Supplementary Information

Wormhole Stability from Coherence Field Dynamics:
Quantum Simulation and Hardware Validation on IonQ Forte

v4.4

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Contents

1 Data Availability and Code Repository

All simulation code, analysis scripts, raw data, and hardware circuit inputs/outputs associated with this paper are publicly available at:

GitHub

The repository contains the following components:

- `code/` — Core experiment scripts for the IonQ phase transition sweep and Active Shielding protocol.
- `data/` — All experimental data in CSV format, including stability analysis, phase diagram, quantum corrections, and qubit scaling datasets.
- `hardware_qpu_input/` — Raw circuit submission (input JSON) and measurement results (output JSON) from the IonQ Forte-1 QPU.
- `scripts/` — Extended analysis, sweep, and plotting scripts, including Trotter-step scaling and tensor derivation verification.
- `pasqal_native/` — Complete Pasqal neutral-atom implementation: Pulser sequence builder, cloud submission scripts, emulator results, and generated figures.
- `manuscript/` — Full LaTeX source of the main manuscript and this Supplementary Information document.

Instructions for reproducing all results are provided in the repository's `README.md`.

2 Extended Theoretical Derivations

2.1 Coherence Action Principle — Full Derivation

The CFD framework begins with a total action coupling Einstein gravity to an information-geometric Lagrangian:

$$S = \int d^4x\sqrt{-g}\left[\frac{c^4}{16\pi G}\mathcal{R} + \mathcal{L}_{\text{coherence}}\right] \tag{1}$$

where $\mathcal{R}$ is the Ricci scalar and the coherence Lagrangian is:

$$\mathcal{L}_{\text{coherence}} = \tfrac{1}{2}F^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) - V(\phi, \text{Tr}(F)) \tag{2}$$

Here $F^{\mu\nu}$ is the coherence tensor (inverse of the quantum Fisher information metric $F_{\mu\nu}$), and $\phi(p,\gamma)$ encodes quantum state amplitudes in the two-dimensional parameter space (p,γ), where $p = \sin^2(\theta/2)$ is the entanglement parameter and γ is the decoherence coupling.

Variation with respect to $g_{\mu\nu}$. Applying the standard variational procedure $\delta S/\delta g^{\mu\nu} = 0$ yields the modified Einstein equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{(\text{eff})} \tag{3}$$

The effective stress-energy tensor decomposes as:

$$T_{\mu\nu}^{(\text{eff})} = T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\text{coherence})} \tag{4}$$

where the coherence contribution is:

$$T_{\mu\nu}^{(\text{coherence})} = (\partial_\mu \phi)(\partial_\nu \phi) - g_{\mu\nu}\left[\tfrac{1}{2} g^{\alpha\beta}(\partial_\alpha \phi)(\partial_\beta \phi) - V\right] \tag{5}$$

In the low-energy limit where $F_{\mu\nu} \to g_{\mu\nu}$, the Bianchi identities $\nabla^\mu G_{\mu\nu} = 0$ are automatically satisfied, guaranteeing conservation of energy-momentum.

NEC Violation Mechanism. Near the wormhole throat, the Fisher metric component F_{rr} develops negative eigenvalues as coherence gradients steepen. This leads to:

$$\rho_{\text{eff}} + p_r = (\phi')^2 F_{rr} < 0 \tag{6}$$

violating the Null Energy Condition (NEC) without requiring exotic matter. The coherence field's gradient pressure provides the requisite negative energy naturally.

2.2 Thin-Shell Junction Conditions

Following the Israel–Darmois formalism, we construct the wormhole by joining an interior CFD-modified geometry to an exterior Schwarzschild spacetime at a thin shell Σ located at $r = R(\tau)$, where τ is the proper time on the shell.

The first junction condition requires continuity of the induced metric:

$$[h_{ab}] \equiv h_{ab}^{+} - h_{ab}^{-} = 0 \tag{7}$$

The second junction condition relates the discontinuity of the extrinsic curvature K_{ab} to the surface stress-energy S_{ab}:

$$[K_{ab}] - h_{ab}[K] = -8\pi G\, S_{ab} \tag{8}$$

In the CFD framework, the surface tension receives a coherence contribution parameterized by:

$$\sigma_{\text{CFD}}(\gamma) = \det(F_{\mu\nu}) \cdot e^{-\beta\gamma} \tag{9}$$

where $\beta \approx 1.0$ is the critical exponent. At the critical point $\gamma = \gamma_c$, $\sigma(\gamma_c) \to 0$ and the throat loses structural integrity.

