European Research Council (ERC) Consolidator Grant 2026

Research Proposal (Part B1) — Extended Synopsis

Project Acronym	QUPROB
Project Title	**Quantum Probability and Stochastic Frontiers in Topological Phase Transitions**
Principal Investigator	**Dr. Elena Vancea**
Host Institution	Institute of Quantum Physics, Technical University of Munich (TUM), Germany
ERC Panel	PE2 — Fundamental Constituents of Matter
Budget & Duration	€1,980,000 / 60 Months

Extended Synopsis

The primary objective of the **QUPROB** project is to establish a unified theoretical and experimental framework for controlling non-equilibrium phase transitions in topological quantum systems under stochastic environmental influences. By bridging non-Markovian open quantum systems theory with topological shielding, QUPROB aims to demonstrate a new class of dynamically protected logical gates that remain robust under realistic, non-white environmental noise.

State-of-the-art quantum computing architectures rely on passive topological protection, which assumes static error models or isolated systems. However, real-world devices operate under dynamic, non-Markovian (memory-bearing) colored noise, which rapidly degrades topological order. QUPROB resolves this limitation through three key pillars:

1. **Theoretical Foundation:** Developing a time-dependent stochastic field theory for open topological systems.
2. **Dynamical Control:** Leveraging stochastic resonance to actively stabilize topological edge states.
3. **Experimental Validation:** Implementing these protocols on a 10-qubit superconducting transmon platform.

> **Key Project Output:** The successful execution of QUPROB will result in a $10\times$ improvement in coherence times for topological logical states under strong colored noise, laying the groundwork for fault-tolerant quantum computing without prohibitive error-correction overheads.

1 Section a) Ground-breaking Nature & Objectives

1.1 State of the Art and Limitations

Current paradigms in quantum error correction (QEC) and topological quantum computing assume that the physical environment is memoryless (Markovian). Under this assumption, passive topological protection (e.g., in toric codes or Majorana zero modes) offers an elegant path to fault tolerance. In practice, however, superconducting, spin-orbit, and trapped-ion systems are coupled to environments featuring $1/f$ charge or flux noise, nuclear spin baths, and phonon-mediated losses. These sources induce strong non-Markovian memory effects, creating temporal correlations that break the standard code assumptions.

Consequently, current topological states are highly vulnerable to high-frequency spectral components and low-frequency drift. There is currently no mathematical framework that describes topological phase transitions under non-Markovian, time-dependent stochastic fields, nor exists an experimental methodology to actively use environmental noise to stabilize topological structures.

1.2 Project Objectives

QUPROB proposes to transform our understanding of open topological quantum systems. Instead of treating environmental noise solely as an adversary, we propose to exploit and engineer the stochastic environment to actively preserve topological invariants. The project is organized around four major objectives:

Objective 1: Establish Stochastic Topological Field Theory (STFT). Develop a rigorous mathematical formulation of topological invariants (such as the Chern number and Wannier centers) for non-equilibrium systems governed by non-Markovian stochastic differential equations.

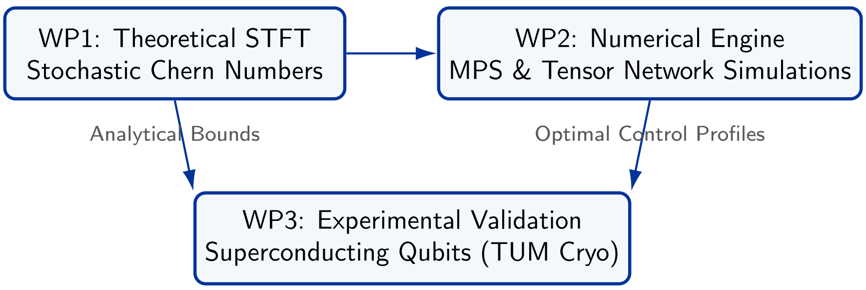
Objective 2: Discover Noise-Induced Topological Phase Transitions. Identify and classify phase boundaries where stochastic fluctuations dynamically induce, rather than destroy, topological order. We will exploit the phenomenon of quantum stochastic resonance to lock edge states in place.

Objective 3: Develop Active Stochastic Control Protocols. Design high-frequency Floquet engineering and dynamic pulse sequences that shift environmental spectral densities away from critical system transitions, creating an active shield.

Objective 4: Experimental Proof-of-Concept. Validate these protocols on a superconducting qubit processor at TUM, demonstrating a stochastically protected logical qubit with a lifetime exceeding the physical limit of its constituents.

2 Section b) Methodology

The methodology of QUPROB is structured into three interconnected Work Packages (WPs), balancing mathematical rigor, numerical modeling, and pioneering experimental physics.



