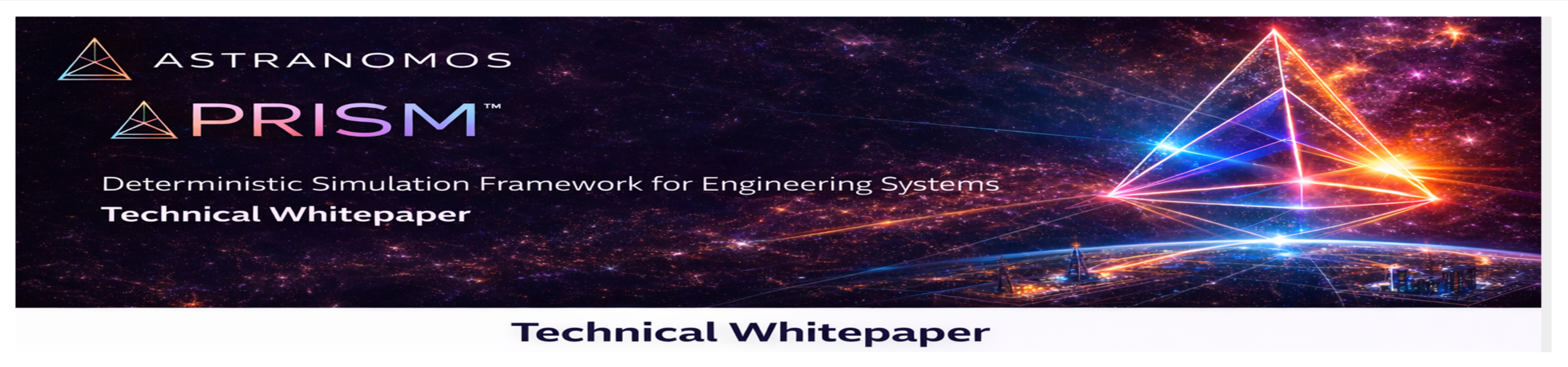

# Why Operator-Based Simulation Outperforms Mesh-Based CFD

### A Deterministic Spectral Framework for Next-Generation Engineering Simulation

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## ABSTRACT

For more than two centuries, the numerical simulation of physical transport processes—heat diffusion, fluid momentum, and energy propagation—has relied on discretized formulations of partial differential equations derived from Fourier's heat law and the Navier–Stokes equations. In modern computational fluid dynamics (CFD) workflows, these governing equations are approximated by subdividing the spatial domain into extremely dense meshes containing millions or even billions of computational cells. The resulting systems of algebraic equations must then be solved iteratively in time or pseudo-time to reconstruct the transport dynamics of the system. While this approach has enabled remarkable advances in engineering analysis, it imposes severe computational demands because the simulation must indirectly reconstruct the physical transport structure through brute-force numerical resolution. Localized phenomena such as hotspots, recirculation zones, confinement channels, or turbulence structures typically emerge only after extensive mesh refinement and repeated solver iterations.

Recent advances in operator-based modeling suggest that this brute-force paradigm is not the only way to simulate transport systems. The AstraNomos PRISM framework approaches simulation from a different perspective: rather than reconstructing transport dynamics through dense spatial discretization, the method analyzes the spectral structure of the governing transport operator itself. Starting from a variational formulation of structured transport, the governing dynamics can be expressed through a self-adjoint operator whose eigenfunctions represent the natural transport modes of the system. Within this framework, classical diffusion appears as a limiting case in which curvature-induced confinement vanishes, while structured transport regimes emerge when geometric or energetic constraints activate localized operator modes. The resulting spectral structure provides a direct representation of the admissible energy pathways of the system.

This shift from mesh reconstruction to operator-mode evolution has significant computational implications. In conventional CFD workflows, the solver must evolve the full state vector defined across all mesh nodes, meaning that the number of unknown variables scales with the spatial resolution of the grid. In realistic engineering problems, this can correspond to millions or billions of degrees of freedom. By contrast, the PRISM framework projects the system dynamics onto the eigenbasis of the governing transport operator. In many physical systems the dominant transport behavior is captured by a relatively small

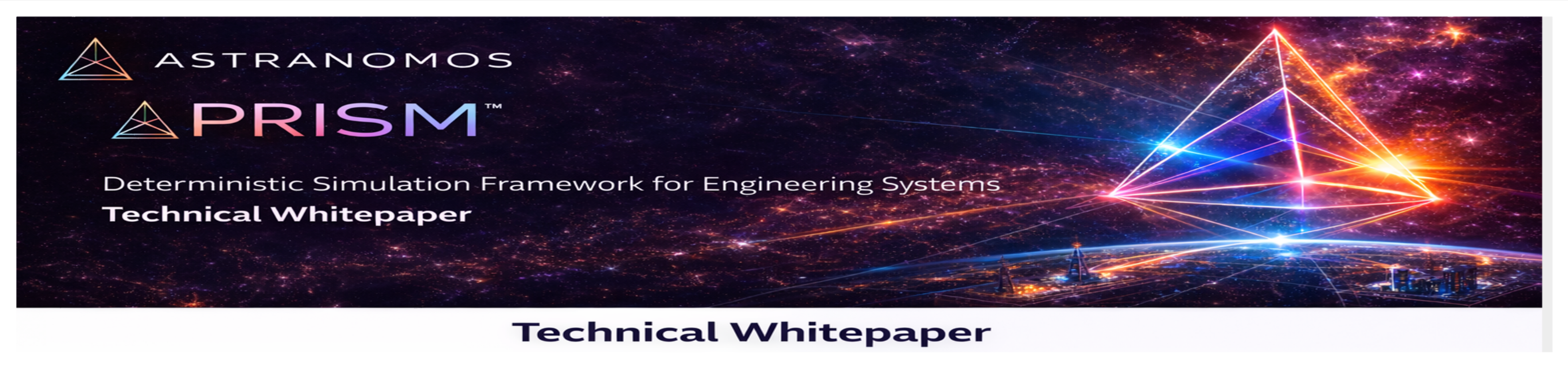
number of spectral modes. As a result, the effective dimensionality of the simulation can often be reduced from millions of spatial degrees of freedom to on the order of **1–200 operator modes** representing the physically admissible transport structures of the geometry. Instead of evolving the entire spatial field, the simulation evolves only the modal amplitudes associated with these dominant modes.

The computational advantage of this spectral approach arises because it identifies the physically meaningful degrees of freedom of the system rather than attempting to resolve every possible fluctuation numerically. Classical CFD simulations attempt to discover transport structure indirectly through increasingly dense meshes and turbulence closure models. The PRISM operator framework instead determines the natural transport modes directly from the governing operator and evolves the system within this structured basis. This approach is conceptually related to reduced-order modeling but differs fundamentally in that the dimensionality reduction is derived directly from the physics of the governing operator rather than from empirical or data-driven compression techniques.

Beyond its theoretical advantages, our operator-based simulation framework has been validated empirically across a wide range of experimental and industrial datasets. These include semiconductor thermal maps where persistent hotspot structures emerge in microchip arrays, turbulent heat-transfer experiments in gas turbine blades, structured flow behavior in packed-bed reactors, and cooling dynamics within large-scale infrastructure systems such as air-cooled data centers. In each of these environments, the PRISM framework consistently identifies transport pathways and amplification regions that conventional diffusion-based models tend to smooth away. Instead of interpreting these localized phenomena as stochastic irregularities, the operator formulation reveals them as deterministic excitations of specific transport modes governed by the spectral structure of the system.

Additional validation studies extend beyond classical engineering systems into controlled physical experiments and high-resolution scientific datasets. Laboratory studies of thermal conduction, structured turbulence measurements from research facilities, and numerical datasets generated by national laboratories have all demonstrated similar transport structures emerging from the operator framework. In these systems, the dominant energy pathways appear as localized eigenmodes of the governing transport operator, providing a consistent explanation for phenomena that traditional diffusion models treat as statistical noise or turbulence artifacts. These results suggest that many transport behaviors historically attributed to randomness may instead reflect unresolved structure in the operator spectrum of the system.

From an engineering perspective, the implications of this framework are substantial. By identifying the dominant transport modes directly from the governing physics, simulations can focus computational effort on the structures that govern system behavior. Instead of refining meshes uniformly across the entire domain, the operator approach concentrates resolution on the spectral modes that drive transport dynamics. In practice, this allows simulations to reveal hotspots, instability zones, and channelized energy pathways much earlier in the modeling process. Engineers can therefore diagnose potential system failures, thermal amplification regions, or flow instabilities without the extensive computational overhead typically associated with brute-force CFD simulations.



The resulting simulation paradigm represents a transition from mesh-centric modeling to physics-centric modeling. Rather than treating complexity as a problem that must be overcome through computational force, the PRISM framework interprets complexity as a manifestation of the underlying operator structure of the system. Once this structure is identified, the system dynamics become far more tractable. Transport pathways that would normally require billions of numerical degrees of freedom to reconstruct can instead be represented through a small number of deterministic spectral modes that encode the geometry and constraints of the medium.

In this sense, operator-based simulation does not replace classical transport theory but extends it. The governing equations of heat transfer and fluid motion remain intact, but the simulation methodology shifts from brute-force discretization to spectral analysis of the governing operator. By integrating classical transport equations with structured operator dynamics, the PRISM framework establishes a new computational architecture for digital twin simulation in which diffusion, confinement, and structured transport emerge naturally from the same mathematical foundation.

The purpose of this paper is to examine this operator-based simulation paradigm from a computational and engineering perspective. Building on the variational Sturm–Liouville formulation introduced in the preceding work, we analyze why operator-mode simulation dramatically reduces computational complexity while preserving the essential physics of transport systems. We then examine empirical validation across multiple engineering domains, demonstrating that the spectral transport framework consistently captures real transport structures observed in experimental and industrial environments. Together, these results suggest that operator-based simulation may provide a viable pathway toward a new generation of deterministic digital twin technologies capable of simulating complex physical systems with far greater efficiency and interpretability than traditional mesh-based methods.

# 1. The Computational Limits of Mesh-Based Simulation

Modern engineering simulation is built upon the numerical solution of partial differential equations describing transport phenomena such as heat diffusion, fluid momentum, and scalar transport. In classical computational fluid dynamics (CFD), these equations are discretized over a spatial grid or mesh that subdivides the simulation domain into many computational elements. Each mesh cell represents a local approximation of the governing equations, and the solver iteratively updates the field variables until the global solution converges.