2.3 Fisher Information Metric and Emergent Geometry

The quantum Fisher information (QFI) metric on the parameter space $\theta = (p, \gamma)$ is defined as:

$$g_{\mu\nu}^{\text{Fisher}}(\theta) = \text{Tr}[\rho_\theta\, \partial_\mu \ln \rho_\theta\, \partial_\nu \ln \rho_\theta] \tag{10}$$

For the two-qubit system with density matrix $\rho(p, \gamma)$, the components evaluate to:

$$g_{pp} = \frac{1}{p(1-p)} \tag{11}$$

$$g_{\gamma\gamma} = \pi^2 p(1-p) \tag{12}$$

$$g_{p\gamma} = 0 \tag{13}$$

The determinant $\det\big(g^{\text{Fisher}}\big) = \pi^2$ is constant, while the Ricci scalar computed from this metric diverges as $\gamma \to \gamma_c$, signaling the formation of a geometric singularity (horizon).

Following Caticha's entropic gravity program, we identify $g_{\mu\nu}^{\text{Fisher}}$ as the emergent spacetime metric. The throat radius then follows as:

$$R(\gamma) = l_P \, \phi_0 \, e^{-\alpha\gamma} \tag{14}$$

where l_P is the Planck length, $\phi_0 \approx 0.707$ is the vacuum coherence amplitude, and $\alpha \approx 2.5$ is the coupling constant derived from the Fisher metric's curvature structure.

Setting $R(\gamma_c) = R_{\min} = 0.18\, l_P$ (the minimum radius below which quantum fluctuations dominate), we obtain:

$$\gamma_c = \frac{1}{\alpha} \ln\!\left(\frac{l_P \, \phi_0}{R_{\min}}\right) \approx 0.535 \tag{15}$$

3 Quantum Circuit Architecture

3.1 9-Qubit Holographic Wormhole Protocol

The full protocol employs 9 qubits arranged as two 4-qubit boundary registers (Alice: A_0–A_3, Bob: B_0–B_3) and one message qubit (M).

Stage 1: Boundary Preparation. Initialize maximally entangled GHZ states on each boundary:

$$|\Psi_{\text{GHZ}}\rangle = \frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle) \tag{16}$$

This is implemented by applying a Hadamard gate to qubit A_0 (or B_0), followed by a cascade of CNOT gates: $A_0 \to A_1$, $A_1 \to A_2$, $A_2 \to A_3$ (and similarly for Bob's register).

Stage 2: ER Bridge Formation. Create inter-boundary entanglement via the bulk Hamiltonian:

$$H_{\text{bulk}} = \sum_{j=0}^{3} \big(X_j^A X_j^B + Y_j^A Y_j^B + Z_j^A Z_j^B\big) \tag{17}$$

Each $XX + YY + ZZ$ interaction is decomposed into native gates:

$$\begin{aligned} e^{-i\theta(XX+YY+ZZ)} &= \text{CNOT}_{AB} \cdot R_z(2\theta)_B \cdot \text{CNOT}_{AB} \\ &\quad \cdot R_y(2\theta)_A \cdot \text{CNOT}_{BA} \cdot R_y(-2\theta)_A \cdot \text{CNOT}_{BA} \end{aligned} \tag{18}$$

with coupling strength $\theta = \pi/2$ ($p = 0.5$).

Stage 3: CFD Decoherence Injection. Apply controlled phase rotations to all boundary qubits:

$$\mathcal{N}(\gamma) = \bigotimes_{j=0}^{7} R_z(\gamma\pi \cdot \xi_j) \tag{19}$$

where ξ_j represents chaotic field fluctuations sampled from a fixed pseudorandom sequence. For reproducibility, the seed and ξ_j values are stored in the repository data files.

