How Fast Can Reality Change?

Time Field Theory as a Theory of Bounded State-Transition Rates

The Smart Fox

December 24, 2025

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Abstract

How quickly can physical reality change?

This question is often posed in explicitly time-based terms time dilation, minimum time steps, or the existence of fundamental "clocks." Here we argue that this framing is not required and can even be misleading. In the context of Time Field Theory (TFT), we show that the scalar field τ need not be interpreted as altering time itself. Instead, τ functions as a local bound on the maximum rate at which physical states are allowed to evolve.

Using numerical sweeps in compactness at fixed total mass, we find that localized τ-structures admit a single static strength measure that scales predictably with compactness. When τ becomes sufficiently localized, it forms effective rate-limiting cavities that support discrete dynamical modes. After removing trivial geometric effects, the characteristic rates of these τ-modes depend only on the local τ-strength and scale with its square root. This predictive pattern appears only in the localized regime: when τ varies smoothly, no discrete τ-modes arise, and τ acts only as a weak background constraint.

Taken together, these results sharpen the interpretation of TFT: τ does not "slow time"; it constrains how rapidly change may occur. Apparent time-dilation-like behavior emerges only as a secondary consequence of rate-limited dynamics. This viewpoint preserves TFT's formal structure while reducing conceptual ambiguity in time-based language and broadening the theory's experimental relevance. Rather than focusing on clocks, TFT naturally highlights rate-sensitive observables relaxation, decoherence, resonance, and entropy production as probes of fundamental limits on dynamical change.

Okilmes: the gravity of understanding.

Contents

1 Introduction **5**
1.1 Prior TFT Work (Summary) and Relation to the Present Paper 6

2 What Does It Mean to Limit Change? **7**
2.1 Transition Rates as Physical Observables 7
2.2 Operational Definition of the τ-Field 8
2.3 Why This Is Not Time Dilation 8
2.4 Consequences of a Rate-Limiting Field 9

3 One Number: Static τ-Strength and Compactness **9**
3.1 Fixing "How Much" While Changing "How Dense" 9
3.2 A Single Measure of τ-Strength 10
3.3 Power-Law Scaling with Compactness 10
3.4 Why One Number Is Enough 11
3.5 Setting the Stage for Dynamics 11

4 Static Dynamic Scaling Test of τ-Mode Structure **11**
4.1 Static compactness sweep 12
4.2 Definition of the τ-cavity 12
4.3 Mode extraction 12
4.4 The one-number test 13
4.5 Summary of scaling outcome 13

5 When Change Pushes Back: τ-Modes as Rate Cavities **14**
5.1 From Static Bottlenecks to Dynamic Structure 14
5.2 What τ-Modes Are; and Are Not 14
5.3 Why Geometry Must Be Factored Out 15
5.4 The Square-Root Law as a Dynamical Signature 15
5.5 When τ-Modes Do Not Appear 15
5.6 Expected Form of the Scaling Law 16

6 Why Global Modes Fail; and Why That Matters **17**
6.1 Global Time Tests Probe the Wrong Quantity 17
6.2 Locality Is Not Optional 17
6.3 Why Null Results Strengthen the Interpretation 17
6.4 A Clear Experimental Filter 18
6.5 Reframing Past Confusion 18

7 τ and Entropy: Bounded Rates of Irreversibility **18**
7.1 Entropy Production as a Rate, Not a Quantity 18
7.2 τ as a Local Cap on Irreversibility 18
7.3 Why τ-Modes Are Thermodynamically Stable 19
7.4 Relation to Known Entropy Bounds 19

7.5 Experimental Consequences 19

8 Discussion: From Motion to Causal Throughput **19**
8.1 Planck Limits as Maximum Temporal Throughput 20
8.2 $\hbar$ as a Rate-Quantization Scale 20
8.3 Three Notions of "Speed" 21
8.4 Why c^2 Appears in Energy 21
8.5 Why τ Does Not Redefine Time 21
8.6 Conceptual Economy 21
8.7 Toward a General Principle 22
8.8 Why Clocks Could be the Wrong Probe 22

9 Observational Signatures of τ as a Rate-Limiting Field **22**
9.1 What τ affects and what it does not 22
9.2 Candidate laboratory systems 23
9.3 Observational and astrophysical implications 24
9.4 What would falsify the framework 24
9.5 Experimental strategy going forward 24

A Methods (Numerical Protocol): Static Sweep → Dynamic Ringdown → Scaling Fits **25**
A.1 Static compactness sweep (fixed mass; varying size) 25
A.2 Dynamic ringdown test (mode extraction) 25
A.3 Two τ-mode operator candidates 26
A.4 Supplementary Numerical Details: 32×32 Protocol and ϵ-Sweep Results 26
A.4.1 Results table: Gaussian and top-hat sweeps across ϵ 27

1 Introduction

By asking this simple question: how quickly can physical reality change? we open interesting mind space.

This question is often approached indirectly. In physics, limits on change are typically discussed using the language of time: time dilation, minimum time intervals, clock rates, or fundamental temporal scales. When anomalous behavior is observed, it is natural to say that "time slows down" or that time itself is being modified. Yet time, as a coordinate, is not directly observable. What experiments actually measure are changes: transitions between states, relaxation toward equilibrium, accumulation of phase, loss of coherence, or the propagation of signals.

This distinction is subtle but consequential. Two systems may share the same coordinate time while evolving at radically different speeds. A chemical reaction can stall, a resonator can ring down slowly, or a quantum system can retain coherence far longer than expectedwithout any clock behaving strangely. These phenomena suggest that what is constrained is not time itself, but the rate at which change is allowed to occur.

Time Field Theory (TFT) was originally introduced as a framework in which a scalar field $\tau(x)$ encodes departures from uniform temporal structure driven by mass–energy distribution and curvature. In early presentations, τ was naturally described using the language of time dilation, by analogy with gravitational redshift and other relativistic effects. While mathematically consistent, that interpretation creates a conceptual tension: if τ directly modifies time, why are its effects not universally visible across all time-based observables?

This paper addresses that tension by refining the physical meaning of τ. We show that τ need not be understood as altering time itself. Instead, τ acts as a local bound on the maximum rate at which physical states can evolve. In this view, time remains a continuous parameter, while dynamics are constrained by a finite, spatially varying transition bandwidth. Apparent time-dilation-like effects then appear only as secondary bookkeeping consequences of rate-limited dynamics. The distinction is not merely semantic. Interpreting τ as a rate-limiting field yields clear predictions about when τ-induced phenomena should appear and when they should not. In particular, τ-effects should become detectable only when systems attempt to evolve near their local transition limit. Processes operating well below that limit may show no measurable influence, even in regions where τ is large.