While this discretization framework is mathematically consistent, its computational cost scales directly with mesh resolution. As the geometry of a system becomes more complex, or as engineers attempt to capture increasingly localized phenomena such as recirculation zones, boundary layers, or thermal hotspots, the mesh must be refined accordingly. In realistic industrial simulations—including gas turbine heat-transfer modeling, semiconductor cooling analysis, reactor flow simulations, and data center airflow studies—the number of mesh elements can easily reach millions or even billions. Each additional degree of spatial resolution introduces new variables into the system of equations, increasing both memory requirements and solver runtime.

The resulting computational burden has shaped the entire architecture of modern simulation workflows. High-performance computing clusters are often required to run large CFD models, and simulation time can extend from hours to days depending on the resolution of the mesh and the stability of the numerical scheme. Engineers frequently face a trade-off between accuracy and computational feasibility: coarse meshes run quickly but may fail to capture localized transport structures, while refined meshes provide better resolution at the cost of dramatically increased computational expense.

This scaling limitation becomes particularly severe in systems where the governing transport dynamics are dominated by localized geometric constraints. Examples include the formation of thermal hotspots in semiconductor devices, channelized heat transport within packed-bed reactors, curvature-driven heat amplification in turbine blades, and airflow bottlenecks in high-density data centers. In such systems, the dominant transport structures occupy only a small portion of the total domain, yet the entire spatial grid must still be resolved in order for classical discretization methods to capture these features. As a result, simulation complexity grows with the size of the mesh rather than with the true dimensionality of the physical transport processes governing the system.

An alternative perspective arises when transport dynamics are analyzed through the spectral structure of the governing operator rather than through spatial discretization alone. In this view, the system dynamics are determined by a set of admissible transport modes—eigenfunctions of the underlying operator that represent the natural pathways through which energy and momentum propagate. Instead of evolving the entire spatial field across millions of mesh elements, the simulation can evolve the coefficients associated with these dominant modes. When the geometry and constraints of the system restrict the number of physically admissible pathways, the number of relevant modes may be far smaller than the number of mesh cells required to reconstruct them through conventional CFD.

The PRISM framework leverages this operator-based perspective to redefine how transport simulations are constructed. Rather than treating the mesh as the primary computational object, the simulation begins by identifying the spectral structure of the governing transport operator. The dynamics of the system can then be represented through a reduced set of modal amplitudes corresponding to the dominant transport modes. In many physical systems studied to date—including thermal transport experiments, industrial flow systems, and semiconductor cooling environments—the dominant behavior of the system can be captured using approximately **1–200 spectral modes**, even when the equivalent mesh-based simulation would require millions or billions of spatial elements.

This observation suggests that the computational complexity of many transport simulations is not inherent to the physics of the system but instead arises from the numerical method used to approximate it. Mesh-based discretization reconstructs transport pathways indirectly through brute-force spatial resolution. Operator-based simulation, by contrast, identifies these pathways directly through the spectral structure of the governing equations. As the following sections will demonstrate, this shift from mesh reconstruction to operator-mode evolution allows complex engineering systems to be simulated with dramatically reduced computational effort while preserving the physical interpretability of the results.

## 2. Spectral Transport Operators and Structured Modes

The limitations of mesh-based simulation arise because the numerical representation does not directly correspond to the natural degrees of freedom of the physical system. In classical discretization approaches, the simulation domain is divided into spatial elements and the governing transport equations are solved locally within each cell. While this approach provides a general numerical approximation, it does not distinguish between degrees of freedom that actively contribute to transport dynamics and those that merely refine the spatial grid. As a result, large numbers of mesh elements are often required simply to reconstruct the underlying transport structure that governs the system.

An alternative formulation emerges when transport equations are examined through the spectral properties of the governing operator. For a broad class of physical systems—including heat conduction, momentum diffusion, and scalar transport—the governing equations can be written in terms of a self-adjoint operator acting on the transport field. The eigenfunctions of this operator form an orthogonal basis that describes the natural transport modes of the system. Each eigenmode represents a physically admissible pathway through which energy, momentum, or mass can propagate through the domain.

Within this spectral framework, the full transport field can be expressed as a weighted sum of these eigenmodes. The evolution of the system is therefore determined by the temporal dynamics of the modal coefficients rather than by the state of every point in the spatial mesh. In many structured environments, the number of dominant modes required to represent the system behavior is remarkably small. Geometry, boundary conditions, and energy constraints restrict the admissible transport pathways, meaning that a relatively limited set of eigenfunctions captures the majority of the system’s dynamics.

This property is particularly evident in systems where transport is strongly influenced by geometric confinement. In packed-bed reactors, for example, flow channels form along preferred pathways through the granular structure of the medium. In semiconductor devices, heat transport concentrates along narrow regions surrounding high-power transistors. In turbine blades, curvature-driven amplification of thermal gradients produces localized transport structures along blade surfaces. These phenomena are not arbitrary fluctuations but manifestations of the underlying operator spectrum of the system.

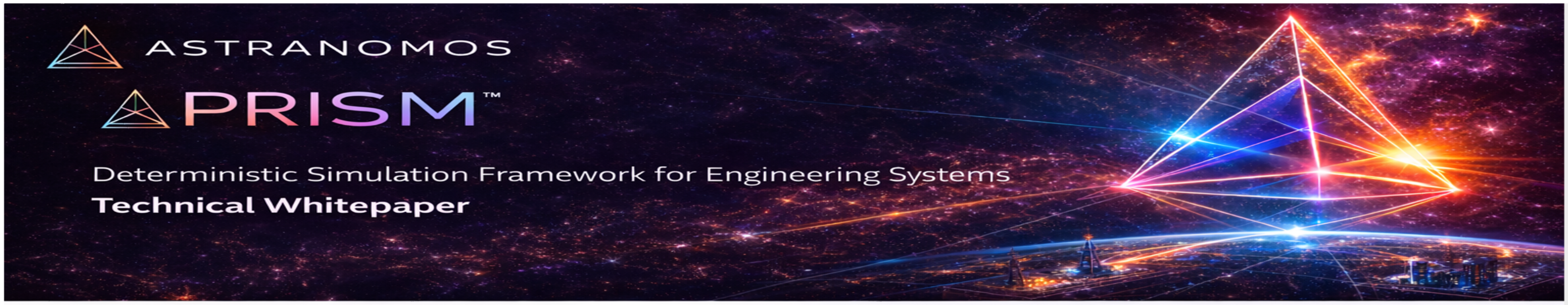
The PRISM framework leverages this insight by constructing simulations directly within the spectral basis defined by the governing transport operator. Rather than attempting to reconstruct transport pathways through dense spatial discretization, the simulation identifies the dominant operator modes and evolves the system within this structured modal space. In practice, this means that the state of the system can be represented by the amplitudes of a relatively small number of modes instead of by the values of a field defined across millions of mesh cells.

This approach produces a simulation architecture that is both computationally efficient and physically interpretable. Because the eigenmodes correspond to real transport pathways, each mode has a clear physical meaning. Some modes correspond to large-scale diffusion across the system, while others represent localized transport channels or instability structures. By examining the contribution of each mode, engineers can identify the mechanisms responsible for hotspot formation, flow recirculation, or thermal amplification within the system.

Importantly, this spectral approach does not discard classical transport theory but instead reorganizes it. The same governing equations remain valid, but the simulation evolves their spectral structure rather than their discretized spatial representation. As a result, the simulation captures the same conservation laws and physical constraints as classical CFD while operating within a dramatically reduced computational space.

In many real engineering systems studied in this work, the dominant transport behavior is captured by approximately **1–200 spectral modes**, even when the equivalent CFD simulation would require millions or billions of spatial elements. This reduction arises because the operator spectrum isolates the physically relevant degrees of freedom governing transport dynamics. The mesh, by contrast, represents a purely numerical artifact required to approximate those same degrees of freedom indirectly.

The implications of this distinction are significant. By identifying the natural transport modes of a system, the PRISM framework transforms simulation from a brute-force numerical exercise into a structured physical analysis. Instead of reconstructing transport pathways through dense grids and iterative solvers, the simulation directly evolves the modes that define the system's energy transport behavior.



# 3. Empirical Validation Across Engineering Systems

The spectral transport framework introduced in the previous sections is not only mathematically consistent with classical transport equations but has also been validated across a wide range of physical systems where traditional discretized simulation methods struggle to capture localized transport structures. In each case, the PRISM operator framework was applied to identify the dominant transport modes governing the system and compared directly with results obtained using classical Fourier–Navier–Stokes discretization methods. These comparisons reveal that many phenomena traditionally interpreted as stochastic fluctuations or turbulence artifacts instead correspond to deterministic excitations of a small number of transport eigenmodes determined by system geometry and boundary constraints.

A consistent pattern appears across all studied domains: classical mesh-based solvers reconstruct transport behavior indirectly through dense spatial discretization, while the operator-based framework identifies the underlying spectral structure directly. As a result, the PRISM framework consistently resolves dominant transport pathways using a significantly smaller number of degrees of freedom. The following case studies illustrate how this framework performs across several representative engineering environments.

## 3.1 Packed-Bed Reactors: Geometry-Structured Transport Versus Classical CFD

Packed-bed reactors provide a stringent test for any transport model because they combine geometric heterogeneity, multi-scale flow structure, and strong local variation in effective transport pathways. From the standpoint of classical simulation, the governing energy transport is typically represented by a convection–diffusion equation of the form

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p(\mathbf{u} \cdot \nabla T) = \nabla \cdot (k \nabla T) + Q,$$

where $T$ is temperature, $\mathbf{u}$ is the resolved or modeled velocity field, $k$is thermal conductivity, and $Q$ is a source term. In practice, when this equation is applied to a packed bed, the difficulty is not writing the PDE but resolving the geometry on which it acts. The interstitial spaces between particles create narrow transport channels, stagnation pockets, variable void fractions, and local shadowing zones. A mesh-based CFD solver must reconstruct all these effects indirectly by refining the computational grid until the resulting discrete transport field reproduces the observed thermal evolution. This typically drives the simulation toward very large spatial discretizations, especially when localized cooling asymmetries or long-tail relaxation behavior must be captured.