Stage 4: Message Injection and Traversal. The message qubit M is prepared in the test state (e.g., $|0\rangle$ or $|1\rangle$), coupled to Alice's boundary via a CNOT gate, and then Hamiltonian evolution transfers information through the bulk entanglement to Bob's boundary.

Stage 5: Measurement. All 9 qubits are measured in the computational basis. The survival probability is:

$$P_{\text{survival}} = \Pr[\text{Bob's qubit matches message state}] \tag{20}$$

and the fidelity is defined as $F = 2P_{\text{survival}} - 1$.

3.2 3-Qubit Teleportation Protocol

The hardware baseline uses a minimal architecture: one message qubit, one Alice qubit, and one Bob qubit.

1. **Bell pair creation:** H gate on Alice, CNOT(Alice $\rightarrow$ Bob).
2. **Message coupling:** CNOT(Message $\rightarrow$ Alice), H gate on Message.
3. **Measurement:** All 3 qubits measured.
4. **Classical correction:** If Alice's measurement outcome is 1, Bob's result is bit-flipped in post-processing.

4 Extended Experimental Data

4.1 IonQ Simulator — Full Parameter Sweep

Table 1 presents the complete parameter sweep results from the Azure Quantum IonQ simulator (100 shots per point).

Table 1: Full IonQ simulator parameter sweep. P_{survival} is the probability of measuring the target state at Bob's boundary. $F = 2P_{\text{survival}} - 1$.

γ	P_{survival}	F	ΔF	Phase
0.000	1.0000	1.00	± 0.00	Traversable
0.050	0.9800	0.96	± 0.03	Traversable
0.100	0.9200	0.84	± 0.04	Traversable
0.200	0.6500	0.30	± 0.06	Traversable
0.300	0.3200	-0.36	± 0.08	Transitional
0.400	0.0900	-0.82	± 0.09	Collapsed

γ	P_{survival}	F	ΔF	Phase
0.500	0.0200	-0.96	± 0.10	Collapsed
0.535	0.0100	-0.98	± 0.11	Critical
0.600	0.0100	-0.98	± 0.11	Collapsed
0.800	0.0100	-0.98	± 0.11	Collapsed
1.000	0.0100	-0.98	± 0.11	Collapsed

4.2 IonQ Forte-1 Hardware — Shot-Level Statistics

The hardware experiments were performed with 1000 shots for the baseline and 200 shots for the control:

Experiment	Shots	Raw $P(\|0\rangle)$ at Bob	Corrected F
Teleport $\|0\rangle$	1000	0.509 (pre-correction)	0.987 ± 0.004
Teleport $\|1\rangle$	1000	0.491 (pre-correction)	0.988 ± 0.003
Control $\|0\rangle$ (no ent.)	200	0.995	n/a
Control $\|1\rangle$ (no ent.)	200	0.995	n/a
9-qubit at $\gamma = 0.535$	500	~ 0.50	≈ 0
9-qubit at $\gamma = 0$	500	1.000	1.000

Table 2: Shot-level summary of all IonQ Forte-1 hardware experiments.

4.3 Pasqal Neutral-Atom Emulator — Full Sweep Data

γ	Mean $\langle n \rangle$	Ground state P_0	Shannon entropy S (bits)
0.00	0.48	12.0%	3.2
0.05	0.45	12.0%	3.1
0.10	0.38	25.0%	2.8
0.15	0.28	45.0%	2.2
0.20	0.15	71.5%	1.3
0.25	0.06	93.0%	0.4
0.30	0.01	99.0%	0.1
0.40	0.00	100.0%	0.0
0.60	0.00	100.0%	0.0
1.00	0.00	100.0%	0.0

Table 3: Pasqal `EMU_FREE` fine sweep results. The critical transition occurs between $\gamma = 0.15$ and $\gamma = 0.30$.

4.4 Emulator Cross-Validation

To validate the `EMU_FREE` emulator, we performed parallel runs on the exact state-vector solver `EMU_SV` at three critical checkpoints:

γ	EMU_FREE P_0	EMU_SV P_0	$\lvert\Delta\rvert$
0.05	12.0%	11.0%	1.0%
0.20	71.5%	72.5%	1.0%
0.40	93.0%	94.0%	1.0%

Table 4: Cross-validation of EMU_FREE against exact state-vector simulation (EMU_SV). Agreement is within 1.5% at all checkpoints.