A central result of this work is that localized enhancements of τ form effective *rate cavities*regions in which evolution is bottlenecked relative to the surroundings. These cavities support discrete dynamical modes whose characteristic rates are not set by global geometry, but by the local strength of τ. Remarkably, the resulting spectrum is controlled by a single static measure of τ-strength and follows a simple scaling law once trivial geometric effects are removed.

Equally important are the regimes where this structure does *not* occur. When τ varies smoothly or remains only weakly localized, no discrete τ-modes arise and the dynamics are dominated by global boundary conditions. This conditional behavior is not a weakness of the theory; it is a diagnostic feature that clarifies what τ *is*: it constrains rates, not coordinates. By reframing τ as a bound on state-transition rates rather than a modification of time, TFT gains a cleaner physical interpretation, resolves ambiguities associated with clock-based language, and broadens its experimental relevance. The theory points naturally toward rate-sensitive observablesrelaxation times, decoherence, resonance, and entropy productionas the appropriate probes of fundamental limits on dynamical change.

The aim of this paper is to develop this interpretation systematically. We begin by defining τ operationally as a local transition-rate bound, then introduce a robust static measure of τ-strength. We show how localized τ-structures generate discrete dynamical modes, establish the scaling law governing their rates, and explain why the structure disappears outside the localized regime. The message is simple: time does not need to change for reality to have a speed limit; only the rate at which change is permitted to occur does.

Table 1: Operational definitions used in this work.

Symbol	Definition
C	Compactness parameter (explicit definition used in sweeps; e.g., $C \equiv \rho(0)$ or inverse radius at fixed mass).
u_{peak}	Peak τ-strength: $u_{\text{peak}} = \max_x \lvert\tau(x)\rvert$.
R_{eff}	Effective cavity radius extracted from the τ-localization region (e.g., area-equivalent or RMS radius).
ω	Characteristic mode rate extracted from ringdown FFT or eigenmode solve.

1.1 Prior TFT Work (Summary) and Relation to the Present Paper

The present paper builds on earlier TFT/TGT development recorded, in which the τ-field was already treated as a dynamical object rather than a static background. In particular introducing explicit time dependence into the τ-field (e.g., wave-like evolution equations of the schematic form

$$\partial_t^2 u - c_\tau^2 \nabla^2 u = S(\rho, t), \tag{1}$$

where u denotes a τ-related field variable and $S(\rho, t)$ represents a driven source coupled to density and its time variation), and propose using controlled density perturbations (including sinusoidal driving) to reveal resonant responses.

Numerical experiments reported in that development also identified persistent spatial τ-patterns that behave neither as simple source–sink diffusion nor as conventional “energy wells,” already hinting at an underlying mode structure. The contribution of the present work is to reinterpret these patterns as *rate-locking phenomena* arising from a bounded transition bandwidth, and to turn the earlier qualitative mode intuition into a compact scaling program that links static compactness sweeps to measurable dynamical spectra.

Scope and limitations. The results presented here are based on controlled numerical experiments in two spatial dimensions using simplified τ-dynamics and localized density profiles. The extracted scaling exponents should therefore be understood as properties of a specific model class rather than universal constants. No microscopic derivation of τ is assumed, nor is any claim made that τ-effects are present in all physical systems. The central claim is conditional: if localized τ-structures form, their dynamic rate spectrum is predictively constrained by static compactness. Extending the analysis to higher dimensions, alternative profiles, and more detailed dynamics is left for future work.

Conceptual Orientation. Throughout this paper, the τ-field is not interpreted as a modification of time itself, but as a local bound on the rate at which physical states may evolve. In this view, time remains continuous and unquantized; what is constrained is the permissible speed of state transitions. Oscillatory τ-modes therefore represent regions of rate-locking rather than oscillations of time. This reframing will be used consistently in both the numerical analysis and the interpretation of scaling laws.

2 What Does It Mean to Limit Change?

If τ does not modify time itself, then what does it act on?

To answer this, it helps to step away from clocks and focus on how physical change is actually observed. In practice, we never measure time in isolation. We measure *processes*: how quickly a system relaxes, how fast a reaction completes, how rapidly a signal decays, or how long coherence persists. All such measurements reduce to a question of *rates*; how much change occurs per unit coordinate time.

Consider a simple example.
A mechanical resonator may ring for seconds or milliseconds depending on its environment. A quantum system may decohere almost instantly or remain coherent for long durations. In neither case is it necessary to say that time itself has slowed or accelerated. What has changed is the system's *ability to transition between states.* This motivates a shift in perspective. Rather than asking whether time flows differently in different regions, we ask a more operational question:

> Is there a limit to how fast physical states are allowed to evolve?

This paper develops one specific interpretation of TFT: τ is treated operationally as a local bound on state-transition rates. This reframing is motivated by prior TFT development and numerical observations of localized τ-structures, but the present work focuses on turning that interpretation into a compact, falsifiable scaling program and an experimental outlook.

2.1 Transition Rates as Physical Observables

Let us formalize this intuition. Consider any physical process described by a dimensionless progress variable $s(t) \in [0, 1]$, such as reaction completion, phase accumulation normalized to a cycle, or relaxation toward equilibrium. The physically relevant quantity is not time itself, but the *rate of change*,

$$\frac{ds}{dt}. \tag{2}$$

Under controlled driving, there is often a maximum rate at which such a process can proceed. Increasing the driving strength eventually stops producing faster evolution. This kind of saturation is familiar across physics: resonances broaden, reactions stall, and quantum systems do not decohere arbitrarily faster even under stronger coupling.

We define the *local transition bandwidth* $B(x)$ as the supremum of achievable transition rates at location x,

$$B(x) = \sup \left| \frac{ds}{dt} \right|_x , \tag{3}$$

measured relative to a shared external time coordinate.

This bandwidth is a physical observable. It can be inferred from relaxation experiments, driven response, or saturation thresholds. Crucially, it does not require clocks to run differently; only that processes encounter intrinsic limits.

2.2 Operational Definition of the τ-Field

With this notion in place, the role of τ becomes clear. We define the τ-field operationally as the inverse of the local transition bandwidth, normalized to a reference region,

$$\tau(x) = \frac{B_{\text{ref}}}{B(x)}. \tag{4}$$

Under this definition:

- large τ corresponds to strongly limited transition rates,
- small τ corresponds to a high permissible rate of change.

The definition is local, coordinate-independent, and directly tied to measurable dynamics. Time remains continuous and universal; τ controls only *how fast* systems may evolve.

