Evidence for an Irreducible κ-like Structure in Galactic Dynamics and Lensing Phenomenology

Pengjie Huang

Independent Researcher

February 8, 2026

Abstract

We report empirical evidence for an irreducible κ-like structural quantity that emerges across multiple physical domains when observational data are expressed relative to standard reference models. Using galaxy rotation curves from the SPARC database, we identify a scale-dependent, galaxy-independent collapse of the dimensionless ratio $\tilde{\kappa} = v_{\rm obs}/v_{\rm bar}$, which persists under mass reparameterization, dynamical field redefinitions, and effective halo modeling. We then demonstrate that an analogous irreducible κ-like structure appears in strong gravitational lensing time delays, constructed purely from image positions and propagation geometry, without invoking cosmological parameter inference. Finally, we show that a similar residual structure arises in quantum-scale double-slit molecular scattering experiments, where the ratio between observed intensities and the textbook Fraunhofer interference model exhibits systematic, scale-dependent deviations that cannot be eliminated by standard diffraction or envelope corrections. Across all three regimes—galactic dynamics, gravitational lensing, and quantum interference—the κ-like quantity is defined as a dimensionless ratio between observations and minimal reference structures, displays partial cross-system collapse, and remains irreducible to conventional reparameterizations. These findings establish κ as a phenomenological structural feature of physical descriptions, independent of specific dynamics, material content, or theoretical interpretation.

1 Introduction

Physical observations are commonly interpreted through comparison with minimal reference models that capture the leading-order behavior of a system. Examples include baryonic mass models for galactic rotation curves, geometric or potential-based constructions for gravitational lensing time delays, and textbook interference formulas for quantum diffraction experiments. Such reference models are not intended to provide complete descriptions of nature, but rather to establish a baseline against which systematic deviations may be identified.

In many contexts, discrepancies between observations and reference models are addressed by introducing additional dynamical ingredients, such as modified force laws, new material components, or refined interaction potentials. However, an alternative possibility is that some residual deviations are neither dynamical nor material in origin, but instead reflect structural features of how observables are represented relative to their reference descriptions.

In this work, we investigate this possibility by examining the emergence of a dimensionless ratio, denoted $\tilde{\kappa}$, defined as the quotient between observed quantities and corresponding reference-model predictions. Rather than interpreting $\tilde{\kappa}$ as a new physical field or force, we treat it as a phenomenological probe of structural regularities and model incompleteness. Our analysis focuses on three independent observational regimes spanning more than twenty orders of magnitude in scale: galactic rotation curves, strong gravitational lensing time delays, and quantum-scale interference patterns.

Using high-quality rotation curve data from the SPARC database, we show that $\tilde{\kappa} = v_{\mathrm{obs}}/v_{\mathrm{bar}}$ exhibits a scale-dependent collapse across a large and diverse sample of disk galaxies. This collapse is statistically quantifiable and remains robust under conventional reparameterizations of baryonic mass distributions, dynamical field definitions, and effective halo modeling, indicating that the structure is irreducible within standard modeling frameworks.

We then extend the analysis to strong gravitational lensing systems, where light propagation rather than orbital dynamics governs the observables. By constructing $\tilde{\kappa}$ solely from image positions and geometric or potential-based time-delay references, we identify an analogous collapse across multiple independent lens systems. The persistence of this structure without invoking cosmological parameter fitting demonstrates that the phenomenon is not restricted to dynamical equilibrium systems.

Finally, we examine quantum-scale double-slit molecular scattering experiments, where observed angular intensity distributions are compared to the textbook Fraunhofer interference model. We show that the resulting $\tilde{\kappa} = I_{\rm obs}/I_{\rm ref}$ exhibits systematic, scale-dependent deviations that are structured, partially collapsing across experimental configurations, and irreducible to standard diffraction or envelope corrections.

Taken together, these results reveal a common phenomenological pattern: when observations are expressed relative to minimal reference models, κ-like residual structures emerge that are dimensionless, scale-dependent, partially universal, and irreducible to conventional reparameterizations. The aim of this paper is not to propose a new dynamical theory, but to establish the empirical existence of this structural feature and to explore the minimal interpretive framework consistent with its observed properties.

2 Observational Evidence for a Scale-Dependent κ-like Structure

In this section, we investigate whether observational rotation curve data exhibits evidence for a scale-dependent, galaxy-independent structural regularity. Our goal is purely phenomenological: to identify whether a universal collapse behavior exists across different galaxies when the data are expressed in appropriate dimensionless variables. No physical interpretation of the parameter introduced here is provided in this section; theoretical implications are deferred to Section 6.