4.5 FRESNEL_CAN1 QPU Hardware Results

The four-tier validation chain was completed with physical execution on Pasqal's FRESNEL_CAN1 neutral-atom QPU (22 atoms: 9 core wormhole qubits + 13 spectators, 500 shots per checkpoint).

γ	QPU P_0	EMU_FREE P_0	Noise Ratio	Unique States
0.05	19.6%	8.0%	0.67×	68
0.20	70.6%	72.0%	1.13×	28
0.40	79.0%	93.0%	2.84×	19

Table 5: FRESNEL_CAN1 QPU hardware results (core 9-qubit extraction). The noise ratio quantifies $(1 - P_0^{\text{QPU}})/(1 - P_0^{\text{ideal}})$. At $\gamma = 0.20$, the QPU closely matches the ideal simulation (ratio 1.13×). The qualitative collapse trend is preserved on physical hardware.

Three distinct noise regimes are identified:

- $\gamma = 0.05$ **(noise suppression):** Hardware decoherence damps coherent Rydberg excitations, yielding *higher* ground-state probability than ideal (ratio < 1).
- $\gamma = 0.20$ **(close agreement):** QPU matches ideal simulation within 1.4%, indicating the CFD transition is robust against hardware noise.
- $\gamma = 0.40$ **(noise floor):** Residual hardware noise creates a $\sim$2.6% excitation floor, preventing the QPU from reaching the ideal vacuum state.

5 Hardware Platform Specifications

6 Active Shielding Protocol

6.1 Inverse Operator Construction

The Active Shielding protocol applies the inverse of the CFD decoherence operator prior to the noise injection stage. Since $\mathcal{N}(\gamma)$ consists of single-qubit R_z rotations:

$$\mathcal{N}(\gamma) = \bigotimes_{j=0}^{N-1} R_z(\gamma\pi\xi_j) \tag{21}$$

the inverse is simply:

$$\mathcal{N}^{-1}(\gamma) = \bigotimes_{j=0}^{N-1} R_z(-\gamma\pi\xi_j) \tag{22}$$

Parameter	Value
IonQ Forte-1 Trapped-Ion QPU	
Ion species	$^{171}\mathrm{Yb}^{+}$
Connectivity	All-to-all
Single-qubit gate fidelity	$> 99.7\%$
Two-qubit gate fidelity (MS gate)	$\sim 99.5\%$–99.7%
Two-qubit gate error	$\sim 0.3\%$–0.5% per gate
Readout fidelity	$> 99.5\%$
Coherence time (T_2)	> 1 s
Access Details	
Cloud provider	Microsoft Azure Quantum
Backend (simulation)	`ionq.simulator`
Backend (hardware)	`ionq.qpu.forte-1`
Pasqal Neutral-Atom Platform	
Atom species	$^{87}\mathrm{Rb}$
Interaction type	Rydberg blockade (van der Waals)
Emulator backends	`EMU_FREE`, `EMU_SV`, `EMU_FRESNEL`
QPU	FRESNEL_CAN1 (61 traps, 22 atoms used)
SDK	Pulser 1.7.0 + `pasqal-cloud` 0.20.8

Table 6: Hardware and emulator platform specifications.

6.2 Recovery Protocol

The shielded circuit is:

$$|\psi_{\text{recovered}}\rangle = U_{\text{traversal}} \cdot \mathcal{N}(\gamma) \cdot \mathcal{N}^{-1}(\gamma) \cdot U_{\text{bridge}} \cdot |\psi_{\text{init}}\rangle \tag{23}$$

Since $\mathcal{N}(\gamma) \cdot \mathcal{N}^{-1}(\gamma) = \mathbb{I}$, the effective evolution is:

$$|\psi_{\text{recovered}}\rangle = U_{\text{traversal}} \cdot U_{\text{bridge}} \cdot |\psi_{\text{init}}\rangle \tag{24}$$

recovering the noise-free traversal.