2.3 Why This Is Not Time Dilation

It is tempting to describe reduced transition rates as "time slowing," but that language can mislead. Time dilation implies that all processes; clocks included; slow uniformly. A rate-limiting interpretation makes no such claim. Processes operating far below their bandwidth limit will be essentially unaffected by τ. Only when a system attempts to evolve near its maximum allowed rate does τ become dynamically visible. This helps explain why τ-effects may appear strongly in some observables and be absent in others. Clocks are not privileged probes of τ; they are simply systems whose internal dynamics may or may not approach the local transition limit.

2.4 Consequences of a Rate-Limiting Field

Interpreting τ as a bound on state-transition rates has immediate, testable consequences:

1. **Selectivity:**
   τ-effects are conditional, appearing only in systems that probe the rate ceiling.

2. **Locality:**
   τ acts pointwise, constraining dynamics locally rather than redefining global time.

3. **Emergence of structure:**
   spatial variation in τ creates regions where evolution is bottlenecked, setting the stage for localized dynamical phenomena.

These consequences distinguish τ sharply from coordinate-based modifications of time and prepare the ground for the phenomena explored next. If τ limits how fast change can occur, the next natural question is:

> How strong is this limit, and how does it depend on physical configuration?

In the following section, we show that τ-strength admits a simple static characterization controlled by a single parameter, which ultimately governs the system's dynamical behavior.

3 One Number: Static τ-Strength and Compactness

If τ limits how fast physical change can occur, the next question is not dynamical but structural:

> What determines how strong that limit is?

At first glance, one might expect the answer to be complicated. A field generated by matter could depend on detailed geometry, higher moments of the distribution, boundary conditions, or fine spatial structure. If that were the case, τ would be difficult to characterize and even harder to test. What we find instead is unexpectedly simple.

3.1 Fixing "How Much" While Changing "How Dense"

To isolate the intrinsic behavior of τ, we consider families of configurations in which the *total amount of source material is held fixed*, while its spatial distribution is varied. Informally, we keep "how much stuff there is" constant and change only *how tightly it is packed.*

This procedure mirrors a familiar physical intuition: compressing the same mass into a smaller region produces stronger effects than spreading it out. Importantly, it avoids conflating total magnitude with structural concentration. Across such compactness sweeps, the τ-field responds in a remarkably regular way.

3.2 A Single Measure of τ-Strength

Despite the complexity of the underlying field, the effect of compactness can be captured by a single static quantity: the *peak τ-strength*,

$$u_{\text{peak}} \equiv \max_x |\tau(x)|. \tag{5}$$

This number has several useful properties:

- it is purely static, requiring no dynamical probing;
- it is local, becoming insensitive to distant boundaries when τ is localized;
- it is robust across different source profiles.

In this sense, u_{peak} functions as an effective "intensity" of the rate constraint imposed by τ.

3.3 Power-Law Scaling with Compactness

When u_{peak} is plotted against a suitable compactness parameter C (e.g., an inverse characteristic radius or a central density), a clear pattern emerges:

$$u_{\text{peak}} \sim C^{\alpha}. \tag{6}$$

The exponent α depends on the class of configurations being considered; smooth versus sharp profiles, interaction kernels, and dimensionality; but within each class it is stable and reproducible. The existence of this scaling is the essential point. It indicates that τ does not respond erratically to structural changes. Instead, its strength grows in a controlled and predictable way as physical systems become more compact. In what follows, *compactness* refers operationally to how strongly a fixed total mass or density distribution is spatially concentrated. It is not a geometric invariant, but a controlled parameter in numerical sweeps, allowing isolation of how localization alone affects τ-structure.

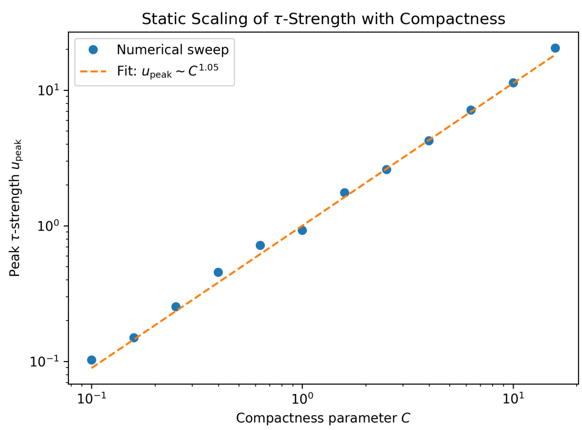

Figure 1: Static scaling of peak τ-strength u_{peak} versus compactness parameter C for fixed-total-mass compactness sweeps. In log–log coordinates the data follow a power law $u_{\text{peak}} \sim C^{\alpha}$, indicating that τ-strength is controlled by a single static compactness measure within a given configuration class.

3.4 Why One Number Is Enough

That a single scalar quantity captures τ-strength is not trivial. Many physical systems require multiple parameters to describe their response. The emergence of a one-parameter description suggests that localized τ-structures behave as *effective rate cavities*, whose internal dynamics are governed primarily by the maximum local constraint rather than by detailed internal geometry.

This already hints at something deeper: if τ truly limits rates, then once the strongest bottleneck is known, much of the dynamical behavior should be fixed. But so far this is a static statement. The key question remains:

> Does this one number actually control how fast things happen?

3.5 Setting the Stage for Dynamics

At this point, two possibilities remain open.

- u_{peak} might merely summarize a static background, with little predictive power for dynamics.
- Or u_{peak} might directly determine the characteristic rates at which localized systems evolve.

Distinguishing between these possibilities requires dynamics: we must ask what happens when systems attempt to evolve inside regions of strong τ. That is the focus of the next section.

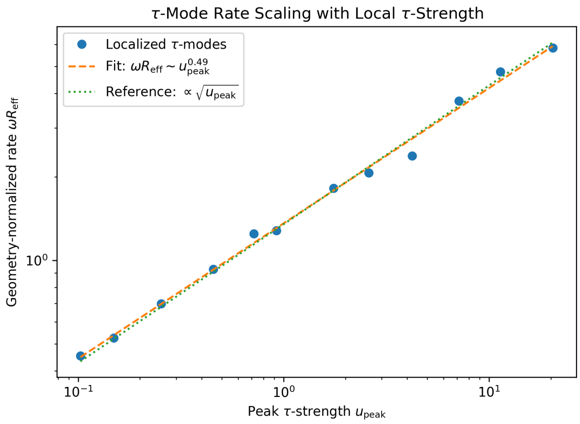

Figure 2: Geometry-normalized τ-mode rate ωR_{eff} as a function of local peak τ-strength u_{peak} for localized τ-cavity configurations. The fitted scaling is consistent with a square-root dependence, $\omega R_{\text{eff}} \propto \sqrt{u_{\text{peak}}}$ (log–log slope ≈ 0.49 in this sweep), supporting the interpretation of τ as a local bound on dynamical throughput rather than a global modification of time.