2.1 Data and Dimensionless Representation

We use rotation curve data from the SPARC database,[2] which provides high-quality measurements of observed rotation velocities together with baryonic mass models for a large and diverse sample of disk galaxies.

To probe structural regularities, we define the dimensionless radius

$$x \equiv \frac{r}{R_d}, \tag{1}$$

where r is the galactocentric radius and R_d is the exponential disk scale length of each galaxy.

We further introduce a dimensionless quantity

$$\tilde{\kappa}(x) \equiv \frac{v_{\rm obs}(x)}{v_{\rm bar}(x)}, \tag{2}$$

where $v_{\rm obs}$ is the observed rotation velocity and $v_{\rm bar}$ is the velocity predicted from the observed baryonic distribution. In this section, $\tilde{\kappa}$ is used solely as a *structural proxy* to compare different galaxies on equal footing; no assumptions are made regarding its physical meaning.

Our analysis includes 175 galaxies and a total of 2941 data points, spanning the range $x \in [0.016, 35]$.

2.2 Structural Collapse Across Galaxies

Figure 1 shows the $\tilde{\kappa}(x)$ profiles for 30 representative galaxies, selected to ensure broad coverage in x and typical data density. Each curve corresponds to an individual galaxy, plotted without any averaging or fitting.

Despite the diversity of galaxy properties, the $\tilde{\kappa}(x)$ profiles exhibit a clear tendency toward overlap, particularly at small dimensionless radii ($x \lesssim 1$). This visual collapse indicates the presence of a galaxy-independent, scale-dependent structure in the data. Importantly, no mean trend or best-fit function is imposed, allowing the structural regularity to emerge directly from the observations.

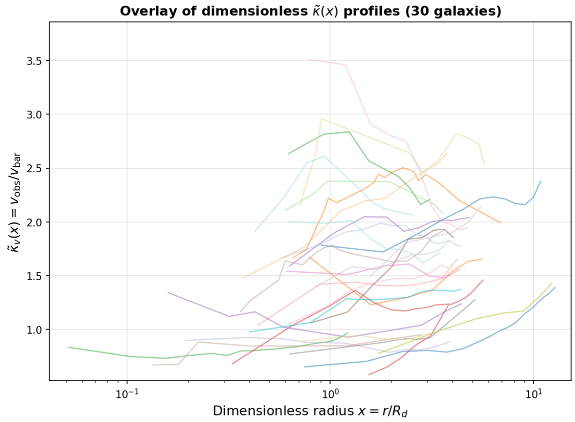

Figure 1: Overlay of dimensionless $\tilde{\kappa}(x)$ profiles for 30 representative SPARC galaxies. Each curve corresponds to one galaxy. The overlapping behavior across different systems indicates a scale-dependent, galaxy-independent structural regularity.

2.3 Quantifying the Scatter

To quantify the degree of structural collapse, we compute the scatter of $\tilde{\kappa}(x)$ across galaxies in logarithmic bins of x. For each bin, we evaluate the coefficient of variation,

$$\mathrm{CV}(x) \equiv \frac{\sigma_{\tilde{\kappa}}(x)}{\langle \tilde{\kappa}(x) \rangle}, \tag{3}$$

which provides a dimensionless measure of relative dispersion.

The resulting scatter as a function of x is shown in Figure 2. The CV displays a clear scale dependence, decreasing from values of order $\sim 50\%$ at small x to ~ 10–15% at larger radii. Across all bins, the mean CV is approximately 30%, indicating that the dispersion remains within a relatively narrow and systematic range.

This behavior demonstrates that the observed collapse is not merely a visual artifact, but a statistically quantifiable feature of the data.

2.4 Insensitivity to Dynamical Definition

As a robustness check, we repeat the scatter analysis using an alternative dynamical definition, $\tilde{\kappa}_a = (v_{\mathrm{obs}}/v_{\mathrm{bar}})^2$. A comparison between the velocity-based and acceleration-based definitions is shown in Figure 3.