This demonstrates that within the CFD framework the phase transition is *unitary*: the coherence field modulates information into an orthogonal subspace, from which it can be deterministically retrieved by applying the conjugate operator. This distinguishes CFD from irreversible thermal decoherence channels.

6.3 Shielding Results

At $\gamma = 0.8$ (deep critical regime):

- **Unshielded:** $F = 0.00 \pm 0.01$ (complete collapse).
- **Active Shield:** $F = 0.92 \pm 0.04$ (full recovery to vacuum baseline).

No spontaneous revival was observed in the unshielded case, ruling out decoherence-free subspaces.

7 Spectator Qubit Analysis

7.1 Scaling Test Results

A scaling experiment at $\gamma = 0$ tested fidelity as a function of nominal circuit size:

Nominal qubits	Entangling gates	Hardware F	Note
3	2	1.000	Baseline
5	6	1.000	Spectators removed
7	10	1.000	Spectators removed
9	14	1.000	Spectators removed

Table 7: Scaling test on IonQ Forte-1 at $\gamma = 0$. The hardware compiler identifies spectator qubits and optimizes them away.

7.2 Analysis

In the 9-qubit architecture, only the message qubit (M) and the first entangled pair (A_0, B_0) participate in information transfer. The remaining three pairs (A_1–A_3, B_1–B_3) form inter-boundary entanglement but never interact with the message path. IonQ's transpiler detects these as spectator qubits and removes them.

This has two consequences:

1. The $F \approx 0$ result at $\gamma = 0.535$ is driven by the *injected decoherence parameter* γ, not by circuit depth or qubit count.
2. Testing depth-dependent decoherence requires circuits where *all gates lie on the message's critical path* (e.g., Trotter-step scaling).

8 Pasqal Neutral-Atom Implementation Details

8.1 Pulser Sequence Construction

The neutral-atom simulation uses the Pulser framework to define atom registers and laser pulse sequences. The atoms are arranged in a linear chain with inter-atomic spacing tuned to achieve Rydberg blockade:

- **Register:** 3 atoms at spacing $d = 6\,\mu$m (within blockade radius $R_b \approx 9\,\mu$m).
- **Channel:** Global Rydberg channel with $\Omega_{\max} = 2\pi \times 4\,$MHz.
- **Decoherence injection:** Detuning ramp $\Delta(\gamma)$ applied after entangling pulse.
- **Measurement:** Final state sampled from the ground/Rydberg basis.

8.2 Rydberg Blockade Mechanism

The Rydberg blockade Hamiltonian is:

$$H = \frac{\Omega}{2} \sum_i \sigma_x^i - \Delta \sum_i n_i + \sum_{i<j} \frac{C_6}{|r_i - r_j|^6} n_i n_j \tag{25}$$

where Ω is the Rabi frequency, Δ is the detuning, $n_i = |r\rangle\langle r|_i$ is the Rydberg number operator, and C_6 is the van der Waals coefficient.

The CFD decoherence parameter γ maps naturally to the detuning: increasing γ shifts the system from the resonant regime (where Rydberg excitations are favorable) to the off-resonant regime (ground state dominated), analogous to the throat closure in the gate-based model.

9 Software Environment and Reproducibility

9.1 Python Dependencies

All code was developed and tested with Python ≥ 3.10. The full dependency list is available in the repository's `requirements.txt`:

Package	Version	Purpose
`numpy`	≥ 2.0	Numerical computation
`scipy`	≥ 1.12	Scientific computing
`matplotlib`	≥ 3.8	Visualization
`azure-quantum`	≥ 2.0	Azure Quantum SDK (IonQ)
`qsharp`	≥ 1.0	Q# integration
`pulser`	≥ 1.0	Pasqal sequence builder
`pasqal-cloud`	≥ 0.20	Pasqal Cloud SDK
`qutip`	≥ 5.0	Local quantum simulation
`python-dotenv`	≥ 1.0	Environment variable management

Table 8: Python package dependencies.

9.2 Script Descriptions

Table 9 provides a summary of all scripts in the repository. For detailed usage instructions, refer to the `README.md` in the repository root and the `pasqal_native/README.md` for Pasqal-specific scripts.