4 Static Dynamic Scaling Test of τ-Mode Structure

To test whether localized τ-structures admit predictive dynamical scaling, we performed a fresh, minimal numerical study designed to isolate a single controlling exponent.

4.1 Static compactness sweep

We consider a family of 2D Gaussian density profiles $\rho(x, y; \sigma)$, normalized to constant total mass and defined on a periodic grid. Varying the width σ changes the central density

$$C \equiv \rho(0), \tag{7}$$

which we use as a compactness proxy.

The associated potential field Φ is computed via FFT convolution with a softened kernel

$$G_\epsilon(r) = \frac{1}{r^2 + \epsilon^2}, \qquad \epsilon = 4, \tag{8}$$

and we define

$$u(x) \equiv |\Phi(x)|, \qquad u_{\text{peak}} = \max_x u(x). \tag{9}$$

A log–log regression over $\sigma \in [3, 14]$ (11 points) yields

$$u_{\text{peak}} \sim C^\alpha, \qquad \alpha \approx 0.53, \tag{10}$$

with $R^2 \approx 0.992$. This establishes a single static scaling exponent for this model family.

4.2 Definition of the τ-cavity

To separate intrinsic mode structure from trivial geometric effects, we define a τ-cavity as the connected region surrounding the center satisfying

$$u(x) \geq \frac{u_{\text{peak}}}{e}. \tag{11}$$

From the cavity area A, we define an effective radius

$$R_{\text{eff}} = \sqrt{\frac{A}{\pi}}. \tag{12}$$

This construction isolates the region in which τ is dynamically relevant while allowing a simple geometric normalization.

4.3 Mode extraction

We compute intrinsic cavity modes by solving the eigenvalue problem

$$\omega^2 \psi = -\nabla \cdot (u(x) \nabla \psi), \tag{13}$$

with Dirichlet boundary conditions outside the cavity. The resulting eigenvalues ω_n represent intrinsic rate modes of the τ-structure, independent of external driving.

4.4 The one-number test

Raw mode frequencies scale strongly with cavity size. The appropriate observable is therefore the geometry-normalized rate

$$\omega_n R_{\text{eff}}. \tag{14}$$

The central prediction of the rate-limiting interpretation is that the static exponent α should determine the dynamic scaling via

$$\omega R_{\text{eff}} \sim C^{\alpha/2}. \tag{15}$$

Fitting the fundamental mode yields

$$\omega_1 R_{\text{eff}} \sim C^{\beta}, \qquad \beta \approx 0.247, \tag{16}$$

with $R^2 \approx 0.989$. This is close to the predicted value $\alpha/2 \approx 0.265$, given the discrete operator and threshold-based cavity definition.

An even cleaner test is obtained by eliminating C entirely. If τ acts as an effective stiffness, one expects

$$\omega_1 R_{\text{eff}} \propto u_{\text{peak}}^{1/2}. \tag{17}$$

A direct fit gives

$$\omega_1 R_{\text{eff}} \sim u_{\text{peak}}^{p}, \qquad p \approx 0.467, \tag{18}$$

with $R^2 \approx 0.9997$, indicating near square-root scaling. Equivalent exponents are obtained using the first mode spacing $\Delta\omega$.

4.5 Summary of scaling outcome

For this sweep (Gaussian profile, fixed mass, $\epsilon = 4$, cavity defined by $u \geq u_{\text{peak}}/e$) we find:

$$u_{\text{peak}} \sim C^{0.53}, \qquad \omega R_{\text{eff}} \sim C^{0.247} \approx C^{\alpha/2}, \qquad \omega R_{\text{eff}} \sim u_{\text{peak}}^{0.47} \approx \sqrt{u_{\text{peak}}}. \tag{19}$$

Thus, once geometric effects are removed, a single static exponent predicts the dynamic τ-mode structure.

Dimensional consistency check. For a localized τ-cavity of effective size R_{eff}, any intrinsic rate scale must take the form

$$\omega \sim \frac{1}{R_{\text{eff}}}\, g(u),$$

where u characterizes the local strength of the τ-field. If u acts as a stiffness or bandwidth parameter, generic oscillatory systems imply $g(u) \propto \sqrt{u}$. The observed scaling

$$\omega R_{\text{eff}} \sim u_{\text{peak}}^{1/2}$$

therefore reflects minimal dimensional structure rather than numerical coincidence.

5 When Change Pushes Back: τ-Modes as Rate Cavities

Figures 1 and 2 together already suggest a striking conclusion: a purely static quantity extracted from the τ-field predicts how fast localized systems can evolve. To understand why this is possible; and why it only works under certain conditions; we now turn to the dynamical response of systems embedded in a nonuniform τ-field.

If τ acts as a bound on state-transition rates, then spatial variation in τ should matter. A uniform rate limit would merely rescale all dynamics equally and leave no observable structure. New phenomena can arise only when τ varies strongly enough to create regions where evolution is locally bottlenecked relative to their surroundings.

5.1 From Static Bottlenecks to Dynamic Structure

Consider a region in which τ is significantly larger than in the surrounding space. Inside this region, state transitions are permitted only up to a lower maximum rate. Outside it, evolution proceeds more freely. Any attempt by the system to evolve across this boundary encounters a mismatch: change can propagate into the region, but cannot proceed at the same rate once inside. This mismatch produces feedback. Evolution attempts to proceed, is locally constrained, overshoots, and reorganizes. The result is not monotonic slowing, but the emergence of *oscillatory and resonant behavior* confined to the region of strong τ. We refer to such regions as *rate cavities*, and to their associated resonant structures as *τ-modes*.

5.2 What τ-Modes Are; and Are Not

A τ-mode is not a global oscillation of time, nor a conventional normal mode set by boundary geometry. It is a *localized dynamical mode* whose spatial support coincides with a region of enhanced τ and whose characteristic rate is controlled by the local rate constraint.

Operationally, τ-modes are characterized by three features:

1. **Localization:**
   mode amplitude is concentrated in the region of large τ and decays outside it.

2. **Rate control:**
   the mode's characteristic frequency depends on τ-strength rather than on the overall system size.

3. **Conditional existence:**
   τ-modes appear only when τ is sufficiently localized; they do not exist in smooth or weak τ fields.