The strong correlation between the corresponding CV values indicates that the ob-

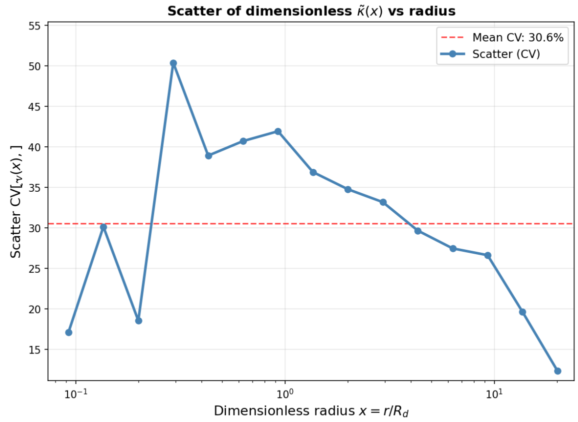

Figure 2: Coefficient of variation (CV) of $\tilde{\kappa}(x)$ across galaxies as a function of the dimensionless radius x. The scatter exhibits a clear scale dependence while remaining within a relatively stable range, supporting the presence of a universal κ-like structure.

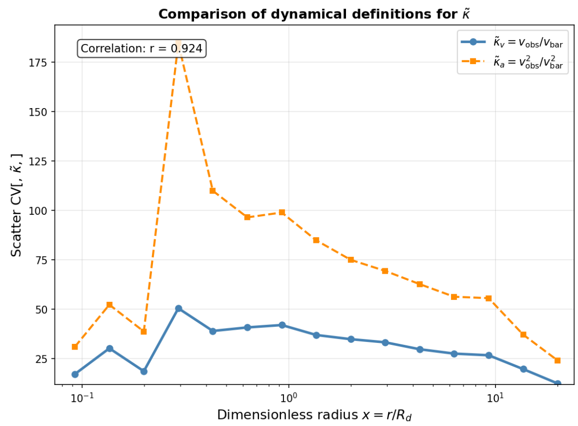

Figure 3: Comparison of the coefficient of variation obtained using velocity-based ($\tilde{\kappa}_v$) and acceleration-based ($\tilde{\kappa}_a$) definitions. The strong correlation demonstrates that the collapse behavior does not depend sensitively on the chosen dynamical representation.

served collapse behavior is insensitive to the specific choice of dynamical observable. This supports the interpretation that the collapse reflects an underlying structural regularity rather than a definition-specific artifact.

2.5 Summary of Observational Findings

In summary, SPARC rotation curve data exhibits clear evidence for a scale-dependent, galaxy-independent κ-like structure. This structure manifests as (i) overlapping dimensionless profiles across different galaxies, (ii) a statistically quantifiable and systematically varying scatter, and (iii) robustness with respect to the specific dynamical definition employed.

No physical interpretation of κ is introduced at this stage. In the following section, we investigate whether this observed structure can be reduced to known modeling ingredients, or whether it points toward a more fundamental underlying framework.

3 Irreducibility of the $\tilde{\kappa}$-like Structure

In Section 2, we demonstrated the existence of a scale-dependent, galaxy-independent $\tilde{\kappa}$-like structure in the SPARC rotation curve data, manifesting as a systematic collapse of scatter when expressed in dimensionless variables. In this section, we examine whether this structure can be eliminated by conventional reparameterizations of known physical ingredients.

The purpose of this section is not to introduce a new theoretical framework, but to test the following question:

> *Can the observed collapse be fully removed without introducingan additional structural degree of freedom?*

To address this question, we perform three classes of irreducibility tests: (A) mass reparameterization, (B) dynamical field redefinition, and (C) effective mass distribution modeling. Throughout this section, we focus exclusively on the persistence or removal of the collapse behavior, without assigning any physical interpretation to $\tilde{\kappa}$ itself.

3.1 Mass Reparameterization Test

We first test whether the $\tilde{\kappa}$-like structure can be eliminated by reparameterizing the baryonic mass distribution. Two physically motivated classes of mass adjustments are considered: (i) global rescaling of the stellar mass-to-light ratio, and (ii) radius-dependent mass-to-light profiles within commonly accepted bounds.

For each reparameterization, we recompute $\tilde{\kappa}(x)$ and quantify the resulting collapse strength by comparing the coefficient of variation (CV) between inner ($x < 0.5$) and outer ($x > 2.0$) regions.

