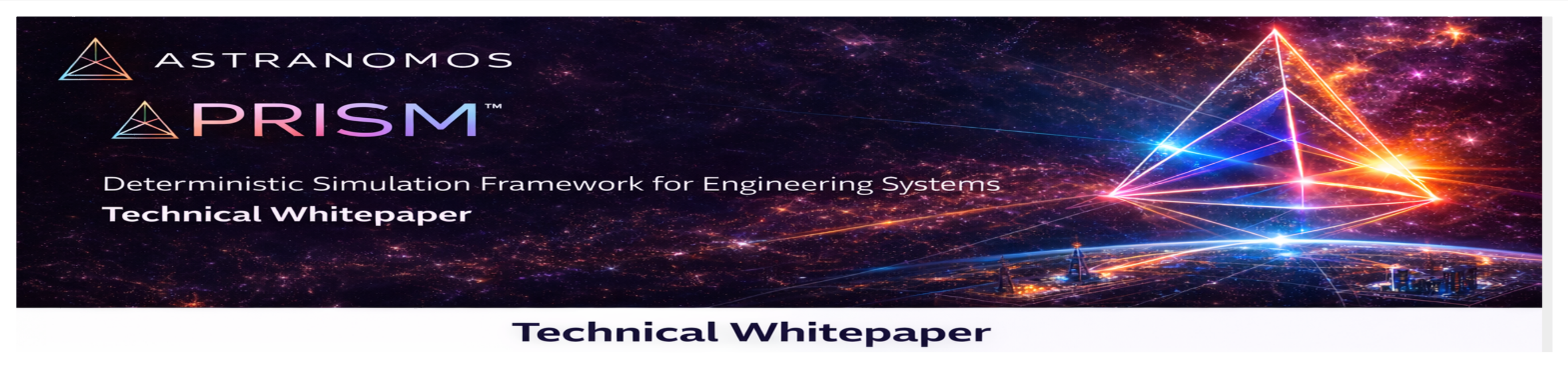

Operator Structure and Low-Dimensional Dynamics in Superconducting Qubit Calibration Data

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ABSTRACT

For over a century, the behavior of physical systems has been interpreted through a dual lens: deterministic laws governing idealized motion, and stochastic models used to describe variability, noise, and uncertainty. From the foundational work of Isaac Newton to the diffusion formalism of Joseph Fourier and the fluid dynamics of Claude-Louis Navier and George Gabriel Stokes, motion has been progressively modeled with increasing complexity. In quantum systems, this trajectory culminates in a framework where coherence, decoherence, and measurement are often treated probabilistically, reinforcing the assumption that variability is fundamentally stochastic.

However, advances in data-driven analysis and operator theory raise a critical question: is apparent randomness intrinsic to physical systems, or is it an artifact of representation? This study addresses that question using real superconducting qubit calibration data, demonstrating that behavior traditionally modeled as noise exhibits strong structural organization and predictable evolution.

We analyze a publicly available dataset of superconducting qubit calibration drift measurements from IBM Quantum systems, containing time-resolved observations of coherence times (T1, T2), gate errors, readout errors, measurement asymmetries, and environmental variables. The dataset is accessible at:

- https://huggingface.co/datasets/phanerozoic/qiskit-calibration-drift

and provides a large-scale empirical foundation for testing whether qubit variability is fundamentally stochastic or structured.

To construct a physically meaningful state representation, we define a state vector:

$$X = [T1, T2, \text{readout\_error}, \text{sx\_error}, \text{prob\_meas0\_prep1}, \text{prob\_meas1\_prep0}]$$

which captures both coherence and control properties of the system. This yields a dataset of 600 valid qubit-state samples and time-aligned subsets for dynamic analysis.

We first evaluate the intrinsic dimensionality of the system using modal decomposition. Principal Component Analysis (PCA) reveals that 86.7% of total variance is captured by a single mode, 96.6% by two modes, and effectively all variance by three modes. This demonstrates that a six-dimensional physical system collapses onto a low-dimensional manifold, indicating that the system's effective degrees of freedom are far fewer than its measured variables suggest. This dimensional collapse is incompatible with a featureless stochastic model, which would distribute variance more uniformly across dimensions. Instead, it suggests that qubit dynamics are governed by a constrained set of dominant modes. To test whether this structure extends to system evolution, we construct an operator-based model of the form:

$$X(t+1) = AX(t)$$

where A is a learned linear operator. This model is compared against a persistence baseline:

$$X(t+1) = X(t)$$

which represents the null hypothesis of unstructured or memoryless behavior. The operator model achieves a 37.7% reduction in prediction error relative to the baseline, demonstrating that system evolution is not random but follows a structured mapping in state space. This result provides direct empirical evidence that qubit calibration dynamics exhibit short-term predictability beyond simple inertia.

Importantly, predictability is not uniform across variables. Coherence parameters (T1, T2) exhibit near-invariant behavior, while control and measurement variables show stronger dynamical evolution. This indicates that the system consists of both stable and active modes, further reinforcing the interpretation of a structured manifold. These findings align naturally with an operator-theoretic description of motion:

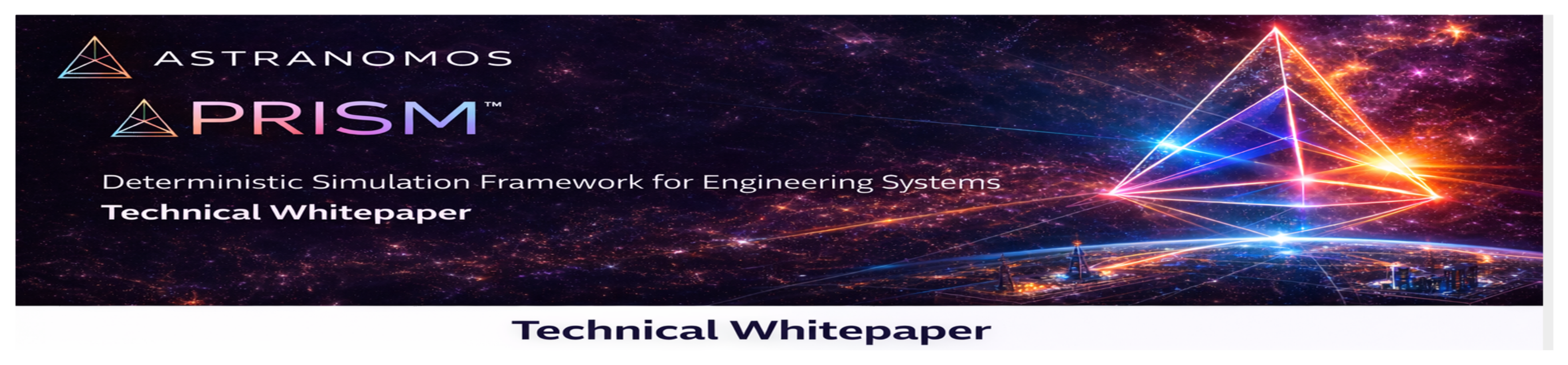
$$\frac{dX}{dt} = \mathcal{O}(X)$$

in which system evolution is governed by an underlying operator acting on a reduced state space. Under this formulation, apparent randomness arises not from intrinsic stochasticity, but from projecting structured dynamics into an incomplete or misaligned basis.