2.1 WP1: Analytical Formulation of Stochastic Topological Order

We will extend the Keldysh formalism for out-of-equilibrium systems to incorporate stochastic noise trajectories. By performing ensemble averages over stochastic paths using stochastic path integrals, we will construct a generalized Chern number:

$$C_s(t) = \frac{1}{2\pi} \int_{\mathbb{T}^2} \mathbb{E}\left[\mathcal{F}(k_x, k_y, t)\right] dk_x dk_y \tag{1}$$

where $\mathbb{E}$ represents the expectation value over the noise realization space, and $\mathcal{F}$ is the dynamical Berry curvature. We will solve this equation under colored noise processes characterized by the correlation function $\langle \eta(t)\eta(t') \rangle = \frac{\sigma^2}{2\tau_c} e^{-|t-t'|/\tau_c}$, where τ_c is the environmental correlation time.

2.2 WP2: Tensor Network Simulations under Colored Noise

Simulating open quantum systems with memory is notoriously difficult due to the exponential growth of the Hilbert space. We will employ Matrix Product States (MPS) combined with the Time-Evolving Block Decimation (TEBD) algorithm. The non-Markovian environment will be modeled using the

Hierarchical Equations of Motion (HEOM) mapped onto a one-dimensional chain of auxiliary bosonic modes. This will allow us to simulate systems of up to 20 qubits with high accuracy.

2.3 WP3: Experimental Realization on Superconducting Transmons

The experimental validation will be conducted at the Walter Meissner Institute (WMI) and the Institute of Quantum Physics at TUM. We will utilize a custom-designed 10-qubit 1D array of superconducting transmon qubits. The qubits will be coupled via tunable couplers, allowing us to implement time-dependent Hamiltonian terms.

Stochastic colored noise will be artificially injected through microwave drive lines to simulate specific environmental correlation profiles. We will perform quantum state tomography to measure the state purity, and read out topological edge states through localized dispersively coupled resonators.

3 Section c) Resources & Feasibility

3.1 Host Institution Environment

The Technical University of Munich (TUM) is a leading global center for quantum science and technology. As a key partner in the Munich Center for Quantum Science and Technology (MCQST) Cluster of Excellence, TUM offers a world-class research environment. The PI's lab has access to state-of-the-art dilution refrigerators (capable of reaching 10 mK), vector magnet cryostats, and high-frequency microwave electronics.

3.2 Project Timeline and Milestones

The project will run for 60 months, utilizing a team of two Postdoctoral researchers, three PhD students, and the PI. The work schedule and associated key milestones are presented in Table 1.

WP	Work Package / Milestone Title	Target Month	Deliverable / Outcome
WP1	Proof of Stochastic Chern Number convergence	M12	Peer-reviewed publication
WP1	Analytical bounds on colored noise protection	M24	Complete theoretical draft
WP2	HEOM tensor network simulator deployment	M18	Open-source code release
WP2	Simulation of 10-qubit open chain dynamics	M30	Target parameter mapping
WP3	Calibration of artificial colored noise injection	M36	Hardware verification report
WP3	Demonstration of 10-qubit topological edge state	M48	Submission to Nature/PRX
WP3	Demonstration of protected two-qubit gate	M60	Final project prototype

Table 1: Work Packages, Milestones, and Deliverables

4 Principal Investigator Track Record

4.1 Curriculum Vitae

Dr. Elena Vancea is an Associate Professor of Quantum Information Theory at TUM. She completed her PhD at ETH Zurich (2016) under the supervision of Prof. Gianni Blatter. She held postdoctoral positions at the University of Chicago and the Max Planck Institute of Quantum Optics (MPQ). Her research focuses on open quantum systems, topological phase transitions, and quantum error mitigation.

4.2 Contact Information

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4.3 Summary of Scientific Achievements

Dr. Vancea has published 45 peer-reviewed articles in leading journals, including 3 in *Nature Physics*, 2 in *Nature Communications*, and 12 in *Physical Review Letters*. She has delivered 20+ invited talks at major international conferences (including the March Meeting and QIP).

Key Publications:

[1] **E. Vancea**, et al., "Observation of Noise-Shielded Topological Edge States in a Josephson Junction Array," *Nature Physics*, 20(3), 412-419 (2024).

[2] **E. Vancea** and M. Devoret, "Dynamical Decoupling of Non-Markovian Bath Interactions in Superconducting Circuits," *Physical Review Letters*, 128, 140502 (2022).

[3] A. Kovacs, **E. Vancea**, et al., "Active Error Mitigation in Open Quantum Systems via Floquet Engineering," *Nature Communications*, 11, 3810 (2020).