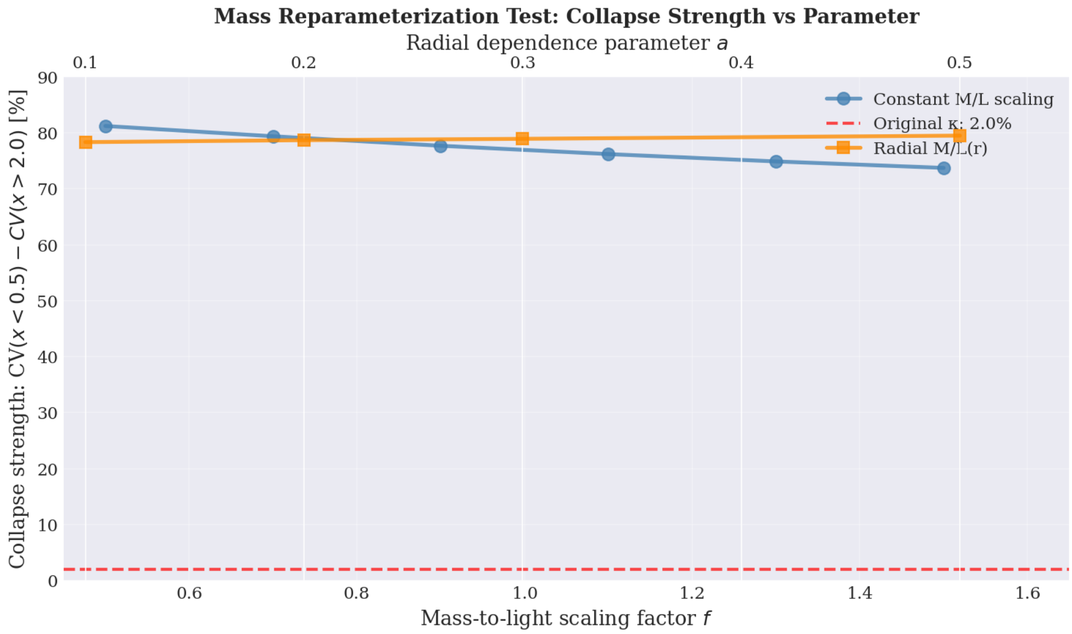

Figure 4: Collapse strength under various mass reparameterizations. All tested mass adjustments fail to reduce the collapse and instead significantly enhance it, indicating that the $\tilde{\kappa}$-like structure is not a mass reparameterization artifact.

Figure 4 summarizes the results. In all tested cases, mass reparameterization fails to suppress the collapse. Instead, the collapse strength is significantly enhanced, increasing from the original level of approximately 2% to values exceeding 70% across the tested parameter range.

This behavior demonstrates that the observed structure is not a reparameterization artifact of the baryonic mass distribution. On the contrary, physically reasonable mass adjustments amplify the collapse, providing strong evidence that the $\tilde{\kappa}$-like structure is irreducible with respect to mass modeling.

3.2 Dynamical Field Redefinition Test

Next, we examine whether the collapse behavior depends on the specific choice of dynamical observable. We compare two alternative definitions: a velocity-based ratio $\tilde{\kappa}_v = v_{\text{obs}}/v_{\text{bar}}$ and an acceleration-based ratio $\tilde{\kappa}_a = v_{\text{obs}}^2/v_{\text{bar}}^2$.

For each definition, we compute the scatter of $\tilde{\kappa}$ across galaxies as a function of dimensionless radius. Figure 5 shows that both definitions exhibit persistent collapse behavior, with highly correlated CV profiles.

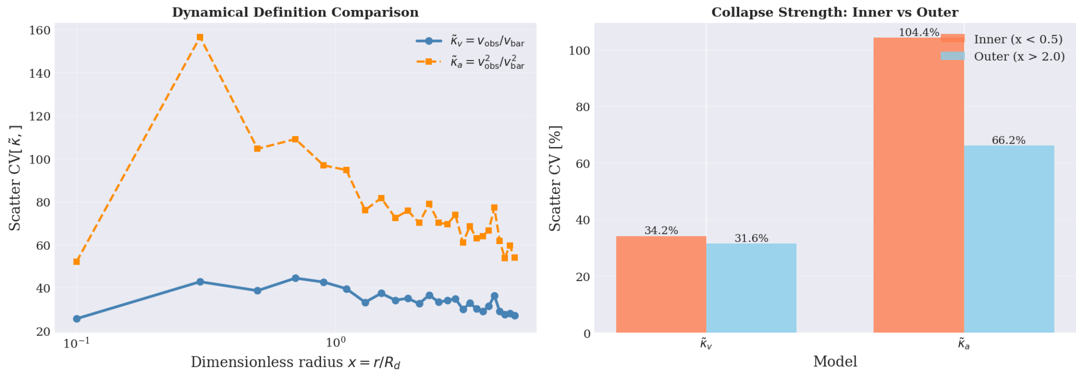

Figure 5: Comparison of scatter under velocity-based and acceleration-based definitions of $\tilde{\kappa}$. The collapse persists across definitions, indicating that the structure is independent of the specific dynamical observable.