From a historical perspective, this result can be viewed as a continuation of the trajectory from classical mechanics to modern operator theory. While early physics sought to describe motion deterministically, later frameworks introduced probabilistic descriptions to account for complexity. Operator theory, developed through the work of Hermann Weyl and John von Neumann, provides a bridge between these views by describing systems in terms of spectral structure rather than trajectories alone. Our results suggest that this operator perspective may extend beyond idealized systems into real, noisy physical environments. Even in superconducting quantum hardware—one of the most complex and noise-sensitive physical systems studied today—behavior exhibits strong structural constraints and predictable evolution.

This has significant implications for how quantum motion is understood. Rather than treating decoherence and drift as fundamentally random, they may instead reflect structured interactions within a constrained manifold shaped by geometry, coupling, and environmental conditions. More broadly, this study supports a unifying hypothesis: that across physical domains, apparent randomness often emerges from unresolved structure rather than intrinsic stochasticity. This has been observed in thermal transport, structural systems, and now quantum hardware, suggesting a potential general principle governing motion.

While this work does not claim a complete deterministic description of quantum systems, it provides strong empirical evidence that variability is structured and partially predictable. This reframes the role of noise from a fundamental property to a representation-dependent phenomenon. In conclusion, we demonstrate that superconducting qubit calibration data exhibits low-dimensional structure and operator-driven evolution, challenging the assumption that variability is purely stochastic. This represents a foundational step toward a framework in which motion, across domains, is understood as structured dynamics evolving on constrained manifolds rather than as fundamentally random processes.



1. Introduction

The behavior of complex physical systems is frequently modeled using stochastic frameworks, particularly when variability appears irregular or difficult to predict. In superconducting quantum hardware, calibration drift, coherence fluctuations, and measurement errors are typically described in terms of noise processes, environmental perturbations, or random defect dynamics. These descriptions, while effective for engineering practice, implicitly assume that variability is fundamentally unstructured, arising from high-dimensional interactions that cannot be reduced to a smaller set of governing principles.

However, an alternative perspective has emerged: apparent randomness may instead arise from **unresolved structure** within a system that evolves on a lower-dimensional manifold. In this view, what is commonly interpreted as noise is not intrinsic randomness, but rather the projection of structured dynamics into a representation that does not align with the system's natural modes. This work investigates that hypothesis using real superconducting qubit calibration data. Rather than replacing existing physical models, our goal is to determine whether observed behavior is more consistent with:

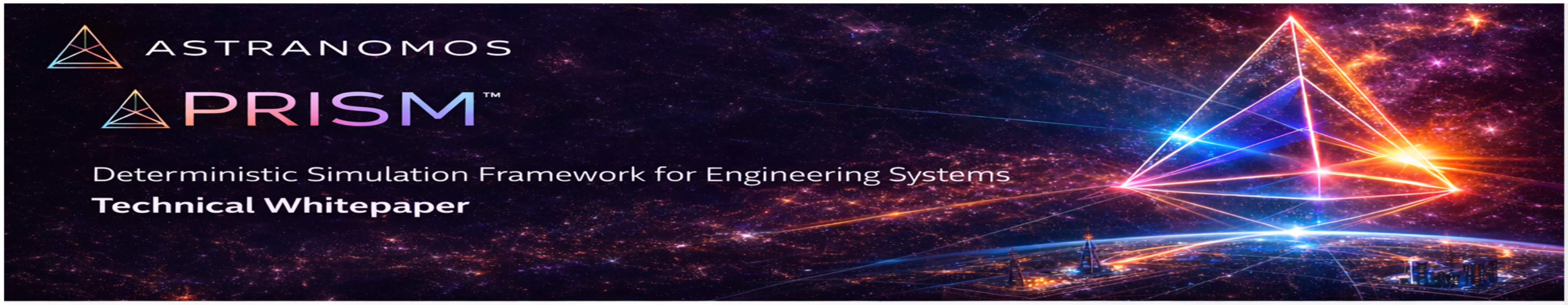
- High-dimensional stochastic variation, or
- Structured evolution governed by a reduced set of modes

To formalize this perspective, we adopt an operator-based representation of system dynamics:

$$\frac{d}{dt}X(t) = \mathcal{O}(X(t))$$

where $X(t)$ represents the system state and $\mathcal{O}$ is a geometry-conditioned operator governing its evolution. Under this formulation, the system admits a spectral decomposition:

$$X(t) = \sum_{i=1}^{m} a_i\,(t)\,\phi_i$$



where ϕ_i are eigenfunctions of the operator and $a_i(t)$ are time-dependent modal coefficients. Crucially, the number of active modes m is often much smaller than the number of measured variables, implying that the system evolves on a **low-dimensional spectral manifold**.

This formulation is closely related to classical Sturm–Liouville theory, which describes how differential operators define admissible modes of physical systems. In traditional applications, Sturm–Liouville theory is used to solve boundary value problems by identifying eigenfunctions that form a complete basis for the system. However, in practice, modern simulation frameworks do not operate directly in this spectral space. Instead, they reconstruct system behavior numerically through discretization, often obscuring the underlying modal structure. The approach presented here can be viewed as a **reversal of this paradigm**. Rather than approximating solutions to differential equations through dense meshes and recovering structure indirectly, we seek to identify the governing operator and its dominant modes directly from data. In doing so, we effectively extend Sturm–Liouville theory from a purely analytical tool to a **data-driven framework for identifying the spectral structure of real physical systems**.

It is important to emphasize that this is not a reduced-order model in the conventional sense. Classical reduced-order modeling techniques, such as Proper Orthogonal Decomposition (POD) or other statistical compression methods, derive low-dimensional representations by fitting data after simulation or measurement. These approaches reduce dimensionality for computational efficiency, but do not necessarily reveal the governing structure of the system. By contrast, the framework presented here does not impose dimensional reduction as an approximation. Instead, it **reveals that the system itself is intrinsically low-dimensional**, with admissible dynamics constrained by the operator structure. The reduction emerges from the physics, not from post hoc compression. As such, this is not a curve-fitting exercise or a surrogate modeling technique, but an attempt to identify the **causal structure underlying system evolution**.

This distinction is critical. In stochastic modeling, variability is treated as irreducible uncertainty, and predictive models are evaluated primarily in terms of statistical fit. In the operator framework, variability is interpreted as structured motion within a constrained manifold, and predictive capability arises from identifying the correct representation of that structure. Superconducting qubit systems provide an ideal testbed for this hypothesis. These systems are widely regarded as inherently noisy, with behavior influenced by complex interactions between device geometry, control electronics, and environmental factors such as temperature and electromagnetic interference. If any system were to exhibit fundamentally stochastic behavior, it would be expected to appear here.

By analyzing calibration data from such systems, we can directly test whether their dynamics are better described by stochastic models or by structured operator evolution. If strong low-dimensional structure and predictability are observed, this would suggest that even in highly complex physical systems, apparent randomness may be an artifact of representation rather than a fundamental property. More broadly, this work contributes to a growing body of evidence across multiple domains—including thermal transport, structural mechanics, and now quantum hardware—that physical systems often exhibit **spectral organization** that is not captured by traditional modeling approaches. This raises the possibility of a unifying principle: that motion, variability, and noise are manifestations of structured dynamics governed by underlying operators, rather than inherently random processes. In this context, the present study represents a first step toward bridging classical spectral theory and modern data-driven analysis, demonstrating that the mathematical structure of physical law may be more directly observable in empirical data than previously assumed.