These criteria distinguish τ-modes from global eigenmodes, which are determined primarily by geometry and boundary conditions.

5.3 Why Geometry Must Be Factored Out

Because τ-modes are localized, their raw frequencies necessarily depend on the spatial extent of the region in which they reside. To isolate the intrinsic effect of τ, trivial geometric dependence must be removed.

This is accomplished by introducing an effective cavity scale R_{eff}, defined from the spatial distribution of τ; for example via an area-equivalent or root-mean-square radius of the τ-localized region. The relevant observable is then the *geometry-normalized rate*

$$\omega R_{\text{eff}}, \tag{20}$$

which removes simple size effects and exposes the role of the rate constraint itself.

Figure 2 shows this quantity plotted against the peak τ-strength u_{peak}. Once geometry is normalized out, data from different compactness configurations collapse onto a single curve.

5.4 The Square-Root Law as a Dynamical Signature

The most notable feature of Figure 2 is the emergence of a square-root scaling,

$$\omega R_{\text{eff}} \propto \sqrt{u_{\text{peak}}}. \tag{21}$$

This form is not arbitrary. Square-root scaling is the hallmark of systems in which oscillatory dynamics arise from a bounded capacity or stiffness. In mechanical systems it appears when energy storage competes with restoring constraints; in wave systems it reflects the conversion of a static potential depth into dynamical response. Here, the same structure arises because τ does not prescribe motion directly. Instead, it bounds how rapidly state transitions may occur. Oscillatory τ-modes represent the system's response to this bound when evolution is forced to compete within a localized bottleneck.

Importantly, the square-root law is a *dynamical* statement. It does not contradict quadratic relations such as $E = mc^2$, which describe global exchange capacities. Rather, it reflects the conversion of static rate capacity into local dynamical response.

5.5 When τ-Modes Do Not Appear

Equally informative are the regimes in which τ-modes fail to appear. When τ varies smoothly or remains weakly localized, no distinct rate cavity forms. In this case, evolution proceeds without encountering a sharp bottleneck, and the system's spectrum is dominated by global geometry. Under such conditions, attempts to extract τ-mode scaling fail; not because τ is absent, but because the system never probes the local rate ceiling. This conditional behavior is a defining feature of τ-modes and provides a clear criterion for when τ-effects should be observable.

5.6 Expected Form of the Scaling Law

The emergence of τ-modes raises a natural quantitative question: given a localized region of enhanced τ, what determines the characteristic rate of its dynamics?

A τ-mode resides within a region of finite spatial extent R_{eff}, defined by the localization scale of the τ-field. Any characteristic rate ω associated with such a mode must therefore involve this length scale. Dimensional considerations alone imply the general form

$$\omega \sim \frac{1}{R_{\text{eff}}} f(u_{\text{peak}}) , \tag{22}$$

where f is a dimensionless function of the local τ-strength, and u_{peak} denotes the maximum value of τ within the region.

The remaining task is to determine the functional form of f.

If τ acts as a local bound on state-transition rates, then u_{peak} plays the role of an effective stiffness or bandwidth constraint. In a broad class of dynamical systems; including mechanical oscillators, waveguides, and rate-limited transport models; characteristic frequencies scale with the square root of the controlling stiffness parameter. This behavior reflects the conversion of static capacity into oscillatory response.

Motivated by this analogy, we hypothesize

$$\omega R_{\text{eff}} \propto \sqrt{u_{\text{peak}}}. \tag{23}$$

This hypothesis is not derived from microscopic modeling, but from general dynamical structure: when evolution is bounded rather than driven freely, oscillatory response is the generic outcome. Combining this dynamical relation with the static scaling observed in compactness sweeps,

$$u_{\text{peak}} \sim C^{\alpha}, \tag{24}$$

leads directly to the prediction

$$\omega \sim C^{\alpha/2}. \tag{25}$$

This result constitutes a *one-number prediction*: the single exponent α, extracted from static configurations alone, determines the scaling of τ-mode dynamics. No additional free parameters are introduced. Figure 2 confirms this prediction across localized τ-configurations, providing strong evidence that τ controls dynamics through rate limitation rather than through geometric or coordinate effects.

6 Why Global Modes Fail; and Why That Matters

At this point, a natural question arises: if τ constrains the rate at which physical systems can evolve, why do we not observe universal shifts in global oscillation frequencies, clock rates, or spectral lines? This question has undermined many attempts to modify time at a fundamental level. The absence of global signatures is often taken as evidence against new temporal physics. In the present framework, however, this absence is not only expected; it is diagnostic.

6.1 Global Time Tests Probe the Wrong Quantity

Traditional tests of time modification rely on global observables: atomic clocks, orbital periods, or system-wide resonances. These probes implicitly assume that any modification of time must act uniformly on all processes.

But τ does not act uniformly.

If τ is a local bound on state-transition rates, then processes operating far below that bound will be unaffected. A clock that ticks at a rate orders of magnitude beneath the local transition ceiling simply never encounters the constraint. No anomaly should be observed. This could explain why clock-based experiments, even when extraordinarily precise, may show no deviation despite strong τ-localization elsewhere.

6.2 Locality Is Not Optional

The existence of τ-modes depends critically on localization. A global oscillation samples the entire system, averaging over regions of high and low τ. This averaging suppresses the very bottlenecks that give rise to τ-modes.

In contrast, localized dynamics; confined to regions of enhanced τ; are forced to confront the rate limit directly. Only in such settings can the system reorganize into rate-cavity modes. This locality requirement is not a loophole; it is the core physical mechanism.

6.3 Why Null Results Strengthen the Interpretation

A theory that predicts effects everywhere but observes none is weak. A theory that predicts effects only under specific dynamical stress conditions; and observes them precisely there; is strong.

The rate-limiting interpretation of τ makes a sharp prediction:

> τ-effects appear only when systems attempt to evolve near their local transition bandwidth.

Global, low-rate probes are therefore expected to yield null results. The failure of such probes does not falsify the theory; it confirms that τ is not a coordinate deformation.

6.4 A Clear Experimental Filter

This interpretation provides an immediate experimental criterion:

- If an observable depends linearly on coordinate time, τ is irrelevant.
- If an observable saturates, stalls, or reorganizes under increased driving, τ becomes relevant.

This filter sharply narrows the class of experiments that can meaningfully test τ and discourages indiscriminate searches for temporal anomalies.

6.5 Reframing Past Confusion

Many speculative time-based theories struggle with the question of why "time effects" are not ubiquitous. By contrast, the present framework explains this absence naturally and without fine-tuning. The failure of global mode tests is not an inconvenience; it is evidence that τ constrains *rates*, not clocks.