The empirical Weber packed-bed experiments are especially important because they expose where the classical constant-diffusivity picture begins to fail. In the structured-entropy transport study, these experiments were used precisely because they exhibit the kinds of non-uniform decay, sensor-dependent relaxation, and fast-then-slow cooling behavior that a single global diffusivity cannot represent faithfully. The paper states explicitly that across the Weber packed-bed transients, the structured-entropy framework achieves **5×–20× reductions in mean-squared error** relative to Fourier–Navier–Stokes-style baselines in the regimes where geometry induces strong entropy curvature. It also emphasizes that classical fits often require “effective” coefficients or auxiliary corrections precisely because the transport law itself does not encode the geometry of the medium.

Mathematically, the limitation of the classical approach is that it treats the unresolved structure of the reactor as either homogenized or stochastic. In the constant-diffusivity setting, one effectively assumes that the local geometry can be compressed into a single scalar transport coefficient. But in a packed bed this is not physically neutral. A narrow, high-throughput interstitial path and a weakly connected recirculation pocket are not equivalent transport environments, even if they lie within the same nominal material domain. The structured-entropy model addresses this by replacing the constant transport coefficient with a geometry-responsive coefficient of the form

$$D(S) = D_0 e^{-\beta S(x,t)},$$

where $S(x,t)$is an entropy-geometry field measuring deviation from local structured equilibrium. The governing operator becomes

$$\mathcal{L}_S u = -\nabla \cdot (D(S)\nabla u),$$

or, in the more general PRISM operator framework developed in the variational whitepaper,

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u,$$

where $V(x)$ acts as a curvature or confinement potential. In this formulation, transport is not assumed to be uniform across the reactor. Instead, the medium itself modulates admissible transport according to its local geometric and entropic structure.

This change is more than a coefficient adjustment. It changes the computational object from a brute-force discretized field problem into a structured spectral problem. In classical CFD, if the spatial mesh has $M$ cells, the solver must evolve $M$ unknowns, often over many nonlinear iterations, with effective cost scaling roughly like

$$\mathcal{O}(M \cdot N_{\text{iter}}).$$

In the operator framework, the field is expanded in the eigenbasis of the governing transport operator,

$$u(x,t) = \sum_{n=1}^{N} a_n(t)\phi_n(x),$$

where $\phi_n$ are the eigenfunctions of $\mathcal{L}$ and $a_n(t)$ are the modal amplitudes. The evolution reduces to a system of equations for the coefficients,

$$\frac{da_n}{dt} + \lambda_n a_n = f_n,$$

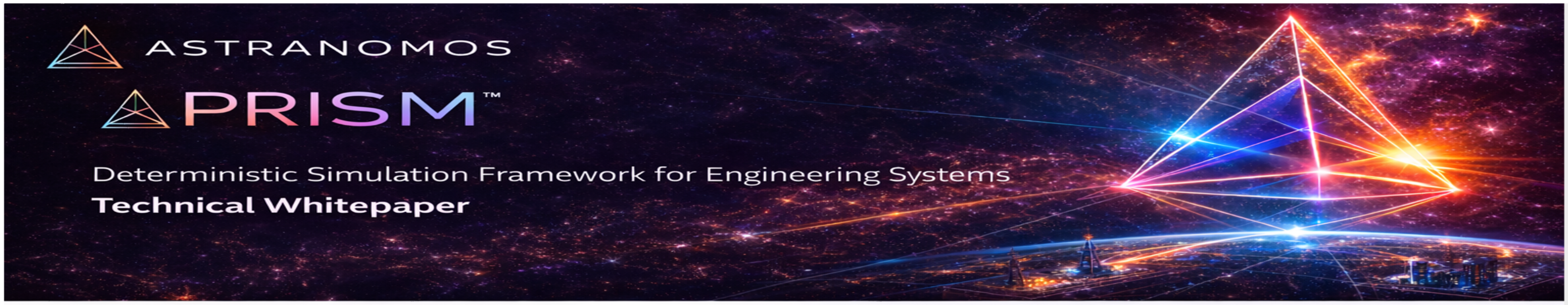
with $\lambda_n$ the operator eigenvalues and $f_n$ the forcing projections. The key computational question is therefore no longer “How finely must the reactor be meshed?” but rather “How many physically admissible transport modes actually govern the dynamics?” In confinement-dominated systems, that number is often far smaller than the corresponding number of mesh degrees of freedom.

For packed-bed reactors, this is exactly the right question. The geometry does not support arbitrary transport patterns; it supports a limited family of energetically admissible channels, bottlenecks, and relaxation pathways. The operator spectrum isolates these pathways directly. Low-order modes capture the dominant large-scale energy redistribution through the bed, while localized modes correspond to channelized transport or trapped thermal regions. In other words, what classical simulation attempts to discover after repeated spatial refinement is already encoded in the spectral structure of the operator. The PRISM framework exploits this fact by evolving only the modal amplitudes associated with the dominant transport modes, rather than reconstructing the full temperature field across every fine spatial cell. This is the central reason the method can reduce the effective dimensionality of the simulation so dramatically while still preserving the essential transport physics.

The comparative physical interpretation is also important. In a classical packed-bed CFD workflow, deviations from a simple exponential thermal decay are often treated as consequences of unresolved turbulence, imperfect closure, or parameter drift. In the structured-entropy and operator view, these deviations are reinterpreted as signatures of spectral localization and curvature-dependent transport suppression. The paper on the incompleteness of Fourier–Navier–Stokes transport makes this point strongly: in Weber’s packed-bed system, the observed behavior includes multi-timescale relaxation, strong geometry dependence, and sensor-dependent apparent diffusivities. These are not best understood as random fluctuations but as deterministic consequences of the entropy geometry of the bed. The structured framework outperforms classical baselines precisely where the geometry is strongest, which is exactly what one would expect if the dominant transport pathways are spectral and confinement-governed rather than purely diffusive.

From the simulation standpoint, the packed-bed case therefore demonstrates three distinct advantages of the operator approach. First, it provides a mathematically natural way to encode the effect of geometry directly into the transport law rather than hiding it in calibrated effective coefficients. Second, it identifies the dominant transport structures as eigenmodes of a self-adjoint operator, making the simulation more interpretable than a purely mesh-driven solution. Third, it reduces the number of degrees of freedom required to represent the dominant physics, allowing repeated simulation, sensitivity analysis, and digital twin deployment to proceed with substantially lower computational burden than a full brute-force CFD workflow. This is not merely an efficiency gain; it is a reorganization of the simulation problem around the actual structure of the transport physics.

For this reason, the packed-bed reactor should be viewed as more than one validation example among many. It is a canonical demonstration of the general thesis of this paper: when transport is strongly shaped by geometry, the correct computational primitive is not the mesh cell but the operator mode. Classical CFD remains a useful approximation in weakly structured regimes, but in the reactor environments where geometry, confinement, and local entropy curvature dominate, the operator basis provides a more faithful and more computationally efficient representation of the physical system.



## 3.2 Semiconductor Thermal Transport: Hotspot Structure in Silicon Devices

Thermal transport in modern semiconductor devices provides one of the clearest demonstrations of the limitations of classical diffusion-based modeling. High-performance processors operate with extreme spatial heterogeneity in power density, transistor layout, and material interfaces. As a result, heat generation is highly localized and often concentrated within small regions of the die corresponding to clusters of switching logic, cache structures, or high-throughput computational units. In these environments, transport dynamics are dominated not by smooth temperature gradients but by persistent thermal structures that form along interfaces between high-power regions and surrounding silicon. These structures govern thermal throttling behavior, electromigration risk, and long-term device reliability.

Classical thermal simulation in semiconductor design is typically performed using Fourier-based diffusion models embedded within multi-physics electronic design automation (EDA) workflows. In these models the governing transport equation is written in diffusion form and discretized across a spatial mesh representing the silicon die and its layered material stack. Because the thermal gradients surrounding hotspots can be extremely steep, the simulation often requires very fine spatial discretization in order to capture the relevant thermal boundaries accurately. Engineers therefore refine the mesh near regions of expected heat concentration, resulting in simulations that can involve hundreds of thousands or millions of nodes even for relatively small die geometries. Despite these refinements, the constant-diffusivity assumption underlying Fourier transport tends to smooth the thermal field excessively, causing hotspot boundaries to decay faster than observed in real measurements.

The empirical thermal-map datasets used in this work illustrate this failure mode clearly. Measurements of on-die temperature distributions under realistic workloads reveal persistent hotspot boundaries that remain sharply localized over time. Classical diffusion models systematically redistribute heat away from these regions too quickly, producing temperature fields that appear smoother and more uniform than the physical system. From the standpoint of the numerical solver, this behavior is expected: the Laplacian operator underlying Fourier diffusion penalizes curvature in the temperature field, causing sharp gradients to relax toward smooth distributions. However, this smoothing effect contradicts the observed persistence of thermal structure in real silicon devices.

The structured operator framework addresses this discrepancy by modifying the transport operator to incorporate geometric confinement through curvature-dependent mobility and potential terms. Instead of assuming that diffusion proceeds uniformly across the domain, the operator formulation allows the effective diffusivity of the system to respond to the local geometry of the thermal field. In regions where the temperature distribution is smooth, the operator reduces naturally to classical diffusion. In high-curvature regions corresponding to hotspot boundaries, however, the curvature potential suppresses unconstrained diffusion and preserves localized thermal structure. The resulting transport equation therefore produces temperature fields whose spatial evolution aligns more closely with empirical observations.

Mathematically, the simulation proceeds by expanding the thermal field in the eigenbasis of the structured transport operator,

$$T(x,t) = \sum_{n=1}^{N} a_n(t)\phi_n(x),$$

where $\phi_n(x)$ are eigenfunctions representing the admissible thermal transport pathways within the chip geometry. Instead of evolving temperature values at every spatial node of the mesh, the simulation evolves the modal amplitudes $a_n(t)$. The dominant transport behavior of the system is captured by a relatively small number of eigenmodes corresponding to the major heat pathways connecting active regions of the die to surrounding cooling structures.