2. Dataset

The analysis presented in this work is based on a publicly available dataset of superconducting qubit calibration data, which provides a rich and realistic representation of physical variability in quantum hardware systems. The dataset is hosted at:

- https://huggingface.co/datasets/phanerozoic/qiskit-calibration-drift

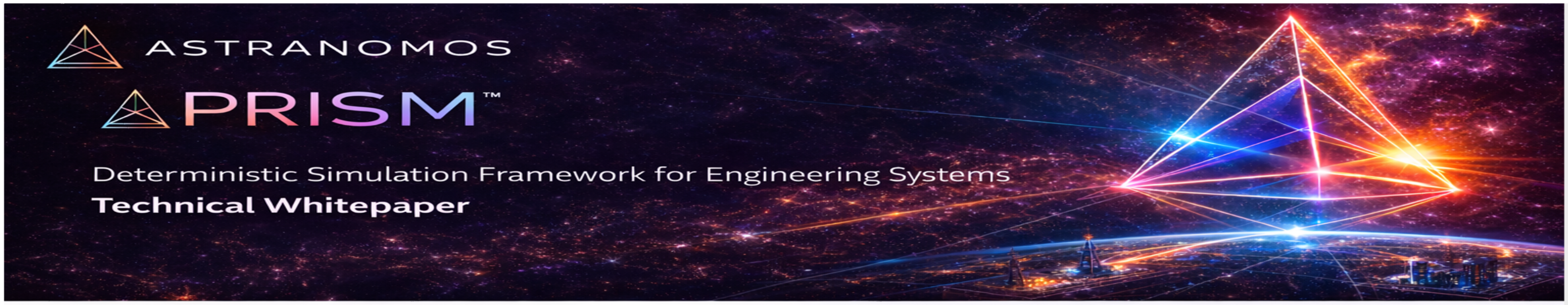
and consists of calibration measurements collected from multiple IBM Quantum backends over time. For the purposes of this study, we utilize the primary data file:

- https://huggingface.co/datasets/phanerozoic/qiskit-calibration-drift/blob/main/data/train-00000-of-00001.parquet

which contains a large-scale collection of time-resolved calibration observations across a range of qubits and system configurations.

The dataset includes a diverse set of physical and operational variables characterizing qubit performance. These include coherence metrics such as energy relaxation time (T1) and dephasing time (T2), which reflect the fundamental stability of quantum states. In addition, it includes gate-level performance indicators such as sx_error, as well as measurement-related quantities including readout_error and asymmetry metrics (prob_meas0_prep1, prob_meas1_prep0). Together, these variables span both intrinsic and operational aspects of the system.

Beyond qubit-specific parameters, the dataset also incorporates environmental variables such as temperature, geomagnetic indices (e.g., kp_index, dst_nt), solar flux measurements, and neutron flux estimates. These variables provide contextual information about the external conditions under which the quantum devices operate, enabling analysis of how environmental structure may influence system behavior.



The dataset is provided in a **long format**, where each row corresponds to a single measurement of a specific property for a given qubit at a given time. While this representation is convenient for storage and logging, it is not directly suitable for operator-based modeling, which requires a consistent state vector representation across variables.

To construct such a representation, the dataset is transformed into a **wide format** using a pivot operation. In this transformation, each qubit is represented by a vector of simultaneously observed properties, effectively embedding the system into a multidimensional state space:

$$X = [x_1, x_2, \dots, x_n]$$

where each component corresponds to a specific physical or operational variable.

A key challenge in this transformation is the asynchronous nature of the data. Not all properties are measured at the same timestamp, leading to missing values when attempting to align them into a single state vector. To address this, we restrict the analysis to a subset of variables that are both physically meaningful and sufficiently well-sampled across the dataset. Specifically, we define a core state vector:

$$X = [T1, T2, \text{readout\_error}, \text{sx\_error}, \text{prob\_meas0\_prep1}, \text{prob\_meas1\_prep0}]$$

This selection captures a balance between coherence properties, control fidelity, and measurement behavior, providing a representative snapshot of qubit system dynamics. After pivoting and filtering for completeness (i.e., removing rows with missing values across the selected variables), the dataset yields **600 valid qubit-state samples**. These samples form the basis for the structural analysis performed in this study, including modal decomposition and dimensionality assessment.

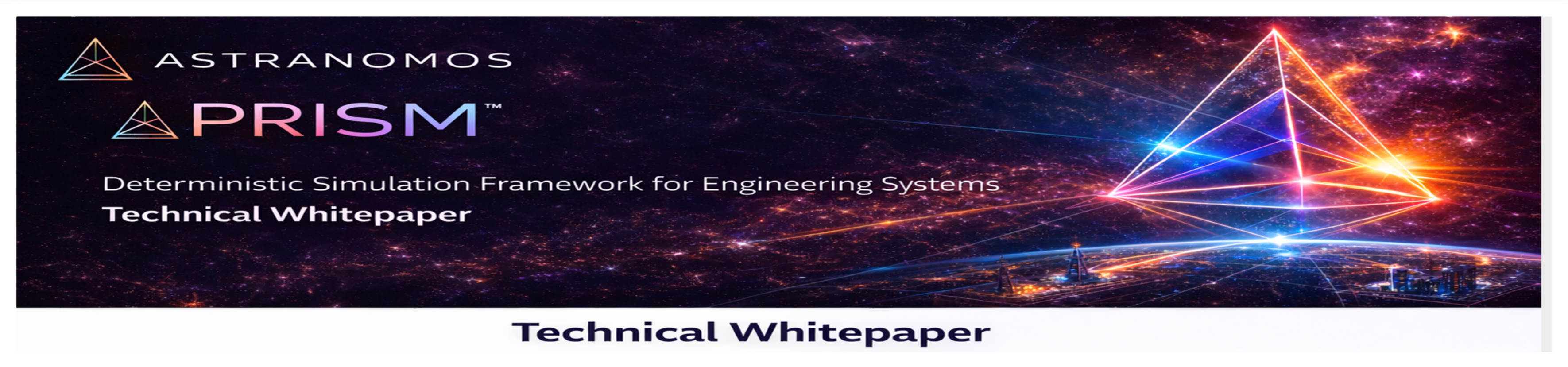
To enable temporal analysis, the dataset is further processed to account for the lack of synchronized measurements across properties. Rather than requiring exact timestamp alignment, we aggregate observations into **coarse time bins**, effectively grouping measurements that occur within a specified temporal window. This binning process allows the construction of approximate system snapshots at discrete times, preserving temporal ordering while mitigating sparsity. After aggregation and filtering, this yields **62 time-aligned snapshots**, which are used to evaluate system evolution and operator-based predictability.

Importantly, this preprocessing approach does not impose artificial structure on the data. Instead, it extracts structure that is already present, while addressing practical limitations of asynchronous measurement. The resulting dataset remains representative of real system behavior, including variability, noise, and environmental influence.