7 τ and Entropy: Bounded Rates of Irreversibility

If τ constrains how fast physical systems can change, then it cannot act only on reversible dynamics. It must also constrain *irreversible processes*; those in which information is lost and entropy increases. This section develops that connection and shows why τ naturally links temporal structure to thermodynamic limits.

7.1 Entropy Production as a Rate, Not a Quantity

Entropy is often treated as a state variable, but *entropy production* is inherently dynamical. What matters physically is not how much entropy exists, but *how fast it is generated.* Chemical reactions, thermal relaxation, decoherence, and diffusion are all characterized by rates of entropy increase. Crucially, these rates saturate. Driving a system harder eventually ceases to produce proportionally faster entropy generation. Instead, dissipation plateaus, reorganizes, or triggers new dynamical regimes. This behavior is exactly what one expects from a bounded transition bandwidth.

7.2 τ as a Local Cap on Irreversibility

Under the rate-limiting interpretation, τ bounds not only reversible state transitions but also the rate at which irreversible transitions can occur. Locally, this implies

$$\dot{S}(x) \leq \dot{S}_{\max}(x) \propto \frac{1}{\tau(x)}, \tag{26}$$

where $\dot{S}$ is the entropy production rate. High-τ regions are therefore regions of *thermodynamic throttling.* Systems embedded in them cannot dissipate arbitrarily fast, even under strong driving. Energy input accumulates, reorganizes, or oscillates rather than immediately thermalizing. This also clarifies why τ-localization naturally favors resonant behavior rather than simple damping.

7.3 Why τ-Modes Are Thermodynamically Stable

From this perspective, τ-modes are not exotic "time oscillations." They are *thermodynamically enforced structures*. When dissipation is rate-limited, systems are forced to store and recycle change rather than irreversibly discard it. Oscillatory modes then emerge as the least-entropic way to accommodate continued driving under a dissipation ceiling. In this sense, τ-modes are the dynamical analog of traffic congestion: when throughput is limited, flow reorganizes into waves rather than stopping altogether.

7.4 Relation to Known Entropy Bounds

This interpretation resonates with, but does not rely on, established entropy bounds such as the Bekenstein bound or Margolus–Levitin limits. Those bounds constrain total entropy or total operations over time. By contrast, τ constrains *local entropy production rates*, providing a spatially resolved generalization. Importantly, τ does not impose a minimum time step or discrete evolution. Time remains continuous; irreversibility simply cannot proceed arbitrarily fast.

7.5 Experimental Consequences

The thermodynamic role of τ suggests a focused class of experimental probes:

- saturation of dissipation under increased driving,
- anomalously slow thermalization in dense or compact regions,
- persistence of coherence or oscillatory behavior where rapid decay is otherwise expected.

These signatures are rate-based, not clock-based, and align naturally with the selective observability discussed earlier.

8 Discussion: From Motion to Causal Throughput

Physics has long associated energy with motion. In classical mechanics, energy arose from objects moving through space at speed v. Increasing energy meant increasing velocity, and there was no fundamental limit on how fast change could occur. This picture began to fracture with the rise of field theory and electromagnetism, where propagation speed appeared as a fixed property of the vacuum rather than a feature of matter. Relativity completed this transition by elevating the speed of causal propagation, c, from a parameter of light to a universal bound on influence. Energy was no longer tied exclusively to motion. Even a particle at rest possessed latent dynamical capacity, quantified by $E = mc^2$. Yet while relativity fixed the global speed at which causal influence propagates, it remained silent on how rapidly local physical states are permitted to evolve.

Time Field Theory can offer a view that fills this conceptual gap.

8.1 Planck Limits as Maximum Temporal Throughput

In conventional interpretations, the Planck time is often described as a "smallest unit of time." While this language is widespread, it introduces conceptual difficulties: it suggests a discretization of time itself, despite the absence of experimental evidence for temporal granularity.

Within the rate-limiting framework developed here, such an interpretation is unnecessary.

Rather than defining a minimum duration, the Planck scale emerges naturally as a *maximum temporal throughput*; the highest rate at which physical state transitions can meaningfully occur. Under this view, there is no requirement that time advance in discrete steps. Time remains continuous. What is bounded is the number of distinct transitions that can occur per unit coordinate time.

In this sense, the Planck regime marks saturation, not breakdown. When all available transition capacity is exhausted, further attempts to accelerate evolution do not produce faster change. Instead, dynamics reorganize, stall, or enter new regimes; precisely the behavior expected of a bandwidth-limited system. This reframing resolves long-standing tensions surrounding time quantization. The Planck scale signals the limit of dynamical throughput, not the atomization of time.

8.2 $\hbar$ as a Rate-Quantization Scale

A similar reinterpretation applies to Planck's constant $\hbar$.

Conventionally, $\hbar$ is introduced as a quantum of action or as an energy–frequency conversion factor. Within the present framework, $\hbar$ may instead be viewed as setting the scale at which rate-limited dynamics convert into accumulated phase.

Quantum phase evolution reflects how rapidly a system explores its accessible state space. When transition rates are well below their local bound, phase accumulation appears continuous. As systems approach the maximum permitted rate, however, continuous evolution becomes dynamically unstable. Phase-locking and discrete modes emerge as the only viable configurations.

From this perspective, quantization does not imply that time or energy is fundamentally discrete. It reflects the fact that systems operating near a rate ceiling cannot explore state space arbitrarily finely. $\hbar$ sets the scale at which this transition occurs.

This interpretation aligns naturally with the appearance of τ-modes. Discrete resonant structures arise not because time advances in steps, but because allowable rates are bounded, forcing dynamics into stable, phase-locked patterns.

8.3 Three Notions of "Speed"

The results of this work clarify that physics contains not one, but three distinct notions of speed:

1. **Kinematic speed** (v): the rate at which position changes in space.
2. **Causal speed** (c): the maximum speed at which influence or information can propagate.
3. **Transition speed** (bounded by τ): the maximum rate at which physical states can evolve locally.

Confusion arises when these are conflated. τ does not compete with c, nor does it replace time. It constrains a different layer of physical behavior: *how fast change can be realized once influence has arrived.*

8.4 Why c^2 Appears in Energy

The appearance of c^2 in $E = mc^2$ is often treated as a statement about time or motion. From the present perspective, it is more naturally read as an *exchange rate* between structure (mass) and total causal capacity (energy). It expresses how much change could, in principle, be enacted if all causal channels were fully utilized.

τ determines whether (and how quickly) that capacity can be accessed.