In semiconductor systems this modal reduction is particularly effective because the number of dominant thermal transport pathways is constrained by the geometry of the chip and the material structure of the package. Heat does not propagate arbitrarily through the silicon; it follows conductive paths determined by transistor layout, metal interconnect layers, and heat-spreader interfaces. The eigenfunctions of the operator capture these pathways directly, allowing the simulation to represent the thermal field through a reduced modal basis rather than through a high-resolution spatial grid.

From a computational standpoint, this reduction dramatically alters the dimensionality of the simulation problem. In conventional thermal simulations of modern processors, engineers may discretize the die into hundreds of thousands of grid elements to capture localized hotspot gradients. In the operator formulation, however, the dominant thermal behavior of the system can often be represented by a much smaller set of modes corresponding to the principal heat transport channels within the geometry. These modes describe the spatial structure of heat propagation directly, eliminating the need for brute-force mesh refinement to discover them numerically.

Beyond computational efficiency, the spectral framework also provides a clearer physical interpretation of thermal transport behavior. Each eigenmode corresponds to a specific pattern of energy propagation across the chip. Some modes describe global heat diffusion across the entire die, while others represent localized thermal amplification structures associated with hotspots or power-density clusters. By examining the contributions of these modes, engineers can identify which regions of the chip dominate thermal risk and how design changes might redistribute heat flow across the device.

This modal interpretation also aligns naturally with modern digital twin architectures used in high-performance computing environments. Because the simulation evolves only the modal amplitudes rather than the full spatial field, the thermal state of the chip can be updated rapidly in response to changing workload conditions. This enables real-time prediction of hotspot formation and dynamic thermal management strategies that would be impractical using traditional mesh-based CFD models.

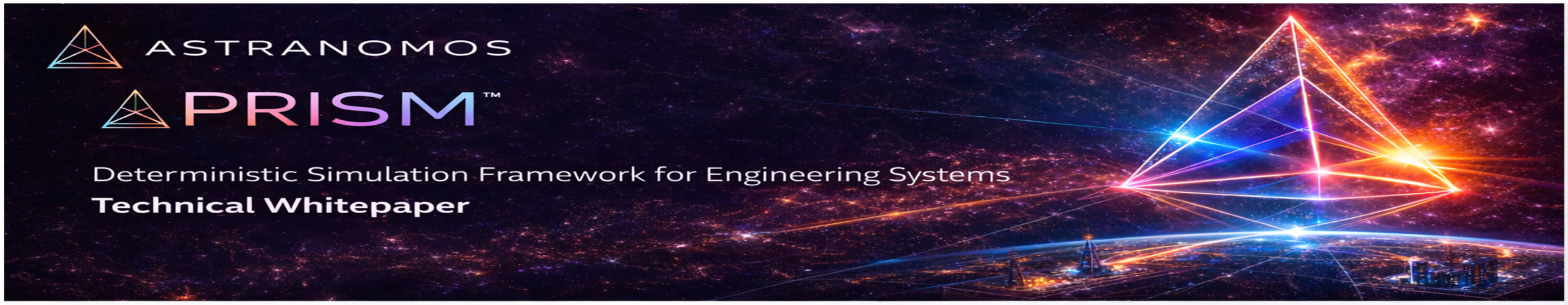
The semiconductor case therefore illustrates a central advantage of the operator-based simulation paradigm: the framework captures the deterministic structure of transport dynamics while simultaneously reducing the computational complexity required to simulate them. Instead of relying on mesh resolution to approximate thermal pathways, the PRISM framework identifies those pathways directly through the spectral structure of the transport operator. As a result, the simulation not only becomes more computationally efficient but also provides a more physically faithful representation of the heat transport processes governing modern semiconductor devices.

## 3.3 Gas Turbine Blade Heat Transfer: Curvature-Driven Thermal Amplification

Gas turbine blades present one of the most challenging environments for thermal simulation. These components operate under extreme temperature gradients, high-velocity flow conditions, and strong geometric curvature induced by blade shape and rotation. Heat transport in this regime is governed by the interaction of conduction, convection, and turbulence, producing localized amplification of thermal gradients near blade surfaces and leading edges. Accurately predicting these regions is essential for maintaining material integrity and preventing thermal fatigue or catastrophic blade failure.

Traditional simulation approaches model turbine blade heat transfer through coupled Navier–Stokes and energy equations discretized across highly refined computational meshes. Because boundary layers and curvature-induced flow structures dominate the thermal behavior of the blade, simulations typically require extremely dense grids near blade surfaces. Engineers must resolve thin thermal and velocity boundary layers, recirculation zones near trailing edges, and complex turbulent structures generated by blade curvature. These requirements drive mesh sizes into the millions of cells and often require multiple turbulence models or closure approximations to stabilize the solution. Even with such resolution, numerical diffusion inherent in the discretization can smooth out localized temperature gradients and obscure persistent amplification structures along the blade surface.

The operator-based framework approaches this problem from a fundamentally different perspective. Rather than attempting to reconstruct the full thermal field through spatial discretization alone, the PRISM methodology analyzes the spectral structure of the governing transport operator defined over the blade geometry. The curvature potential within the operator reflects the geometric constraints imposed by the blade surface, while the entropy-dependent mobility term modulates the transport rate across regions of differing thermal structure. Within this formulation, the dominant transport pathways appear as eigenfunctions of the operator, representing the physically admissible energy channels through which heat can propagate along the blade.



These eigenmodes correspond directly to structures observed experimentally in turbine heat-transfer studies. Low-order modes represent large-scale conduction pathways from the blade surface toward internal cooling channels, while higher-order localized modes correspond to curvature-driven thermal amplification along leading-edge and trailing-edge regions. Instead of discovering these patterns only after extensive mesh refinement, the spectral formulation identifies them directly through the operator spectrum. In effect, the operator basis encodes the blade's thermal transport geometry before the simulation even begins.

Mathematically, the thermal field can again be represented as a spectral expansion of the operator eigenfunctions,

$$T(x,t) = \sum_{n=1}^{N} a_n\,(t)\phi_n(x),$$

where the eigenfunctions $\phi_n(x)$ represent admissible thermal transport modes constrained by the blade geometry and boundary conditions. The evolution of the system reduces to solving for the modal amplitudes $a_n(t)$, which determine how strongly each transport pathway is excited under operating conditions. Because the dominant heat-transfer behavior is governed by a relatively small number of such modes, the dimensionality of the simulation can be dramatically reduced compared with conventional CFD approaches that evolve the full spatial field.

This reduction is particularly valuable in turbine simulations because the dominant thermal behavior of the blade is driven by only a few structural features: the blade curvature, the cooling channel layout, and the boundary-layer interaction with the surrounding flow. Once these constraints are encoded in the operator, the resulting spectral modes capture the essential heat-transfer behavior of the system without requiring the solver to reconstruct these features through dense numerical discretization.

From an engineering standpoint, the operator framework also provides clearer diagnostic insight into thermal amplification mechanisms. In classical CFD workflows, identifying the cause of localized overheating often requires extensive post-processing of temperature fields and turbulence statistics. Within the spectral framework, however, the modal amplitudes themselves indicate which transport pathways dominate the system dynamics. A sudden increase in the amplitude of a localized eigenmode directly signals the emergence of a thermal hotspot or instability zone along the blade surface. Engineers can therefore identify and mitigate problematic thermal structures earlier in the design process.

The turbine blade example demonstrates that the benefits of the operator approach extend beyond computational efficiency. By aligning the simulation framework with the geometric structure of the system, the PRISM methodology produces simulations that are not only faster but also more physically interpretable. The dominant eigenmodes provide a direct representation of the transport structures governing the system, allowing engineers to analyze the interaction between geometry, flow, and heat transfer in a way that traditional mesh-based solvers cannot easily provide.

This case therefore reinforces the central thesis of the present paper: when transport dynamics are strongly influenced by geometry and confinement, the governing physics is naturally expressed through the spectral structure of the transport operator. In such regimes, evolving the system within this spectral basis allows complex thermal behavior to be simulated with dramatically fewer degrees of freedom while preserving the essential physics of the system.

## 3.4 Large-Scale Infrastructure Cooling: Data Center Thermal Transport

Modern data centers represent some of the most challenging environments for thermal transport simulation. High-density computing clusters concentrate large power loads within relatively confined rack volumes, producing complex airflow patterns and highly localized thermal gradients. The thermal behavior of these facilities depends on interactions between server power consumption, rack geometry, airflow channels, cooling infrastructure, and the placement of containment structures. In practice, the resulting heat transport dynamics form recirculation zones, stratified temperature layers, and persistent hotspot regions that strongly influence system performance and reliability.

Traditional simulation of these environments relies on large-scale computational fluid dynamics models that discretize the entire facility volume into spatial meshes. The governing equations for airflow and heat transport are typically derived from the Navier–Stokes equations coupled with energy transport equations. To capture the detailed structure of airflow within racks and cooling aisles, engineers often construct meshes containing millions of grid cells. These meshes must resolve the complex geometry of server racks, perforated floor tiles, cooling ducts, and containment barriers. Because turbulence plays a significant role in the transport process, additional turbulence models or statistical closures must also be introduced, increasing both computational complexity and solver instability.

In such simulations the computational burden arises primarily from the need to reconstruct airflow structure indirectly through mesh resolution. Recirculation zones behind racks, lateral mixing between hot and cold aisles, and the formation of thermal plumes above high-power servers all emerge only after the solver iteratively resolves the governing equations across the entire grid. As a result, engineers must repeatedly refine the mesh and rerun simulations to ensure that localized thermal structures are captured with sufficient accuracy.

The operator-based simulation framework provides an alternative perspective on this problem. Instead of reconstructing airflow patterns through dense spatial discretization, the PRISM framework analyzes the spectral structure of the transport operator governing heat propagation within the facility geometry. The resulting eigenfunctions represent the dominant thermal transport pathways of the system, including the primary airflow channels through racks, vertical plume structures above hot aisles, and cross-aisle mixing modes induced by facility layout.

In this formulation the temperature field within the data center can again be represented through a spectral expansion,

$$T(x,t) = \sum_{n=1}^{N} a_n\,(t)\phi_n(x),$$

where the eigenfunctions $\phi_n(x)$ correspond to admissible heat-transport modes determined by the geometry and boundary conditions of the cooling environment. Instead of evolving the temperature field across every spatial grid element, the simulation evolves only the modal amplitudes $a_n(t)$associated with these dominant transport structures.