From the perspective of operator modeling, the dataset is particularly valuable because it spans multiple backends, qubits, and operating conditions. This diversity ensures that any observed structure is not an artifact of a single device or configuration but reflects broader system behavior. Moreover, the inclusion of both physical and environmental variables provides an opportunity to explore how external conditions interact with internal system dynamics. While this study focuses primarily on the core qubit state variables, the presence of environmental data suggests a natural extension toward a coupled operator framework in which external drivers are incorporated explicitly. The dataset also exhibits a key property that motivates this study: apparent variability across measurements. At first glance, fluctuations in T1, T2, and error rates appear irregular and difficult to predict, reinforcing the conventional interpretation of noise.

However, the central question of this work is whether this variability is truly random, or whether it reflects structured dynamics that can be uncovered through appropriate representation. By transforming the dataset into a consistent state-space representation and analyzing its structure, we can directly test this question. The combination of real hardware data, multiple variables, and temporal information provide a robust empirical foundation for evaluating the presence of low-dimensional structure and operator-driven evolution.

In summary, the dataset used in this study provides a comprehensive and realistic view of superconducting qubit behavior. Through careful preprocessing and representation, it enables the investigation of whether complex, seemingly noisy systems are in fact governed by structured dynamics. This makes it an ideal testbed for the operator-based framework proposed in this work.



3. Methodology

3.1 Modal Decomposition

The first objective of the analysis is to determine the intrinsic dimensionality of the system. To do this, we apply Principal Component Analysis (PCA) to the state matrix X, which consists of qubit-level physical and operational variables. PCA is commonly interpreted as a dimensionality reduction technique; however, in the context of this work, it serves a different purpose. Rather than compressing data for efficiency, PCA is used to identify the **dominant modes of variation** that define the admissible structure of the system. In this sense, PCA acts as a data-driven analogue of spectral decomposition in operator theory.

Formally, let $X \in \mathbb{R}^{N \times d}$ represent the dataset, where N is the number of samples and d is the number of observed variables. PCA computes a set of orthogonal basis vectors $\{\phi_i\}$ such that:

$$X = \sum_{i=1}^{d} a_i \, \phi_i$$

where a_i are scalar coefficients representing the projection of the data onto each mode. These basis vectors correspond to eigenvectors of the covariance matrix:

$$\Sigma = \frac{1}{N} X^T X$$

and the associated eigenvalues quantify the variance captured by each mode. The ordered spectrum of eigenvalues thus provides a direct measure of the system's effective dimensionality.

In classical settings, such decompositions are often interpreted as statistical summaries of the data. However, in this work, we interpret the resulting modes as approximations of the **eigenfunctions of an underlying operator** governing the system. This interpretation aligns PCA with the spectral framework of Sturm–Liouville theory, where system behavior is expressed as a superposition of admissible modes. Under this perspective, a rapid decay in the eigenvalue spectrum is not merely a property of the data, but an indication that the system itself is constrained to evolve within a **low-dimensional spectral manifold**. That is, the apparent dimensionality of the observed variables overestimates the true degrees of freedom governing the system.

Importantly, this interpretation distinguishes the present approach from classical reduced-order modeling techniques. In standard approaches such as Proper Orthogonal Decomposition (POD), the goal is to approximate high-dimensional data using a smaller number of modes for computational efficiency. Here, by contrast, the objective is to determine whether the system is inherently low-dimensional, independent of any approximation. Thus, PCA is used not as a modeling tool, but as a diagnostic instrument to test whether the system exhibits **intrinsic modal structure**. If the majority of variance is captured by a small number of modes, this suggests that the system's dynamics are governed by a constrained operator rather than by high-dimensional stochastic processes.

3.2 Operator-Based Evolution Model

Having established the presence of low-dimensional structure, the next step is to determine whether this structure extends to the **temporal evolution** of the system. To this end, we construct an operator-based model of the form:

$$X(t+1) = AX(t)$$

where $X(t) \in \mathbb{R}^d$ represents the system state at time t, and $A \in \mathbb{R}^{d\times d}$ is a linear operator that maps the system forward in time. The operator A is estimated using least-squares regression, solving:

$$A = \arg\min_{A} \ \| X(t+1) - AX(t) \|^2$$

overall observed transitions in the dataset. This formulation provides the best linear approximation to the system's evolution in the chosen state space. It is important to emphasize that this operator is not introduced as an arbitrary fitting mechanism. Rather, it is intended as a **discrete approximation of an underlying continuous operator**:

$$\frac{dX}{dt} = \mathcal{O}(X)$$

such that:

$$A \approx I + \Delta t \cdot \mathcal{O}$$

for sufficiently small-time increments Δt. In this sense, the learned operator A provides insight into the structure of the governing dynamics. To evaluate whether the system exhibits structured evolution, we compare the operator model against a persistence baseline:

$$X(t+1) = X(t)$$

This baseline represents the null hypothesis that the system has no meaningful temporal structure beyond inertia. Under a purely stochastic or memoryless model, the persistence baseline is often difficult to outperform. Model performance is evaluated using Root Mean Squared Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{t} \| X(t+1) - \hat{X}(t+1) \|^2}$$

where $\hat{X}(t+1)$ is the predicted state. A significant improvement over the persistence baseline indicates that the system's evolution is not random but follows a **structured mapping** in state space. It implies that knowledge of the current state provides predictive information about the future state, consistent with an operator-driven model. To ensure robustness, the operator is evaluated both globally and at the level of individual variables. This allows us to determine whether different components of the system exhibit varying degrees of predictability, and whether certain modes dominate the evolution.

In addition, the operator formulation naturally enables further analysis of system structure through its spectral properties. The eigenvalues of Acharacterize stability and growth or decay of modes, while the eigenvectors describe coupling between variables. Although a full spectral analysis is beyond the scope of the present study, this provides a clear pathway for future work.

It is also important to note that the use of a linear operator does not imply that the underlying system is linear. Rather, the operator should be viewed as a first-order approximation of potentially nonlinear dynamics. The key question is not whether the model is exact, but whether it captures sufficient structure to outperform a null model.

From a methodological standpoint, this approach differs fundamentally from statistical forecasting techniques. Traditional time-series models, such as autoregressive (AR) or ARIMA models, are designed to capture temporal correlations without necessarily revealing the underlying structure of the system. In contrast, the operator-based model explicitly seeks to identify the mapping that governs system evolution. Thus, the combination of modal decomposition and operator-based modeling provides a two-stage framework:

1. Identify the intrinsic dimensionality of the system
2. Determine whether the system evolves predictably within that reduced space

Together, these steps allow us to test the central hypothesis of this work: that variability in superconducting qubit systems is not purely stochastic, but reflects structured dynamics governed by an underlying operator.

4. Results

4.1 Low-Dimensional Structure

The first set of results concerns the intrinsic dimensionality of the qubit system. Applying Principal Component Analysis (PCA) to the six-dimensional state vector reveals a striking concentration of variance within a small number of modes. Specifically, the first principal component accounts for **86.7%** of the total variance, indicating that most of the system behavior is aligned along a single dominant direction in state space. This alone suggests a strong degree of structure, as a purely stochastic system would not exhibit such concentration.