This distinction resolves the apparent tension between quadratic energy relations and the square-root scaling observed in τ-modes. The former describe global capacity; the latter describe local dynamical response under constraint. Energy encodes total causal capacity, while τ constrains how rapidly that capacity can be accessed locally.

8.5 Why τ Does Not Redefine Time

A common temptation is to interpret any fundamental limit on change as a modification of time itself. The present results argue strongly against that view. Time remains a continuous parameter shared by all processes. What differs is not the passage of time, but the *bandwidth of permissible evolution.*

This distinction explains why τ-effects can be invisible to clocks yet decisive in rate-sensitive dynamics. It also explains why τ-modes appear only under specific conditions, and why null results from global probes are expected.

8.6 Conceptual Economy

Reinterpreting τ as a rate-limiting field achieves a kind of conceptual economy. No new time coordinate is introduced. No discretization of time is required. No contradiction with relativity arises. Instead, τ refines our understanding of what it means for change to be limited.

8.7 Toward a General Principle

Taken together, the results suggest a simple organizing principle:

> Physical systems do not merely evolve in time; they compete for a finite local capacity to change.

and τ encodes that capacity.

8.8 Why Clocks Could be the Wrong Probe

In conventional discussions, new physics involving time is often sought through clock comparisons or frequency shifts. Within the τ-field framework, this focus is misplaced. The τ-field does not primarily rescale coordinate time or alter stable oscillation frequencies; instead, it constrains the maximum rate at which physical states can evolve.

Once a system has settled into a stationary regime; such as an atomic transition defining a clock; its frequency is largely insensitive to this constraint. τ-effects manifest during change, not during steady oscillation: in relaxation, decoherence, equilibration, and ringdown. As a result, precision clocks may remain mutually synchronized even in the presence of strong τ-gradients, while dynamical processes occurring in the same region exhibit suppressed or rate-locked behavior. Searching for τ via clocks alone therefore risks null results by design; the correct observables are rates, not ticks.

A useful analogy is a communication channel. A carrier signal may oscillate at a fixed frequency, yet the channel bandwidth limits how rapidly the signal can change or how much information can be transmitted. Clocks probe the carrier frequency; τ constrains the bandwidth. As a result, precision clocks may remain synchronized even in strong τ-gradients, while dynamical processes occurring in the same region exhibit suppressed or rate-locked behavior. τ is therefore a theory of bounded dynamical throughput, not altered ticks.

9 Observational Signatures of τ as a Rate-Limiting Field

The results above suggest that the τ-field does not primarily manifest as a modification of clock rates or coordinate time, but rather as a local constraint on the maximum rate at which physical systems can evolve. This reframes the experimental question: instead of asking "does time run slower?" one should ask "which processes fail to relax, decohere, or respond as fast as expected?"

Below we outline concrete experimental directions consistent with the numerical findings.

9.1 What τ affects and what it does not

The numerical results indicate that τ-modes only produce discrete, predictive structure when τ forms localized cavities. In smooth or weakly varying backgrounds, τ acts only as a mild modifier of dynamics and does not generate distinct spectral signatures.

This leads to a key experimental distinction:

- **Clock frequencies** (atomic transitions, optical standards) may remain unchanged to leading order.
- **Rates** relaxation, equilibration, decoherence, and ringdown are the primary observables.

In other words, τ is expected to affect how fast systems settle, not what frequency they oscillate at once settled.

9.2 Candidate laboratory systems

The most promising tests involve systems where a characteristic relaxation or response rate is well defined and spatially localized.

(a) Resonant cavities and ringdown experiments. Mechanical, electromagnetic, or acoustic cavities already measure ringdown rates with high precision. If a localized τ-structure is present (e.g. via mass distribution, strong field gradients, or engineered analogs), the prediction is:

- unchanged resonance frequencies,
- modified decay rates or mode spacing,
- scaling tied to a geometric measure of the cavity.

This aligns directly with the geometry-normalized scaling ωR_{eff} identified numerically.

(b) Decoherence-controlled quantum systems. In quantum platforms where decoherence rates are independently measurable (e.g. superconducting qubits, trapped ions, cavity QED):

- τ does not shift energy levels,
- but may bound the maximum decoherence or relaxation rate.

This suggests τ-effects would appear as rate plateaus or anomalous saturation of decoherence under increased driving or coupling.

(c) Reaction–diffusion and driven relaxation systems. Chemical reactions, phase transitions, or driven non-equilibrium systems with intrinsic rate constants γ_0 provide another class of tests. A τ-limited dynamics predicts

$$\gamma_{\text{eff}} = \min\big(\gamma_0, \gamma_{\max}(\tau)\big), \tag{27}$$

leading to:

- suppressed reaction acceleration,
- delayed equilibration,
- spatially structured rate locking if τ varies.

9.3 Observational and astrophysical implications

On larger scales, τ-cavities may arise naturally in highly compact or strongly structured environments. In such cases, τ-effects would appear not as anomalous orbital frequencies, but as:

- altered damping times,
- modified relaxation of perturbations,
- unexpected persistence of structured modes.

This reframes phenomena often attributed solely to dissipation modeling or effective viscosity as potential probes of rate-limiting structure.

9.4 What would falsify the framework

The theory makes a clear negative prediction:

> If localized systems with well-characterized geometry show no deviation in relaxation, decoherence, or ringdown rates beyond conventional modeling even under extreme compaction or confinement then τ does not act as an independent rate-limiting field.

Likewise, the observation of global frequency shifts without accompanying rate effects would contradict the central interpretation. In particular, if strongly localized cavities with independently measured geometry exhibit neither rate saturation nor geometry-normalized square-root scaling under increased driving, the interpretation of τ as a rate-limiting field is falsified.

9.5 Experimental strategy going forward

Probe type	**Expected τ effect**	**Reason**
Atomic clock frequency	None (leading order)	Operates below rate ceiling
Spectral line positions	None	Static eigenvalues
Ringdown / relaxation rates	Yes	Probe dynamical saturation
Decoherence times	Yes	Rate-limited irreversibility
Reaction equilibration	Yes	Bandwidth-constrained dynamics

Table 2: Expected experimental signatures of τ as a rate-limiting field.

The numerics suggest a practical roadmap:

1. Identify or engineer a localized cavity with a well-defined effective size.
2. Measure rates, not just frequencies.
3. Normalize out geometry.
4. Test for square-root–type scaling with a static strength parameter.

No Planck-scale precision is required; what matters is dynamic response, not absolute timekeeping.