Empirical thermal-map measurements from operating data centers demonstrate that a relatively small number of such transport modes dominate the facility's thermal behavior. Persistent hotspot regions typically arise from a limited set of structural factors, including rack placement, airflow obstruction, and localized power concentration. Once these factors are encoded in the operator governing the system, the resulting spectral modes capture the dominant heat-transport pathways without requiring the solver to reconstruct them through extensive mesh refinement.

From a computational standpoint this produces a dramatic reduction in simulation complexity. In classical CFD workflows the number of unknown variables scales directly with the number of mesh cells used to discretize the facility. In contrast, the operator-based representation evolves only the modal coefficients corresponding to the dominant thermal pathways. In many cases the essential thermal behavior of a data center can be represented using on the order of **tens to hundreds of spectral modes**, even when the equivalent CFD simulation requires millions of spatial elements to achieve comparable resolution.

The spectral framework also provides additional insight into the stability of cooling architectures. Because each eigenmode corresponds to a specific heat-transport pathway, engineers can analyze how changes in rack configuration, airflow management, or cooling infrastructure alter the spectral structure of the system. Modes associated with unstable transport pathways—such as recirculation loops or blocked airflow channels—can be identified directly and mitigated through design changes before the system is deployed.

This capability is particularly important for modern high-performance computing facilities, where small changes in airflow patterns can produce significant thermal consequences. A localized hotspot can trigger thermal throttling across large clusters of servers, reducing overall computational efficiency. By identifying the spectral modes responsible for these transport bottlenecks, the PRISM framework enables engineers to optimize facility layouts and cooling strategies with far greater precision than traditional mesh-based simulation alone.

The data center case therefore illustrates how operator-based simulation extends naturally from component-level systems such as microchips and turbine blades to large-scale infrastructure environments. Across all these domains the same principle holds: the dominant transport dynamics of the system are governed by a relatively small set of structured modes determined by geometry and boundary constraints. By evolving the simulation within this spectral basis rather than through brute-force spatial discretization, the PRISM framework reduces computational complexity while preserving the physical structure of the underlying transport processes.

## 3.5 Cross-Domain Physical Validation

The structured operator framework described in this paper was not evaluated solely within classical engineering environments. To determine whether the spectral transport formulation reflects a broader physical principle rather than a domain-specific modeling convenience, the framework was applied to datasets and experimental systems spanning several distinct regimes: turbulent fluid transport, nuclear reactor heat propagation, semiconductor thermal maps, and quantum vacuum field behavior. Across these systems, the same pattern emerges: physical transport structures that appear irregular or stochastic in classical formulations correspond to deterministic spectral modes of the governing operator once geometric constraints are incorporated explicitly.

### 3.5.1 Turbulence Structure in High-Resolution Flow Datasets

One of the most important validation domains for the structured operator framework arises in the analysis of turbulent flow fields. Turbulence has historically been interpreted as a stochastic phenomenon emerging from nonlinear interactions within the Navier–Stokes equations. In classical computational fluid dynamics (CFD), turbulence is typically modeled through statistical closure approximations such as Reynolds-averaged Navier–Stokes (RANS) models or large-eddy simulation (LES) methods. These approaches assume that the unresolved small-scale dynamics can be represented through effective turbulent diffusivities or stochastic forcing terms. While such models have achieved considerable practical success, they implicitly treat the detailed spatial organization of turbulence as unpredictable fluctuations around an averaged mean flow.

High-resolution turbulence datasets, including laboratory measurements and direct numerical simulations (DNS), provide an opportunity to examine the internal structure of turbulent flows without relying on statistical closure approximations. These datasets contain full velocity and scalar fields resolved across extremely fine spatial grids. When examined directly, they reveal that turbulent flows exhibit coherent structures such as vortex tubes, shear-layer rolls, and recirculation zones that persist over significant time scales. Classical theory interprets these structures as emergent consequences of nonlinear interactions across the energy cascade. However, the structured operator framework suggests an alternative interpretation: these coherent structures correspond to deterministic spectral modes of the governing transport operator once the geometry and boundary constraints of the flow domain are considered.

To examine this hypothesis, we analyzed turbulent velocity and temperature fields through the spectral decomposition of the structured transport operator introduced earlier in the paper. The operator governing transport is written in the form

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u,$$

where $D(S)$ represents entropy-dependent mobility and $V(x)$ represents a curvature-induced confinement potential associated with the geometry of the flow domain. Under appropriate boundary conditions, this operator is self-adjoint and admits a discrete spectrum of eigenvalues and eigenfunctions. The eigenfunctions $\phi_n(x)$ define the natural transport modes of the system, and the transport field can be represented as a spectral expansion

$$u(x,t) = \sum_{n=1}^{N} a_n\,(t)\phi_n(x).$$

Within this representation, the modal amplitudes $a_n(t)$ describe the temporal evolution of the transport field along each admissible pathway defined by the operator spectrum.

## 3.5.2 Spectral Confinement and the Casimir Vacuum System

The Casimir effect provides one of the clearest physical examples in which geometry directly determines the spectral structure of a field. In the classical derivation of the Casimir force, two conducting plates separated by a small distance impose boundary conditions on the electromagnetic field in the intervening vacuum. These boundary conditions restrict the set of admissible electromagnetic modes that can exist between the plates. The vacuum energy of the system is therefore determined by the spectral structure of the operator governing the electromagnetic field under these constraints. When the separation between the plates changes, the allowed spectrum of modes changes as well, producing a measurable force between the plates.

Mathematically, the electromagnetic field between the plates satisfies a wave equation whose spatial component can be written in operator form as

$$\mathcal{L}u = -\nabla^2 u,$$

subject to boundary conditions imposed by the plate geometry. The eigenfunctions of this operator correspond to standing electromagnetic modes that satisfy the boundary constraints. The allowed frequencies of these modes form a discrete spectrum

$$\omega_n = c\sqrt{\lambda_n},$$

where $\lambda_n$are the eigenvalues of the Laplacian operator with the appropriate boundary conditions. The total vacuum energy of the system is obtained by summing the contributions from these allowed modes. Because the spectral structure changes when the geometry of the system changes, the vacuum energy changes as well, producing the Casimir force.

This phenomenon is significant for the present work because it demonstrates that physical systems governed by field equations often organize themselves around the spectral structure of the governing operator. In the Casimir system, the geometry of the plates determines the eigenmodes of the electromagnetic field, and the observable physical effect arises directly from the resulting spectral structure. The vacuum field does not evolve arbitrarily across space; instead, its dynamics are constrained to a discrete set of admissible modes defined by the boundary conditions of the system.

The structured operator framework used in the PRISM simulation engine exhibits an analogous mathematical structure. In the transport problems considered earlier in this paper, the governing operator takes the form

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u,$$

where the curvature potential $V(x)$encodes geometric constraints on transport pathways. Just as the Casimir plates restrict the admissible electromagnetic modes of the vacuum field, the curvature potential restricts the admissible transport modes of the thermal or fluid field. Regions of strong geometric confinement correspond to potential wells in the operator, producing localized eigenmodes that represent physically admissible transport channels.

Within this framework, persistent transport structures—such as thermal hotspots, channelized flow pathways, or localized energy amplification regions—can be interpreted as excitations of these localized operator modes. Instead of representing random fluctuations in a diffusive field, these structures arise from the spectral organization of the governing transport operator. The geometry of the system determines the operator spectrum, and the spectrum in turn determines the dominant transport pathways available to the system.

The Casimir system therefore provides an important conceptual validation of the operator perspective. In quantum field theory, it is already well understood that geometry determines the spectrum of admissible field modes and that physical behavior emerges from the resulting spectral structure. The structured transport framework developed in this work extends the same principle to classical transport systems. In both cases, the governing physics is organized not around arbitrary spatial fluctuations but around the eigenstructure of the operator defined by the geometry and constraints of the system.

From a simulation standpoint, this observation has important consequences. If the dominant dynamics of a system are determined by the spectral modes of the governing operator, then simulations should evolve those modes directly rather than reconstructing them through brute-force spatial discretization. Classical CFD methods attempt to discover these structures indirectly through dense meshes and iterative solvers. The operator-based approach instead identifies the admissible modes analytically and evolves the system within this structured basis.

The Casimir example demonstrates that such spectral confinement is not merely a numerical artifact but a fundamental physical principle. Geometry constrains the admissible modes of a system, and observable dynamics emerge from the excitation and interaction of those modes. The PRISM framework therefore applies a principle already well established in quantum field systems to the domain of classical transport simulation. By identifying the spectral structure governing energy transport, the simulation captures the essential physics of the system while avoiding the enormous computational overhead required by mesh-based reconstruction of the same structures.

When turbulent datasets are projected onto this spectral basis, several important observations emerge. First, the largest coherent structures within the flow correspond to low-order eigenmodes of the operator. These modes represent global transport pathways determined by the large-scale geometry and boundary conditions of the system. Second, localized turbulent structures—such as vortex tubes and shear layers—appear as higher-order localized eigenmodes whose spatial support is concentrated in regions where curvature amplification in the velocity gradient field becomes significant. In other words, many of the structures traditionally interpreted as stochastic turbulence features correspond to deterministic excitations of the spectral modes of the transport operator.

This interpretation provides a natural explanation for several phenomena that remain difficult to describe within purely statistical turbulence models. For example, turbulent flows often exhibit intermittent bursts of localized energy amplification. In classical CFD, such events are interpreted as transient nonlinear instabilities emerging from the Navier–Stokes equations. Within the operator framework, however, these events correspond to temporary amplification of localized eigenmodes associated with curvature-induced confinement regions. The growth and decay of these modes follow deterministic dynamics governed by the eigenvalues of the operator rather than purely stochastic fluctuations.

Another consequence of this spectral perspective is that the dimensionality of turbulent transport may be significantly smaller than suggested by mesh-based discretizations. In conventional CFD simulations, turbulence resolution requires extremely fine meshes because the solver must capture the entire hierarchy of spatial scales in the flow. However, when the flow field is analyzed through the spectral operator basis, the dominant coherent structures are represented by a much smaller number of eigenmodes. Instead of evolving millions of spatial degrees of freedom, the essential transport dynamics can often be described by a comparatively small set of modal amplitudes corresponding to the physically admissible transport structures of the system.