Extending this analysis, the first two principal components together account for **96.6%** of the total variance. This implies that nearly all observable variability in the system can be described within a two-dimensional subspace, despite the presence of six measured variables. The inclusion of the third component captures essentially all remaining variance, with the cumulative explained variance exceeding **99.99%**. Beyond this point, additional components contribute negligibly, indicating that the effective dimensionality of the system is limited to approximately three degrees of freedom.

This result is highly nontrivial. In systems dominated by independent noise sources, variance is typically distributed more evenly across dimensions. The observed spectral decay instead indicates that the system is governed by a small number of **coherent, coupled modes**. From a geometric perspective, this implies that the system does not occupy the full six-dimensional state space but instead evolves on a **low-dimensional manifold embedded within that space**. The observed data points cluster along directions defined by the dominant eigenvectors, rather than filling the space uniformly.

This finding aligns with the operator-theoretic interpretation introduced in the methodology. The dominant principal components can be viewed as empirical approximations of the eigenfunctions of an underlying operator, suggesting that system behavior is constrained by a spectral structure. Importantly, this dimensional collapse is not the result of imposed reduction or model simplification. It emerges directly from the data, indicating that the system itself possesses fewer effective degrees of freedom than the number of measured variables would suggest.

Figure 1.

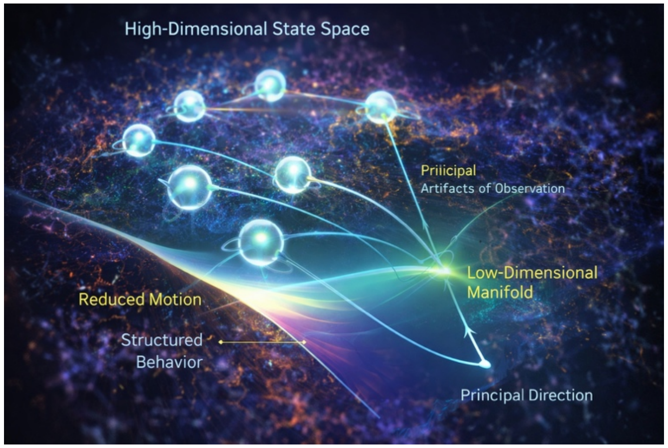


Figure 1. The convergence of multiple qubit trajectories onto a smooth surface, together with the highlighted principal direction, indicates that the system’s motion is constrained to a low-dimensional manifold and dominated by a small number of modes, rather than freely exploring a high-dimensional space—shifting from an old view of noise as intrinsic randomness to a new view of motion as structured and mode-governed.

4.2 Structured Temporal Evolution

Having established that the system exhibits low-dimensional structure, we next examine whether this structure extends to temporal evolution. To do so, we construct time-aligned snapshots of the system using coarse time binning to address the asynchronous nature of the measurements. This yields a set of sequential states suitable for evaluating one-step evolution. We then fit an operator model of the form:

$$X(t+1) = AX(t)$$

and compare its predictive performance against a persistence baseline:

$$X(t+1) = X(t)$$

which represents the absence of structured dynamics.

The results show that the operator model achieves a Root Mean Squared Error (RMSE) of **0.0460**, while the persistence baseline yields an RMSE of **0.0739**. This corresponds to a **37.7% reduction in prediction error**. This improvement is significant. In systems where variability is dominated by noise or random fluctuations, simple persistence models often perform well, as there is little structured evolution to exploit. The observed improvement indicates that the system contains **predictive structure beyond inertia**.

In other words, knowledge of the current state provides meaningful information about the future state, consistent with the existence of an underlying operator governing system evolution. This result directly challenges the assumption that qubit calibration drift is purely stochastic. Instead, it suggests that system behavior follows a **structured trajectory within the state space**, even in the presence of environmental variability. Furthermore, the success of a linear operator model indicates that, at least over short time horizons, the system can be approximated by a **locally linear mapping**. This is consistent with the interpretation of A as a first-order approximation to a continuous operator. The improvement over the baseline also implies that the system retains memory of its previous state, contradicting the notion of memoryless noise processes. This temporal coherence is a key indicator of structured dynamics.

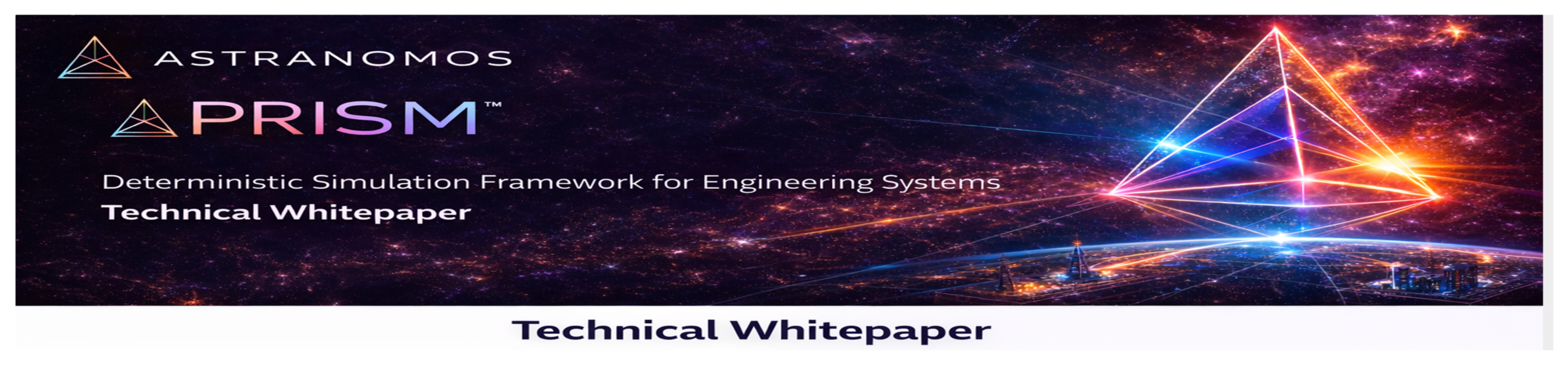
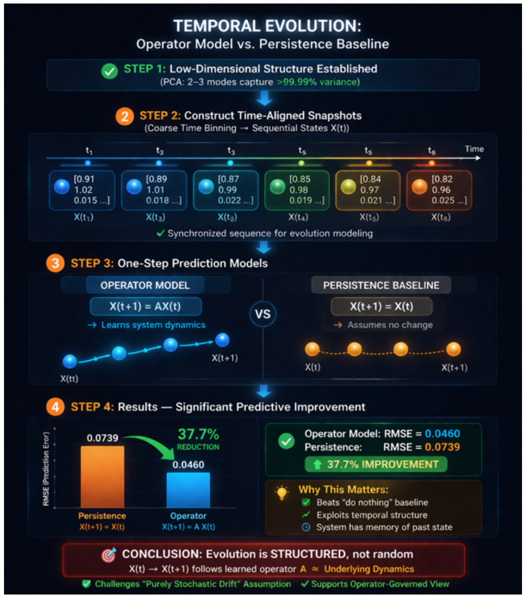


Figure 2.



