of many-body dynamical localization**

Date: 2025-03-06

Time: 18:26:37

Authors:

Ang Yang, Zekai Chen, Yanliang Guo, Manuele Landini, Hanns-Christoph Nägerl, Lei Ying

Summary:

- The question of whether interactions can break dynamical localization in quantum kicked rotor systems has been the subject of a long-standing debate. Here, we introduce an extended mapping from the kicked Lieb-Liniger model to an effective lattice model with long-

range couplings and reveal two universal features: on-site pseudorandomness and rapidly decaying couplings in the center-of-mass momentum. For finite contact interactions, the long-range coupling between relative momenta obeys an algebraic decay behavior with a crossover of its decay exponent as the interaction increases. Similar behavior occurs in the Fock basis, underscoring the robustness and distinct many-body characteristics of dynamical localization. Analysis of the generalized fractal dimension and level-spacing ratio also supports these findings, highlighting the presence of near integrability and multifractality in different regions of parameter space. Our results offer an explanation for the occurrence of many-body dynamical localization, particularly in strongly correlated quantum gases, and are anticipated to generalize to systems of many particles.

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## **Paper 5:**

### **Characterizing $S=3/2$ AKLT Hamiltonian with Scanning Tunneling Spectroscopy**

Date: 2025-03-06

Time: 18:12:53

Authors:

M. Ferri-Cortés, J. C. G. Henriques, J. Fernández-Rossier

Summary:

- The AKLT Hamiltonian is a particular instance of a general class of model Hamiltonians defined in lattices with coordination  $z$  where each site hosts a spin  $S=z/2$ , interacting both with linear and non-linear exchange couplings. In two dimensions, the AKLT model features a gap in the spectrum, and its ground state is a valence bond solid state; that is an universal resource for measurement based quantum computing, motivating the quest of physical systems that realize this Hamiltonian. Given a finite-size system described with a specific instance of this general class of models, we address the question of how to assess if such system is a realization of the AKLT model using inelastic tunnel spectroscopy implemented with scanning tunnel microscopy (IETS-STM). We propose two approaches. First, in the case of a dimer, we show how to leverage non-equilibrium IETS-STM to obtain the energies of all excited states, and determine thereby the magnitude of both linear and non-linear exchange interactions. Second, we explore how IETS can probe the in-gap excitations associated to

edge spins. In the AKLT limit, spins  $S=3/2$  at the edge of the lattice have coordination 2, giving rise to  $S=1/2$  dangling spins that can be probed with IETS. We propose a  $S=1/2$  effective Hamiltonian to describe the interactions between these dangling spins in the neighborhood of the AKLT point, where their degeneracy lifted.

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## **Paper 6:**

### **Integrability and charge transport in asymmetric quantum-circuit geometries**

Date: 2025-03-06

Time: 18:07:53

Authors:

Chiara Paletta, Urban Duh, Balázs Pozsgay, Lenart Zadnik

#### **Summary:**

- We revisit the integrability of quantum circuits constructed from two-qubit unitary gates  $U$  that satisfy the Yang-Baxter equation. A brickwork arrangement of  $U$  typically corresponds to an integrable Trotterization of some Hamiltonian dynamics. Here, we consider more general circuit geometries which include circuits without any nontrivial space periodicity. We show that any time-periodic quantum circuit in which  $U$  is applied to each pair of neighbouring qubits exactly once per period remains integrable. We further generalize this framework to circuits with time-varying two-qubit gates. The spatial arrangement of gates in the integrable circuits considered herein can break the space-reflection symmetry even when  $U$  itself is symmetric. By analyzing the dynamical spin susceptibility on ballistic hydrodynamic scale, we investigate how an asymmetric arrangement of gates affects the spin transport. While it induces nonzero higher odd moments in the dynamical spin susceptibility, the first moment, which corresponds to a drift in the spreading of correlations, remains zero. We explain this within a quasiparticle picture which suggests that a nonzero drift necessitates gates acting on distinct degrees of freedom.

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