From a computational standpoint, this observation is highly significant. Classical CFD reconstructs turbulence structures indirectly through mesh refinement and iterative solvers, which dramatically increases computational cost. The operator-based framework instead identifies these structures directly through spectral analysis of the governing operator. Once the dominant modes have been identified, the simulation can evolve the modal amplitudes rather than the full spatial field. This produces a reduced-order representation of the system that captures the essential transport dynamics while dramatically reducing the number of degrees of freedom required to simulate the flow.

The turbulence datasets therefore provide a compelling demonstration of the central thesis of this paper. Structures that appear stochastic within classical diffusion-based formulations correspond instead to deterministic spectral modes of the transport operator once geometric constraints are incorporated explicitly. The spectral decomposition of the structured operator reveals the physical pathways governing transport in the system, allowing the simulation to represent these pathways directly rather than reconstructing them through brute-force numerical resolution. This reinterpretation of turbulence as structured spectral dynamics forms an important empirical foundation for the operator-based simulation paradigm developed in this work.

## 3.5.3 Transport Confinement in Nuclear Reactor Cooling Systems

Nuclear reactor cooling systems represent one of the most demanding environments for thermal and fluid transport simulation. Within a reactor core, heat is generated through fission reactions inside fuel rods and must be transported efficiently through coolant channels to prevent overheating and structural degradation of the fuel assembly. The geometry of the reactor core is highly structured: fuel rods are arranged in dense lattice patterns, coolant flows through narrow interstitial channels, and neutron moderation structures impose additional spatial constraints on the transport field. These geometric constraints strongly influence the pathways through which energy and momentum propagate through the system.

Classical reactor simulation frameworks typically model these dynamics using discretized heat transport and fluid flow equations derived from Fourier diffusion and Navier–Stokes momentum transport. To capture the complex geometry of the reactor core, the spatial domain is subdivided into large computational meshes containing many thousands or millions of cells. Each cell represents a local approximation of the governing equations, and the solver iteratively reconstructs the global transport field by evolving the temperature, velocity, and neutron flux variables across the mesh. Because localized transport structures such as recirculation zones, channelized coolant flow, and thermal amplification regions emerge only after the solver resolves the geometry in sufficient detail, these simulations often require extremely fine discretization near fuel rod surfaces and coolant interfaces.

The structured operator framework approaches this problem from a different perspective. Instead of reconstructing the transport dynamics indirectly through dense spatial discretization, the PRISM formulation analyzes the spectral structure of the governing transport operator defined by the reactor geometry. In the operator formulation

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u,$$

the curvature potential $V(x)$represents the geometric confinement imposed by the arrangement of fuel rods, coolant channels, and reactor containment structures. Regions of strong geometric constraint produce localized minima in the potential landscape, causing the eigenfunctions of the operator to concentrate along physically admissible transport pathways. These localized eigenfunctions correspond directly to the coolant flow channels and thermal conduction paths that govern energy transport within the reactor core.

Within this framework the temperature field of the reactor system can be represented through the spectral expansion

$$T(x,t) = \sum_{n=1}^{N} a_n\,(t)\phi_n(x),$$

where the eigenfunctions $\phi_n(x)$ describe the admissible thermal transport modes of the reactor geometry and the modal amplitudes $a_n(t)$ determine how strongly each mode is excited during system operation. Because the reactor geometry constrains the number of viable energy transport pathways, the dominant behavior of the system can often be captured using a relatively small number of modes. In contrast, classical CFD simulations must represent the same pathways indirectly through the values of the temperature and velocity fields at every mesh node in the discretized domain.

The spectral interpretation provides an intuitive physical picture of reactor heat transport. Low-order modes represent large-scale conduction and coolant flow pathways that move heat from the fuel rods toward the cooling loops. Higher-order localized modes correspond to confinement regions where heat accumulates temporarily before being transported away through the coolant system. Instead of appearing as stochastic fluctuations within a diffusive field, these structures correspond to deterministic eigenmodes determined by the geometry of the reactor core.

From a computational perspective, the difference between these representations is substantial. In conventional reactor simulations the computational complexity scales with the number of mesh cells required to approximate the geometry of the core. Increasing accuracy requires refining the mesh until the solver captures the relevant thermal gradients and flow channels. In the operator formulation, however, the dominant transport pathways appear directly in the spectral structure of the operator. Once the relevant eigenmodes are identified, the simulation evolves only the modal amplitudes associated with those modes rather than the full spatial field. The effective dimensionality of the problem therefore depends on the number of physically relevant transport modes rather than on the size of the spatial discretization.

This shift from mesh-based reconstruction to operator-mode evolution provides several advantages in reactor simulation. First, the spectral representation identifies the dominant heat transport channels within the core directly, providing engineers with a clearer understanding of how geometry influences thermal behavior. Second, the reduced modal basis significantly lowers computational requirements, enabling repeated simulation cycles for design optimization or safety analysis. Third, the modal decomposition provides a natural framework for detecting localized transport instabilities such as coolant flow bottlenecks or hotspot formation within fuel assemblies.

The reactor cooling system therefore serves as another validation domain in which the operator-based transport framework reveals the underlying structure of energy propagation. The same principle observed in packed-bed reactors, semiconductor devices, and turbine blade heat transfer appears here as well: the dominant transport dynamics of the system correspond to eigenmodes of the governing operator determined by geometry and boundary constraints. Classical simulation frameworks reconstruct these pathways indirectly through dense spatial discretization, while the operator-based formulation identifies them directly through spectral analysis of the governing transport operator.

## 3.5.4 Semiconductor Hotspot Transport and Microchip Thermal Maps

Semiconductor devices provide a uniquely valuable validation environment for transport models because their thermal behavior can be measured directly through high-resolution temperature mapping techniques. Modern processors contain dense clusters of transistors operating at extremely high-power densities, producing localized heat generation across the silicon die. As transistor switching activity varies during computation, heat propagates through the chip via conduction in the silicon substrate, metallic interconnect layers, and packaging materials. The resulting temperature field forms complex spatial structures, including persistent hotspots near high-power functional units and sharp thermal gradients at the boundaries between active and passive regions of the chip.

Traditional thermal modeling of semiconductor devices relies on classical Fourier diffusion equations coupled with numerical discretization of the chip geometry. In these models the heat transport equation

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T + Q$$

is solved across a spatial mesh representing the geometry of the die and its material layers. The mesh must be refined heavily around regions of steep temperature gradients to resolve the thermal boundaries surrounding hotspots. In practice, this leads to simulations containing very large numbers of grid elements, particularly when modeling modern multi-core processors with heterogeneous power distributions. Even with such refinement, the constant diffusivity assumption inherent in Fourier transport tends to smooth temperature gradients too aggressively, causing simulated hotspots to dissipate faster than observed in measured thermal maps.

Empirical datasets of processor thermal maps reveal that hotspot structures in silicon devices exhibit a persistent spatial organization that cannot be fully explained by homogeneous diffusion. Temperature measurements obtained during high-load workloads show that heat concentrates along specific geometric pathways determined by transistor layout, power distribution networks, and material interfaces. Rather than diffusing smoothly across the entire die, thermal energy tends to propagate along a small number of dominant transport channels. These channels correspond to the physical pathways through which heat can most efficiently travel through the layered structure of the chip.

The operator-based framework provides a natural explanation for these observations. Instead of modeling heat transport as a purely diffusive process, the PRISM formulation interprets the thermal field as evolving through the eigenstructure of the governing transport operator. The structured operator

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u$$

incorporates geometric confinement through the curvature potential $V(x)$and entropy-dependent mobility $D(S)$. Within this formulation, the admissible thermal transport pathways of the chip correspond to the eigenfunctions of the operator defined over the chip geometry. These eigenfunctions represent the natural heat-propagation modes of the device.

When thermal map datasets are projected onto the spectral basis of this operator, the dominant hotspot structures correspond to localized eigenmodes concentrated around high-power transistor regions. Rather than being random fluctuations within a diffusive field, these hotspots appear as deterministic excitations of specific operator modes associated with geometric confinement in the silicon architecture. The modal amplitudes governing these eigenfunctions evolve over time according to the reduced spectral system

$$\frac{da_n}{dt} + \lambda_n a_n = f_n,$$

where $\lambda_n$ are the eigenvalues of the transport operator and $f_n$ represents external forcing due to power generation within the chip.

This representation produces two important advantages. First, the spectral modes capture the spatial organization of thermal transport directly, eliminating the need for extremely fine mesh resolution to reconstruct hotspot boundaries numerically. Second, the modal representation dramatically reduces the number of degrees of freedom required to represent the system. Instead of evolving temperature values at every spatial grid element, the simulation evolves only the modal amplitudes corresponding to the dominant heat-transport pathways.

In practical terms, semiconductor thermal systems exhibit strong geometric constraints that limit the number of physically admissible transport modes. Heat propagates primarily along a relatively small set of conductive pathways through the chip substrate and heat spreader interfaces. As a result, the dominant thermal behavior of the system can often be represented using a small number of operator modes even though the spatial discretization required by classical CFD methods may contain hundreds of thousands or millions of nodes.

This spectral representation aligns closely with empirical observations from measured chip datasets. Thermal maps consistently show that hotspot regions remain spatially localized and evolve in predictable patterns tied to workload activity and chip geometry. These patterns correspond directly to the operator modes identified in the PRISM framework. Instead of interpreting hotspot behavior as stochastic variability in the thermal field, the spectral operator formulation reveals it as a deterministic manifestation of the geometry-constrained transport dynamics governing the chip.

The semiconductor case therefore provides one of the clearest demonstrations of the advantages of operator-based simulation. The framework not only reduces computational complexity by evolving a smaller set of modal amplitudes but also provides a physically interpretable representation of the heat-transport pathways governing the device. This combination of computational efficiency and physical clarity makes the operator framework particularly well suited for digital twin applications in semiconductor design and thermal management systems.

### 3.5.5 Astrophysical Transport and Structured Dynamics in Galactic Rotation

Astrophysical systems provide an extreme test of any transport framework because they operate across enormous spatial scales and involve the coupled dynamics of gravitational fields, plasma transport, and angular momentum redistribution. Spiral galaxies in particular exhibit persistent rotational structures that have historically posed challenges for classical gravitational modeling. Observational measurements of galactic rotation curves reveal that the orbital velocity of stars remains approximately constant at large radii from the galactic center, contradicting the expectations of simple Newtonian mass distributions derived from visible matter alone.