TEMPORAL EVOLUTION:
Operator Model vs. Persistence Baseline

✓ **STEP 1:** Low-Dimensional Structure Established
(PCA: 2–3 modes capture >99.99% variance)

② **STEP 2:** Construct Time-Aligned Snapshots
(Coarse Time Binning → Sequential States X(t))

✓ Synchronized sequence for evolution modeling

③ **STEP 3:** One-Step Prediction Models

OPERATOR MODEL
X(t+1) = AX(t)
→ Learns system dynamics

VS

PERSISTENCE BASELINE
X(t+1) = X(t)
→ Assumes no change

④ **STEP 4:** Results — Significant Predictive Improvement

✓ Operator Model: RMSE = 0.0460
Persistence: RMSE = 0.0739
37.7% IMPROVEMENT

Why This Matters:
✓ Beats "do nothing" baseline
Exploits temporal structure
System has memory of past state

CONCLUSION: Evolution is STRUCTURED, not random
X(t) → X(t+1) follows learned operator A ≈ Underlying Dynamics
✓ Challenges "Purely Stochastic Drift" Assumption ✓ Supports Operator-Governed View

Figure 2. Within the scope of this experiment, the results indicate that the future state $X(t+1)$ is not independent of the present state $X(t)$, but can be partially predicted through a structured mapping of the form:

$$X(t+1) = AX(t),$$

where A is a learned operator. The observed reduction in prediction error relative to the persistence baseline:

$$X(t+1) = X(t)$$

demonstrates that $X(t)$ contains measurable information about its own short-term evolution. Importantly, this predictability is local in time and limited to the variables and time scales examined, rather than implying full long-term determinism. In this sense, the model provides empirical evidence that near-future states can be forecast with meaningful accuracy, even in systems typically modeled as noisy. Thus, temporal evolution is better described as structured and partially predictable, rather than fundamentally memoryless.

4.3 Variable-Level Behavior

To further understand the nature of the observed dynamics, we examine the predictive performance of the operator model at the level of individual variables. The results reveal a heterogeneous pattern. Variables associated with control and measurement—particularly **sx_error** and **readout_error**—exhibit the largest improvements relative to the persistence baseline. This indicates that these quantities are more dynamically active and more strongly coupled to the system's evolution.

In contrast, coherence variables such as **T1** and **T2** show relatively small improvements. This suggests that these variables are more stable over time, with less pronounced short-term dynamics. Measurement asymmetry variables (**prob_meas0_prep1** and **prob_meas1_prep0**) exhibit intermediate behavior, reflecting a balance between stability and dynamical variation.

This pattern suggests that the system is composed of two distinct types of modes:

- **Near-invariant modes**, corresponding to stable physical properties
- **Active modes**, corresponding to dynamically evolving control and measurement processes

From a spectral perspective, this implies that the operator governing the system has a mixture of eigenvalues near unity (slow or negligible evolution) and eigenvalues corresponding to more active dynamics. The presence of both stable and dynamic components reinforces the interpretation of the system as evolving on a structured manifold. The stable modes define the underlying geometry of the manifold, while the dynamic modes govern motion within it. This decomposition is consistent with the broader operator framework, in which system behavior is determined by a combination of invariant structure and evolving coefficients.

Moreover, the fact that different variables exhibit different levels of predictability indicates that the system is not uniformly random but instead exhibits **structured variability with variable-specific dynamics**. Taken together, the results of the modal decomposition and operator-based analysis provide a coherent picture: the system exhibits strong low-dimensional structure, evolves predictably over short time horizons, and consists of both stable and dynamic components. These findings are difficult to reconcile with a purely stochastic interpretation and instead support a structured, operator-driven view of system behavior.

5. Interpretation

The results obtained in this study support a fundamentally structural interpretation of superconducting qubit dynamics. Rather than occupying a high-dimensional stochastic space, the system is observed to evolve within a **low-dimensional manifold**, as evidenced by the strong concentration of variance and the success of the operator-based predictive model.

This distinction is critical. In a conventional stochastic framework, variability is treated as irreducible randomness, arising from independent or weakly coupled sources of noise. Under such a model, system behavior should exhibit high effective dimensionality, with variance distributed across many degrees of freedom. The empirical results presented here contradict this expectation, showing instead that the system's variability is highly organized and concentrated within a small number of dominant modes.

The observed dimensional collapse indicates that the system's state space is not fully explored but is instead constrained by underlying structure. This implies that the apparent complexity of the system arises not from many independent variables, but from the projection of a low-dimensional process into a higher-dimensional representation.

From this perspective, apparent noise can be understood because of **representation mismatch**. When a system evolving on a structured manifold is observed in a coordinate system that does not align with its natural modes, its behavior appears irregular and difficult to predict. However, when expressed in the appropriate basis—corresponding to the dominant eigenmodes—the same system exhibits coherence and predictability. This interpretation is consistent with the operator-based formulation introduced earlier:

$$\frac{dX}{dt} = \mathcal{O}(X)$$

where $\mathcal{O}$ is an operator governing the system's evolution. Under this framework, the state X evolves according to the spectral properties of $\mathcal{O}$, and the dominant modes identified through PCA can be interpreted as approximations of its eigenfunctions. The success of the discrete operator model:

$$X(t+1) = AX(t)$$

provides further support for this view. The observed improvement in predictive accuracy relative to a persistence baseline demonstrates that the system's evolution is not memoryless but instead follows a structured mapping in state space. This is a defining characteristic of operator-driven dynamics. Importantly, the presence of predictability does not imply that the system is fully deterministic in a classical sense. Environmental factors, measurement noise, and unresolved interactions still play a role in shaping system behavior. However, the results suggest that these influences are not purely random but instead act within a **structured dynamical framework**.

This distinction is subtle but significant. Rather than viewing environmental effects as sources of independent randomness, they may be better understood as perturbations that move the system within its admissible manifold. In this sense, variability reflects motion within a constrained space, rather than excursions into arbitrary configurations. The variable-level analysis reinforces this interpretation. The presence of both stable and dynamic variables indicates that the system contains a mixture of near-invariant and evolving modes. This is consistent with an operator spectrum that includes both slow and fast components, corresponding to different physical processes.

From a geometric standpoint, the system can be viewed as evolving along trajectories defined by its dominant modes. These trajectories are not random walks, but structured paths shaped by the operator. Apparent irregularities arise from the interaction of these modes and from observation in a non-optimal coordinate system. This perspective provides a natural explanation for why simple linear operators can capture a significant portion of system behavior. Even if the underlying dynamics are nonlinear, they may be well approximated locally by linear mappings within the manifold. The operator A can thus be interpreted as a local linearization of the true governing dynamics.

More broadly, these findings suggest that the distinction between deterministic and stochastic descriptions may be, in part, a matter of representation. Systems that appear stochastic in one basis may reveal structured, partially deterministic behavior when expressed in terms of their natural modes. This interpretation resonates with the broader trajectory of mathematical physics, in which complex systems are understood through their spectral properties rather than through explicit trajectory-based descriptions. By identifying the modes that define admissible motion, one can capture the essential behavior of a system without resolving every detail.

In the context of superconducting qubits, this has important implications. Calibration drift, coherence fluctuations, and measurement errors—often treated as noise—may instead reflect structured dynamics governed by the interplay of device physics and environmental conditions. Understanding this structure could lead to more effective calibration and control strategies. Furthermore, the observation of similar behavior across different physical domains suggests that this may not be a system-specific phenomenon, but part of a more general principle. If diverse systems exhibit low-dimensional structure and operator-driven evolution, this points toward a unifying framework for understanding variability in physical systems.