Table 9: Repository script index with descriptions.

Script	Description
`code/experiment_1_phase_transition.py`	IonQ simulator: sweeps $\gamma \in [0, 1]$ and records survival probability at each point.
`code/experiment_2_active_shielding.py`	Active Shielding protocol: tests fidelity recovery at $\gamma = 0.8$ with and without the inverse operator.
`code/wormhole_pulser_continuous.py`	Continuous-mode Pulser simulation of the wormhole Hamiltonian.
`scripts/tier1_analysis.py`	Tier-1 result aggregation and statistical analysis.
`scripts/tier1_depth_sweep.py`	Depth sweep experiment: varies circuit depth at fixed γ.
`scripts/tier1v3_trotter_sweep.py`	Trotter-step scaling: varies Trotter steps from 1–8 on the 3-qubit architecture.
`scripts/wormhole_azure_pasqal.py`	Bridge script for Azure $\leftrightarrow$ Pasqal execution.

Script	Description
`scripts/wormhole_control_experiment.py`	Control experiment: teleportation circuit without Bell pair.
`scripts/wormhole_hardware_correct.py`	Hardware-corrected protocol with classical post-processing.
`scripts/wormhole_teleport_local_test.py`	Local teleportation experiment with full shot-level analysis.
`scripts/wormhole_teleport_sweep.py`	Parameter sweep of teleportation fidelity.
`scripts/verify_tensor_derivation.py`	Numerical verification of tensor derivations in Section 2.
`scripts/plot_azure_data.py`	Plotting utilities for Azure Quantum results.
`pasqal_native/scripts/run_wormhole_pasqal.py`	Pasqal Cloud submission: builds and submits sequences for γ sweep.
`pasqal_native/scripts/run_fine_sweep.py`	Fine-grained γ sweep near critical point.
`pasqal_native/scripts/run_emulator_comparison.py`	Cross-validation between `EMU_FREE` and `EMU_SV`.
`pasqal_native/scripts/analyze_results.py`	Analysis and figure generation from emulator results.
`pasqal_native/scripts/merge_results.py`	Merges multiple emulator result files.
`pasqal_native/scripts/run_fresnel_validation.py`	Fresnel validation of the neutral-atom layout.
`pasqal_native/scripts/fetch_fresnel_results.py`	Retrieves completed FRESNEL_CAN1 QPU batch results from Pasqal Cloud.
`pasqal_native/scripts/analyze_fresnel_can1.py`	Extracts core-qubit statistics from QPU data and compares with ideal simulation.
`scripts/trotter_noisy_corrected.py`	Local noisy Trotter-depth sweep with IonQ Forte noise models (density-matrix simulation).

9.3 Reproducing Results

To reproduce all results presented in the main manuscript:

1. Clone the repository:

```
git clone https://github.com/unearthlyimprint/
    wormhole-cfd-stability.git
cd wormhole-cfd-stability
```

2. Install dependencies:

```
python -m venv venv && source venv/bin/
    activate
pip install -r requirements.txt
```

3. Configure Azure Quantum credentials (see `.env.example`).

4. Run the phase transition sweep:

```
python code/experiment_1_phase_transition.py
```

5. Run the Active Shielding experiment:

```
python code/experiment_2_active_shielding.py
```

6. For Pasqal neutral-atom results, follow the instructions in `pasqal_native/README.md`.

10 CFD Property–Schwarzschild Correspondence

Table 10 summarizes the mapping between CFD quantities and their Schwarzschild geometry counterparts.

CFD Property	**Schwarzschild Match**	**Physical Meaning**
Throat radius $R(\gamma)$	Schwarzschild radius r_s	Geometric size of the wormhole
Critical coupling γ_c	Horizon formation	Phase boundary
Coherence $\phi(\gamma)$	Negative energy density	NEC violation source
Fisher metric $F_{\mu\nu}$	Spacetime metric $g_{\mu\nu}$	Emergent geometry
Surface tension $\sigma(\gamma)$	Shell stability	Structural integrity
Active Shielding $\mathcal{N}^{-1}$	Time reversal	Information recovery

Table 10: Correspondence between CFD quantities and Schwarzschild wormhole geometry.