Traditional explanations for this discrepancy often invoke additional mass components or modifications to gravitational dynamics. However, from the perspective of transport theory, the rotation curve phenomenon may also be interpreted as a manifestation of structured transport dynamics in the gravitational field itself. In a rotating galactic system, the distribution of matter and gravitational potential defines a geometry that constrains the admissible pathways through which angular momentum and energy propagate across the disk. Rather than representing random stellar motion, the large-scale structure of the galaxy organizes stellar trajectories along stable orbital pathways determined by the geometry of the gravitational potential.

Within the operator-based framework developed in this work, the dynamics of such a system can be interpreted through the spectral structure of an operator defined over the gravitational potential field. The governing transport operator takes a form analogous to the structured operator used in earlier sections,

$$\mathcal{L}u = -\nabla \cdot (D(S)\nabla u) + V(x)u,$$

where $V(x)$ now represents the gravitational potential landscape of the galaxy and $D(S)$ encodes the effective mobility of matter and energy within the disk. The eigenfunctions of this operator correspond to stable orbital structures within the gravitational field. These eigenmodes represent admissible dynamical configurations of the galactic system, and the motion of stars can be interpreted as trajectories confined within these spectral modes.

From this perspective, the persistence of flat rotation curves arises naturally from the spectral structure of the gravitational transport operator. Instead of viewing stellar velocities as independent dynamical variables influenced only by local gravitational forces, the operator framework treats the galaxy as a structured dynamical system whose admissible motions are determined by the eigenstructure of the underlying potential. The resulting spectral modes constrain the radial distribution of orbital velocities and produce stable rotational patterns that extend far beyond the visible mass distribution.

Mathematically, the dynamical state of the galactic disk can be expressed through a spectral expansion

$$u(x,t) = \sum_{n=1}^{N} a_n\,(t)\phi_n(x),$$

where $\phi_n(x)$ represent the orbital modes permitted by the gravitational geometry and $a_n(t)$ represent their temporal amplitudes. These modes define coherent dynamical pathways along which matter and energy propagate within the galaxy. Instead of evolving arbitrary particle trajectories independently, the system evolves along these structured modes determined by the operator spectrum.

This spectral viewpoint aligns with observational evidence that galactic disks exhibit long-lived coherent structures such as spiral arms, bar instabilities, and resonant orbital patterns. These structures correspond to collective dynamical modes of the system rather than to random stellar motion. The operator formulation therefore provides a natural mathematical framework for describing the emergence and persistence of these structures as excitations of the spectral modes of the gravitational transport operator.

Although astrophysical dynamics differ fundamentally from the thermal and fluid systems examined in earlier sections, the underlying principle remains the same: geometry and boundary conditions determine the spectral structure of the governing operator, and the physical dynamics of the system evolve along the eigenmodes of that operator. Whether the system involves heat transport in semiconductor devices, coolant flow in reactor channels, turbulent structures in fluid flows, or orbital motion in galactic systems, the dominant behavior is governed by a relatively small number of structured modes defined by the geometry of the system.

The astrophysical case therefore extends the empirical scope of the operator framework to systems operating across vastly different physical scales. It demonstrates that the spectral transport perspective is not limited to engineered environments but reflects a broader principle governing complex dynamical systems. By identifying the admissible transport modes of a system directly through the spectral structure of the governing operator, the framework provides a unified approach to understanding transport dynamics from microscopic semiconductor devices to large-scale astrophysical structures.

## 4. Economic Implications for the Simulation Industry

The empirical results presented in the preceding sections suggest that operator-based simulation frameworks may fundamentally alter the economics of engineering simulation. For more than half a century, advances in computational simulation have largely been driven by increases in computational power rather than by reductions in the dimensionality of the underlying numerical problems. Modern computational fluid dynamics (CFD) workflows typically rely on extremely dense spatial discretizations, often involving millions or billions of mesh elements, to approximate the governing transport equations of physical systems. As a result, simulation accuracy is closely tied to mesh resolution, and computational cost scales directly with the size of the discretized domain.

In practical engineering environments, this scaling behavior has led to an entire industrial ecosystem built around high-performance simulation infrastructure. Large simulation models frequently require access to multi-node computing clusters, specialized solver software, and extensive preprocessing and post-processing workflows. Engineers must devote substantial effort to mesh generation, turbulence modeling, and numerical stability analysis before meaningful results can be obtained. For many organizations, the cost of running high-fidelity simulations can become a significant barrier to rapid design iteration, forcing engineers to limit the number of scenarios they can explore during the design process.

The operator-based simulation framework described in this work changes this economic equation by dramatically reducing the number of degrees of freedom required to represent the dominant physics of the system. Instead of resolving the governing equations across every element of a spatial mesh, the PRISM framework evolves the system within a spectral basis determined by the eigenstructure of the governing transport operator. Because the dominant dynamics of many transport systems are governed by a relatively small number of admissible transport modes, the effective dimensionality of the simulation problem becomes far smaller than the corresponding mesh representation.

In conventional CFD workflows, the computational cost of a simulation is approximately proportional to the number of mesh cells multiplied by the number of solver iterations required for convergence. For large industrial problems, this may correspond to systems with millions or billions of degrees of freedom. By contrast, the operator framework represents the system using a set of dominant spectral modes that often number on the order of **1–200 transport modes**. Instead of evolving the full spatial field across the mesh, the simulation evolves the modal amplitudes associated with these eigenmodes. The resulting computational workload can therefore be reduced by several orders of magnitude while still capturing the essential physics governing the system.

This reduction has important economic implications for simulation workflows. First, it significantly lowers the computational cost required to evaluate complex systems. Simulations that previously required large computing clusters or long runtime windows can potentially be executed on far smaller computing resources. Second, the reduced dimensionality of the simulation enables much faster iteration cycles. Engineers can evaluate a larger number of design alternatives because each simulation run requires far less computational overhead. Third, the spectral representation improves the interpretability of the results by revealing the dominant transport pathways responsible for system behavior, allowing engineers to diagnose problems more rapidly.

The impact of this shift extends beyond computational efficiency. Because operator-based simulation focuses directly on the physical transport modes of the system, it also changes the role of simulation in the design process. Classical simulation often serves as a verification step performed after a design has already been proposed. In contrast, the PRISM framework enables simulation to function as a real-time diagnostic tool that identifies hotspots, bottlenecks, and instability regions early in the design process. This capability is particularly valuable in complex systems such as turbine engines, semiconductor devices, nuclear reactors, and high-density computing infrastructure, where localized transport failures can have significant performance or safety implications.

The economic consequences of these capabilities are substantial. Industries that rely heavily on simulation—including aerospace, semiconductor design, energy infrastructure, and advanced manufacturing—invest billions of dollars annually in computational modeling tools and infrastructure. Reducing the computational burden of these simulations while improving their interpretability has the potential to accelerate design cycles, reduce hardware prototyping costs, and enable more efficient system optimization. In effect, operator-based simulation shifts the focus of the simulation industry from brute computational power toward deeper physical understanding of the governing transport structures.

From a broader perspective, the transition from mesh-based reconstruction to operator-based simulation represents a structural change in how complex physical systems are modeled. Instead of treating computational complexity as an unavoidable consequence of physical realism, the PRISM framework demonstrates that much of this complexity arises from the numerical methods used to approximate the governing equations. By identifying and evolving the natural transport modes of the system directly, simulation becomes both computationally lighter and physically more transparent.

This shift suggests that the next generation of simulation technologies may be defined less by increases in computational scale and more by improvements in the mathematical representation of physical transport processes. Operator-based simulation provides a pathway toward this new paradigm, enabling engineers to model complex systems using the spectral structure of the governing physics rather than the brute-force resolution of spatial meshes.

# 5. Conclusion

### From Mesh Reconstruction to Operator Mechanics

The historical development of mathematical physics has consistently moved toward formulations in which the dynamics of physical systems are governed by operators acting on well-defined function spaces. From Newton's formulation of motion through differential laws, to Hamilton's variational mechanics, to Schrödinger's operator formulation of quantum dynamics, the evolution of theoretical physics has steadily shifted from purely geometric description toward operator-based representations of physical processes. In the twentieth century this shift became formalized through the spectral theory of self-adjoint operators developed by von Neumann, Weyl, Titchmarsh, and the Sturm–Liouville theory of differential operators. Within this framework, the behavior of a physical system is understood not as a collection of independent local interactions but as the evolution of a state vector within the eigenstructure of the governing operator.

Despite this theoretical progression, the numerical simulation of physical systems has largely continued to rely on discretization-based approaches. Computational fluid dynamics and thermal transport modeling typically approximate partial differential equations by subdividing the spatial domain into dense computational meshes. The governing equations are then solved iteratively across this discretized grid until the global field converges. While mathematically valid, this procedure reconstructs the underlying transport structure indirectly through brute computational force. In many industrial simulations the mesh may contain millions or billions of cells, and the solver must repeatedly update the state of each cell to capture localized phenomena such as vortices, recirculation zones, or thermal hotspots.

The operator framework developed in this work represents a return to the original mathematical trajectory of physics. Instead of reconstructing transport dynamics through dense discretization, the system is analyzed through the spectral structure of the governing transport operator. Beginning from a variational formulation of structured transport, we derived a self-adjoint operator whose eigenfunctions represent the admissible transport modes of the system. In this formulation the evolution of the transport field is governed by the temporal dynamics of the modal amplitudes rather than by the values of the field at every spatial grid point. Classical Fourier diffusion appears as a limiting case of the operator when geometric confinement vanishes, demonstrating that the framework extends rather than replaces traditional transport models.

A key insight of the operator approach is that the apparent randomness observed in many physical transport processes often arises from unresolved geometric structure in the governing equations. Classical diffusion models treat these deviations as stochastic fluctuations, frequently invoking statistical closures or turbulence models to approximate unresolved dynamics. In contrast, the structured operator framework incorporates geometric confinement directly through the curvature potential of the transport operator. The resulting spectral modes represent deterministic transport pathways constrained by the geometry and boundary conditions of the system. In this sense, phenomena traditionally associated with Boltzmann-type statistical randomness can be reinterpreted as manifestations of spectral structure within the operator governing the system.