At a conceptual level, the results support the hypothesis that apparent randomness is often an emergent property of incomplete representation. When the governing structure of a system is not explicitly identified, its behavior appears irregular. When that structure is revealed, the same behavior becomes interpretable and, to some extent, predictable. In summary, the results indicate that superconducting qubit dynamics are better described as structured motion within a constrained manifold than as purely stochastic processes. The operator-based framework provides a natural language for this interpretation, linking empirical observations to a deeper mathematical structure.

6. Implications

6.1 Modeling

The results presented in this study suggest that purely stochastic models may be incomplete representations of system behavior, particularly in high-dimensional physical systems. While stochastic frameworks are effective for capturing variability at a coarse level, they do not explicitly account for the structured relationships observed in the data. The empirical findings show that the system state X evolves according to a mapping of the form:

$$X(t+1) = AX(t)$$

with measurable predictive accuracy. This indicates that system evolution is not memoryless but instead governed by a structured transformation in state space. Under a purely stochastic model, one would expect:

$$P(X(t+1) \mid X(t)) \approx P(X(t+1))$$

implying that the future state is independent of the present. The observed deviation from this behavior suggests that conditional dependence exists, and that the system retains information about its past state. This does not imply that stochastic models are invalid, but rather that they may be capturing only part of the underlying dynamics. They may approximate variability without identifying the governing structure that produces it.

By contrast, operator-based models provide a more direct representation of system behavior. Instead of describing distributions over states, they describe **how states transform**, making the evolution itself explicit. From this perspective, modeling shifts from fitting probabilistic descriptions of variability to identifying the operator O such that:

$$\frac{dX}{dt} = O(X)$$

This represents a conceptual transition from statistical modeling to **structural modeling**, in which the goal is to uncover the mechanisms governing motion rather than simply characterizing its distribution.

6.2 Simulation

The implications for simulation are equally significant. Traditional simulation approaches, particularly in fields such as computational fluid dynamics and thermal modeling, rely on discretizing governing equations over large spatial meshes. These methods often require millions or billions of degrees of freedom to approximate system behavior. The results of this study suggest that such high-dimensional representations may not always be necessary. If the system evolves on a low-dimensional manifold, then its behavior can be captured using a much smaller set of modes. Formally, instead of evolving the full state:

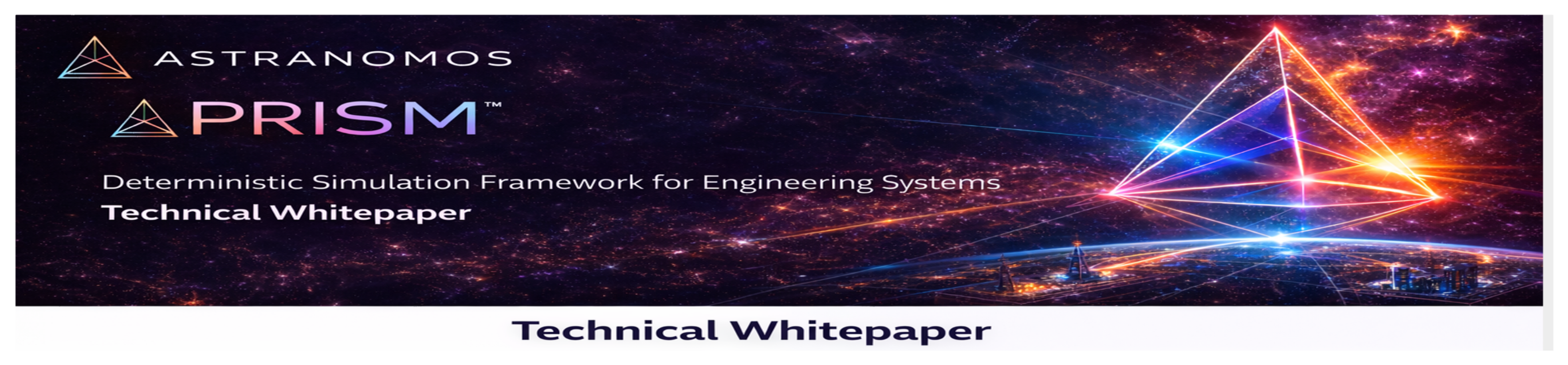
$$X \in \mathbb{R}^N$$

one can approximate:

$$X(t) \approx \sum_{i=1}^{m} a_i\,(t)\,\phi_i, m \ll N$$

where ϕ_i are the dominant modes identified through spectral decomposition. This reduces the effective dimensionality of the simulation problem by orders of magnitude, without discarding the underlying physics. Importantly, this is not an approximation imposed for computational convenience, but a reflection of the system's intrinsic structure.

In this framework, simulation becomes an evolution of modal coefficients $a_i(t)$ rather than a reconstruction of field values across a dense grid. This aligns simulation more closely with the mathematical structure of the system, potentially improving both efficiency and interpretability.



6.3 Quantum Hardware

For superconducting quantum hardware, the implications are particularly relevant. Calibration drift and noise are typically treated as stochastic processes, leading to reactive control strategies that continually adjust system parameters in response to observed deviations. The results of this study suggest that such drift is not entirely random, but instead exhibits structured, partially predictable behavior. The operator model demonstrates that:

$$X(t+1) = AX(t)$$

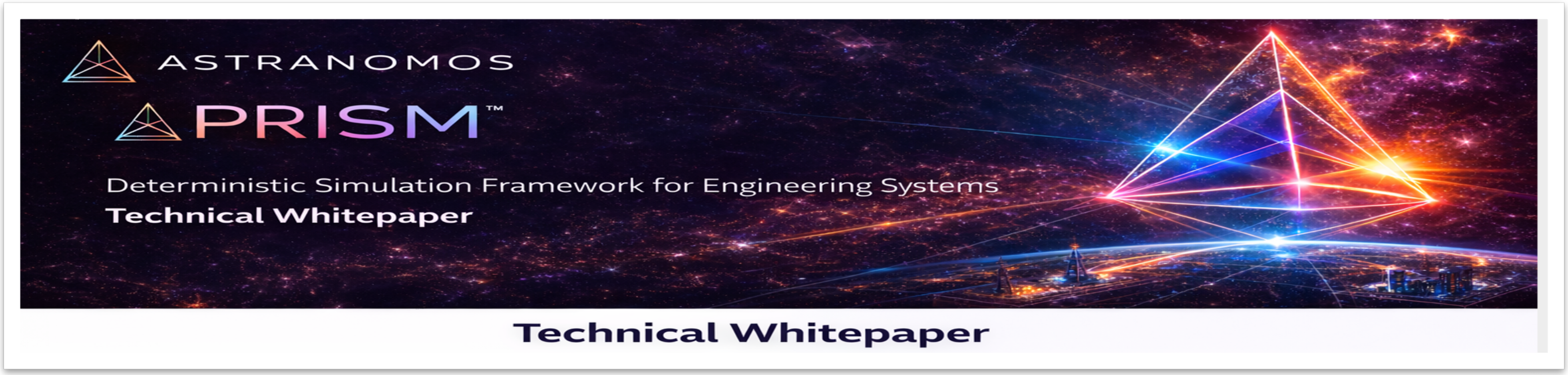
provides a better description of system evolution than a memoryless baseline, indicating that current system states contain information about near-future states.