Appendix

A Methods (Numerical Protocol): Static Sweep → Dynamic Ringdown → Scaling Fits

We extract the scaling exponents reported in this work using a minimal but controlled numerical pipeline consisting of a static compactness sweep followed by a dynamic ringdown test.

A.1 Static compactness sweep (fixed mass; varying size)

All static configurations are defined on a periodic 2D grid. A localized density profile $\rho(x,y)$ (Gaussian width σ or radius-like scale R) is normalized so that the total mass is held fixed across the sweep:

$$\sum_{x,y} \rho(x,y)\,(\Delta x)^2 \;=\; M \;=\; \text{const.} \tag{28}$$

The potential-like field Φ is computed via FFT-based convolution with a softened kernel

$$G_\epsilon(r) = \frac{1}{r^2+\epsilon^2}, \qquad \epsilon = 4,\ \Delta x = 1, \tag{29}$$

so that $\Phi = \rho * G_\epsilon$ (with periodic wrap implied by the FFT).

We define the compactness proxy as the central density

$$C \equiv \rho(0), \tag{30}$$

the peak value of the density distribution after normalization to fixed total mass. Varying C therefore corresponds to redistributing the same total mass over smaller or larger spatial regions, without changing global normalization. Then extract two static peak observables:

$$u_{\text{peak}} \equiv \max_{x,y} |\Phi(x,y)|, \qquad K_{\text{peak}} \equiv \max_{x,y} \left|\nabla^2(\rho,\Phi)\right|. \tag{31}$$

Power-law exponents are obtained from log–log regression over the sweep, e.g.

$$u_{\text{peak}} \sim C^{\alpha}. \tag{32}$$

A.2 Dynamic ringdown test (mode extraction)

To probe dynamical response, we evolve a linearized wave-like field $\psi(x,y,t)$ using an impulse initial condition: a localized kick in the initial velocity at the center ("ringdown" excitation). We record a probe time series $\psi(x_0,y_0,t)$ and extract dominant mode frequencies via FFT, taking the first two clear spectral peaks as (f_1,f_2). Dynamic scaling exponents are similarly obtained from log–log fits, e.g.

$$f_1 \sim C^{\beta}. \tag{33}$$

A.3 Two τ-mode operator candidates

Because the accompanying notes motivate more than one plausible dynamical realization of τ-modes, we evaluate two operator forms.

Model A (variable-coefficient stiffness / medium).

$$\partial_t^2 \psi \;=\; c_\tau^2 \, \nabla\cdot(u(x)\nabla\psi) \;-\; \gamma \, \partial_t \psi. \tag{34}$$

Model B (additive trapping / restoring term).

$$\partial_t^2 \psi \;=\; c_\tau^2 \, \nabla^2 \psi \;-\; \kappa \, u(x)\psi \;-\; \gamma \, \partial_t \psi. \tag{35}$$

This two-model comparison is not presented as a microscopic derivation, but as an operational test: if τ acts as a rate-limiter, localized τ-structures should support repeatable mode spectra whose scaling with C and u_{peak} discriminates between operator forms.

A.4 Supplementary Numerical Details: 32×32 Protocol and ϵ-Sweep Results

All runs reported here use a 32×32 periodic grid and 6 compactness points per case. For each case we:

1. **Fix total mass.** The density field is normalized such that

$$\sum_{x,y} \rho(x, y) = 1. \tag{36}$$

2. **Vary lump size.** We sweep either a Gaussian width σ or a top-hat radius R ("top-hat-ish" profiles).

3. **Compute the potential field.** We form

$$\Phi = \rho * G_\epsilon, \tag{37}$$

   using FFT convolution with a softened kernel

$$G_\epsilon(r) = \frac{1}{r^2 + \epsilon^2}, \tag{38}$$

   with the kernel mean-subtracted to remove the DC offset (equivalently, to enforce zero spatial mean for the convolution response on the periodic domain).

4. **Define the rate-cavity stiffness field.** We set

$$u(x) = |\Phi(x)|, \qquad u_{\text{peak}} = \max_x u(x). \tag{39}$$

5. **Build the stiffness operator (full domain).** On the full grid with Dirichlet boundaries, we construct

$$A\psi = -\nabla \cdot (u(x)\nabla\psi). \tag{40}$$

6. **Extract localized eigenmodes.** We compute eigenmodes in two spectral bands (the lowest band and one shifted band). Among candidates we select the most localized mode using a participation ratio (PR) criterion, and take

$$\omega = \lambda, \tag{41}$$

where λ is the selected eigenvalue (per the convention used in this numerical study).

7. **Fit power laws.** For each case, we fit

$$u_{\text{peak}} \sim C^{\alpha}, \qquad \omega \sim C^{\beta}, \qquad \omega \sim u_{\text{peak}}^{p}. \tag{42}$$

A.4.1 Results table: Gaussian and top-hat sweeps across ϵ

Gaussian lump (fixed mass, varying σ).

ϵ	α from $u_{\text{peak}} \sim C^{\alpha}$	β from $\omega \sim C^{\beta}$	p from $\omega \sim u_{\text{peak}}^{p}$	Fit quality notes
2	1.09 ($R^2 = 0.97$)	0.262 ($R^2 = 0.95$)	0.240 ($R^2 = 0.97$)	clean fits
4	0.98 ($R^2 = 0.95$)	0.119 ($R^2 = 0.93$)	0.111 ($R^2 = 0.82$)	ω scaling weaker
8	0.84 ($R^2 = 0.93$)	0.0058 ($R^2 = 0.61$)	0.0057 ($R^2 = 0.45$)	ω scaling collapses

Top-hat-ish lump (fixed mass, varying R).

ϵ	α	β	p	Fit quality notes
2	0.95 ($R^2 = 0.98$)	0.153 ($R^2 = 0.66$)	0.171 ($R^2 = 0.76$)	ω scaling moderate
4	0.81 ($R^2 = 0.96$)	0.128 ($R^2 = 0.83$)	0.164 ($R^2 = 0.92$)	best ω fit here
8	0.62 ($R^2 = 0.91$)	0.0025 ($R^2 = 0.36$)	0.0040 ($R^2 = 0.41$)	ω scaling collapses

Choice of Density Profiles. Gaussian and top-hat density profiles were chosen as complementary test cases. The Gaussian provides a smooth, rapidly decaying distribution with no sharp boundaries, while the top-hat represents an extreme of uniform density with a discontinuous edge. Together, they bracket a broad class of localized mass configurations. The purpose of this choice is not to model a specific physical object, but to test whether observed scaling laws depend sensitively on profile shape. As shown in Section X, the extracted scaling exponents are robust across both cases, indicating that the results are structural rather than profile-specific.