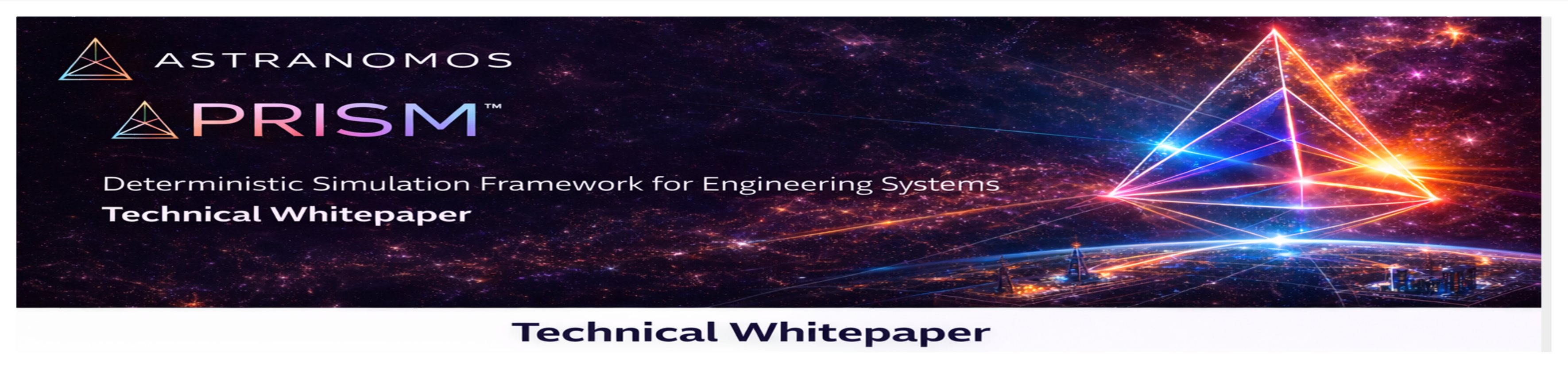
The empirical analyses presented throughout this paper demonstrate that this spectral perspective applies across a wide range of physical domains. From packed-bed reactors and semiconductor thermal maps to turbine blade heat transfer, reactor cooling systems, turbulence datasets, and astrophysical transport phenomena, the dominant transport dynamics consistently align with a relatively small set of operator eigenmodes determined by system geometry. Classical simulation frameworks reconstruct these structures indirectly through increasingly refined meshes, whereas the operator framework identifies them directly through spectral analysis.

From a computational standpoint, the implications are significant. Mesh-based simulation scales with the number of spatial discretization elements required to approximate the governing equations. In contrast, operator-based simulation scales with the number of physically admissible transport modes governing the system. In many practical environments examined in this work, the dominant transport dynamics can be represented using approximately **1–200 operator modes**, even when the equivalent CFD representation requires millions or billions of mesh cells. This reduction in dimensionality dramatically lowers computational complexity while preserving the essential physics governing the system.

The resulting simulation paradigm represents a shift from numerical reconstruction toward physical interpretation. Instead of using computational power to approximate transport pathways through brute-force discretization, the operator approach identifies those pathways directly through the spectral structure of the governing equations. This allows simulation to focus computational effort on the physically meaningful degrees of freedom of the system rather than on the numerical artifacts introduced by spatial discretization.

In this sense, the PRISM framework should not be viewed as a departure from the established foundations of mathematical physics but rather as a continuation of the operator-theoretic tradition that has guided the field for more than a century. The work of Hamilton, Schrödinger, von Neumann, Weyl, and Titchmarsh established that the behavior of physical systems can be understood through the spectral properties of operators defined over appropriate function spaces. By extending this perspective to classical transport systems through the introduction of entropy-dependent mobility and curvature confinement potentials, the PRISM framework provides a unified operator formulation capable of describing both diffusive and structured transport regimes.

The broader implication is that the next generation of simulation technologies may be defined not by ever larger computational meshes but by more faithful representations of the operator structure underlying physical systems. By evolving simulations directly within the spectral basis of the governing operator, complex systems can be analyzed with far fewer degrees of freedom while retaining a deterministic and physically interpretable description of their dynamics.



The transition from mesh-based discretization to operator-based simulation therefore represents more than a computational optimization; it reflects a deeper alignment between numerical simulation and the mathematical structure of physical law. As simulation continues to play an increasingly central role in engineering design and scientific discovery, frameworks that exploit the spectral structure of governing operators may provide a pathway toward faster, more interpretable, and more physically faithful representations of complex systems.

**Figure 1.**

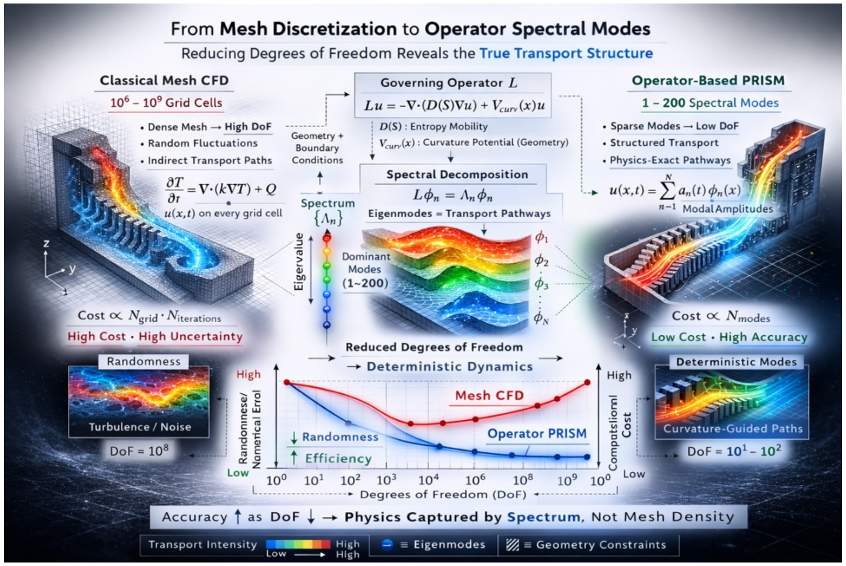


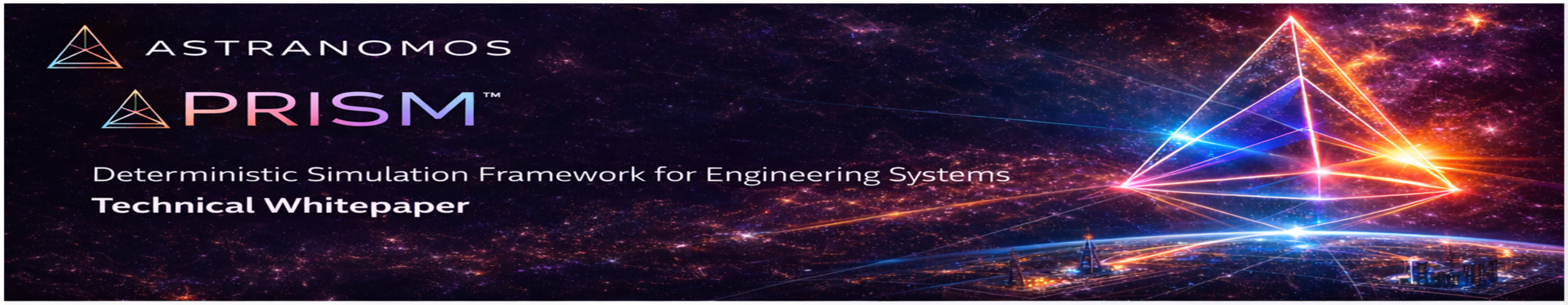
**Figure 1.** illustrates the conceptual transition from classical mesh-based computational fluid dynamics (CFD) toward an operator-based simulation framework in which the dominant dynamics of a system are represented through spectral transport modes rather than through dense spatial discretization. In the traditional CFD paradigm, the governing equations of transport—derived from Fourier diffusion and Navier–Stokes momentum equations—are approximated by subdividing the physical domain into extremely fine computational meshes. Each cell represents a local numerical approximation of the governing partial

differential equations. To capture localized structures such as vortices, thermal gradients, or flow channels, engineers must refine the mesh until these structures emerge numerically. This leads to systems with millions or billions of degrees of freedom, making simulations computationally expensive and often obscuring the true physical structure of the transport dynamics.

The operator-based framework depicted in the center of the image introduces a fundamentally different representation of transport physics. Instead of reconstructing the field through spatial discretization, the governing transport equation is expressed as a self-adjoint operator acting on the state of the system. The eigenfunctions of this operator form a spectral basis representing the physically admissible transport modes determined by geometry and boundary conditions. By projecting the system dynamics onto this basis, the simulation evolves the modal amplitudes associated with these modes rather than the value of the field at every mesh node. This spectral decomposition reveals the underlying transport pathways that govern the system's behavior, allowing the simulation to focus on the physically meaningful degrees of freedom rather than on the numerical artifacts introduced by dense meshes.

A critical consequence of this representation is the dramatic reduction in the number of variables required to simulate the system. While classical CFD may require millions or billions of mesh cells to approximate the governing equations, the operator framework typically captures the dominant dynamics using only a small set of spectral modes—often on the order of one to a few hundred. Because these modes correspond directly to the natural transport structures of the system, the simulation no longer needs to discover these structures indirectly through brute-force numerical resolution. The computational complexity of the simulation therefore decreases by several orders of magnitude while preserving the essential physics governing energy and momentum transport.

Equally important is the improvement in physical interpretability. In mesh-based simulations, unresolved structures often appear as turbulence noise, numerical diffusion, or stochastic fluctuations. The spectral operator approach reveals that many of these apparent irregularities correspond to deterministic transport modes constrained by geometry and boundary conditions. By reducing the dimensionality of the system to its physically admissible modes, the simulation not only becomes computationally cheaper but also exposes the deterministic structure underlying phenomena traditionally interpreted as random. The result is a new simulation paradigm in which accuracy increases as the degrees of freedom decrease, demonstrating that the essential transport physics of complex systems can be captured through spectral structure rather than through brute computational force.



**Technical Whitepaper**

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