This opens the possibility of **predictive calibration strategies**, in which control parameters are adjusted based on expected future behavior rather than solely on current measurements. Such strategies could improve stability, reduce calibration overhead, and enhance overall system performance. Moreover, the identification of dominant modes suggests that control efforts could be focused on a small number of key variables, rather than distributed across all parameters. This could simplify both hardware design and control algorithms.

6.4 General Physical Systems

Beyond quantum hardware, the findings of this study point toward a broader principle applicable across physical domains. Similar patterns of low-dimensional structure and structured evolution have been observed in thermal systems, structural dynamics, and other complex environments. This suggests that the distinction between deterministic and stochastic descriptions may often be a consequence of representation rather than a fundamental property of the system. When the governing structure is not explicitly identified, behavior appears random; when it is revealed, the same behavior becomes interpretable and, to some extent, predictable.

In this context, apparent randomness can be understood as arising from projecting structured dynamics into an incomplete or misaligned coordinate system. The underlying system may still be governed by a constrained operator, even if this is not immediately evident in the observed variables.



This leads to a unifying perspective:

- *Apparent randomness in physical systems often reflects unresolved structure rather than intrinsic stochasticity.*

While this statement should be interpreted carefully and within the limits of empirical validation, it provides a powerful lens for re-examining variability across domains. In summary, the implications of this work extend beyond a single dataset or application. They suggest a shift toward viewing complex systems as structured, operator-governed entities, with randomness emerging as a secondary effect of representation.

7. Conclusion

We have demonstrated that superconducting qubit calibration data exhibits:

- Strong low-dimensional structure
- Measurable short-term predictability

These findings are not merely technical observations, but carry deeper implications for how motion, variability, and time itself are understood in physical systems. The results show that a system traditionally described as noisy and stochastic can instead be represented within a low-dimensional manifold and evolved through a structured mapping of the form:

$$X(t+1) = AX(t)$$

This indicates that the present state contains measurable information about its own future evolution, implying that system dynamics are not memoryless, but retain **temporal coherence**. This observation aligns naturally with the broader operator formulation:

$$\frac{dX}{dt} = \mathcal{O}(X)$$

which can be viewed as a data-driven extension of classical variational principles, particularly those derived from the Euler–Lagrange equation. In this context, motion is not an arbitrary sequence of states, but a trajectory constrained by an underlying functional structure.

Similarly, the identification of dominant modes and spectral structure connects directly to Sturm–Liouville theory, in which admissible system behavior is defined by the eigenfunctions of an operator. The present results suggest that such spectral structure is not confined to idealized mathematical systems, but is observable in real, noisy physical data. Taken together, these perspectives point toward a reinterpretation of variability. Rather than treating noise as fundamentally random, it may be more accurately described as **structured motion within a constrained manifold**, arising from incomplete representation rather than intrinsic indeterminacy.

This raises a deeper question concerning the nature of time. In classical physics, from Hendrik Lorentz to Albert Einstein, time is treated as a continuous parameter along which states evolve, with relativity introducing geometric structure but not necessarily intrinsic memory at the level of system dynamics. In statistical and quantum frameworks, time often appears as a sequence of probabilistic updates, reinforcing the notion of uncertainty as fundamental. The results presented here suggest a more nuanced view. The ability to predict $X(t+1)$ from $X(t)$ implies that time evolution retains information about prior states, and that this information is encoded in the structure of the system itself. In this sense, time is not merely a passive parameter, but a **direction along which structured information propagates**.

Importantly, this does not contradict established physical theories but rather complements them by emphasizing the role of representation. The frameworks of relativity and quantum mechanics describe how systems evolve under fundamental laws, while the present work highlights how those evolutions may manifest as structured, low-dimensional dynamics when observed appropriately. From this perspective, the persistence of identity in physical systems—the fact that objects retain coherence, form, and continuity over time—can be understood because of their evolution along constrained operator-defined trajectories. The system does not randomly reconstruct itself at each moment; it follows a structured path that preserves its defining characteristics.

This interpretation is consistent with the empirical results obtained across multiple domains in our prior work, including thermal systems, structural dynamics, and now quantum hardware. In each case, apparent randomness gives way to structured behavior when analyzed through the appropriate spectral and operator-based framework. While the present study is limited in scope and does not claim a complete deterministic description of quantum systems, it provides strong evidence that variability is not purely stochastic. Instead, it suggests that physical systems exhibit **structured, partially predictable dynamics**, even in regimes traditionally considered noisy.

Thus, the significance of this work lies not in replacing existing theories, but in reframing how their consequences are observed and interpreted. By identifying the operator structure underlying system evolution, we move from describing motion as a sequence of uncertain events to understanding it as

structured progression within a constrained space. In conclusion, this study supports a broader hypothesis: that motion, across physical domains, is governed by underlying structure, and that apparent randomness often reflects the limits of representation rather than the absence of order.

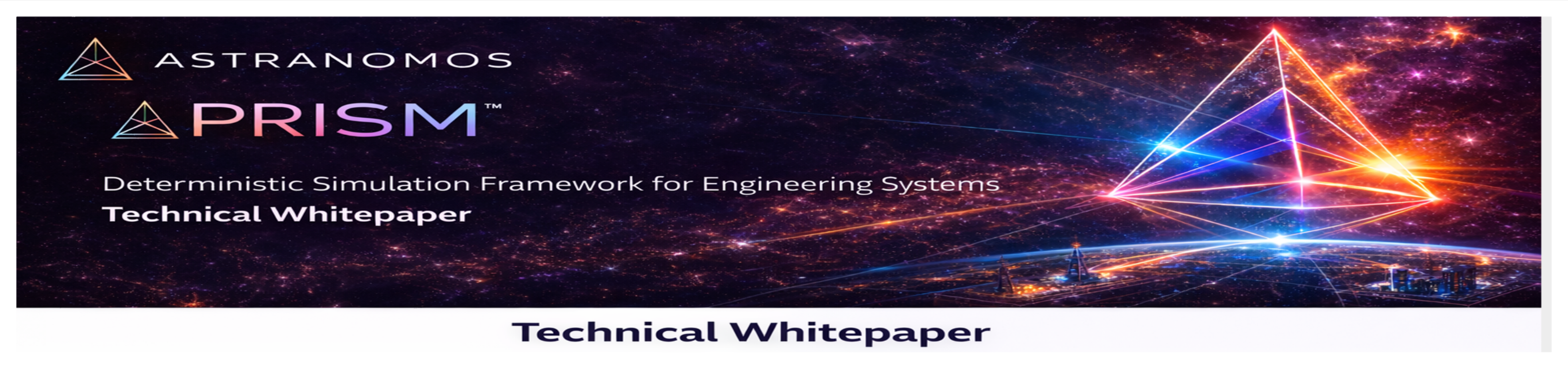
8. Data Availability

The dataset used in this study is publicly available at:

- https://huggingface.co/datasets/phanerozoic/qiskit-calibration-drift

Specifically:

- https://huggingface.co/datasets/phanerozoic/qiskit-calibration-drift/blob/main/data/train-00000-of-00001.parquet



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