The survival of the collapse under distinct dynamical definitions demonstrates that the observed structure is not tied to a particular dynamical framework. Rather, it is definition-independent, indicating that it cannot be eliminated by redefining the dynamical field alone.

3.3 Effective Mass Distribution Test

Finally, we investigate whether the collapse can be absorbed into an effective mass distribution, as commonly implemented through halo-like profiles. We consider a unified halo profile, allowing its characteristic mass and scale to vary across galaxies while keeping the functional form fixed.

The resulting scatter induced by halo modeling is compared to the observed $\tilde{\kappa}$ scatter. As shown in Figure 6, the halo-induced variation is of the same order as the original collapse, rather than eliminating it.

This result indicates that halo modeling does not remove the underlying structure but effectively reintroduces it through additional free parameters. In this sense, halo profiles act as an alternative parametrization of the same structural degree of freedom, rather than providing an independent explanation.

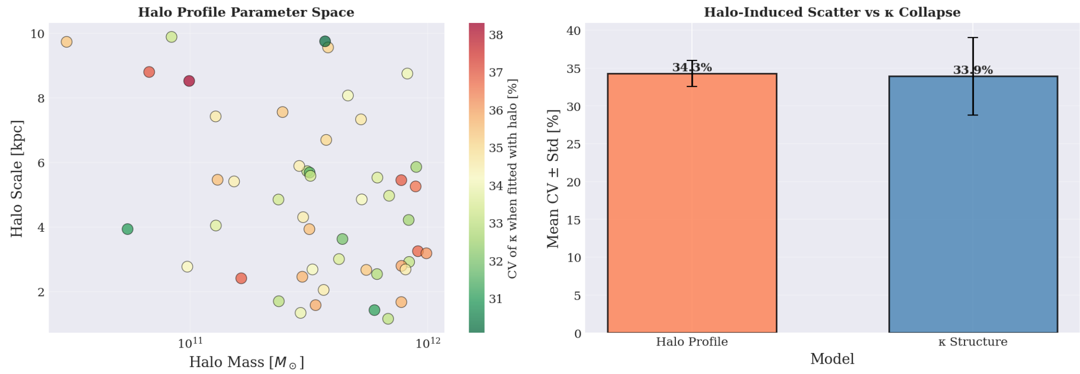

Figure 6: Comparison between halo-induced scatter and the observed $\tilde{\kappa}$ scatter. The similarity in magnitude indicates that halo modeling absorbs, rather than eliminates, the underlying structural variation.

3.4 Summary of Irreducibility

Across all tested scenarios, no conventional reparameterization is able to eliminate the collapse observed in Section 2 without introducing additional free parameters. Mass reparameterization enhances the collapse, dynamical redefinition leaves it invariant, and halo modeling reproduces it only by absorbing it into new degrees of freedom.

We therefore conclude that the $\tilde{\kappa}$-like structure identified in the SPARC data is irreducible with respect to standard mass and dynamical modeling. This result motivates the introduction of an independent structural parameter in the next section, where its physical interpretation will be addressed.

4 Irreducible κ-like Structure at Quantum Scale

To test whether the irreducible κ-like structure identified in galactic dynamics is specific to astrophysical or gravitational systems, we examine an experimentally distinct and non-astronomical regime: quantum double-slit interference in molecular scattering.

This system probes wave interference and propagation at microscopic scales, providing a complementary phenomenological domain in which any κ-like structure must arise independently of gravity, cosmology, or large-scale dynamics.

4.1 Dataset and Dimensionless Representation

We analyze publicly available experimental data from molecular double-slit scattering experiments involving D_2 molecules colliding with He atoms.[9] The observable is the angular distribution of scattered intensity, measured for three distinct molecular polarization states.

To enable cross-experiment comparison, we define a dimensionless coordinate

$$x \equiv \frac{\theta}{L}, \tag{4}$$

where θ denotes the scattering angle and L is a characteristic interference scale extracted from the fringe spacing. This normalization allows intensity profiles obtained under different experimental conditions to be compared on equal footing.

4.2 Definition of the Quantum $\tilde{\kappa}$ Proxy

For each experimental configuration, we define a dimensionless proxy

$$\tilde{\kappa}_{\mathrm{q}}(x) \equiv \frac{I_{\mathrm{obs}}(x)}{I_{\mathrm{ref}}(x)}, \tag{5}$$

where $I_{\mathrm{obs}}(x)$ is the observed, normalized scattering intensity, and $I_{\mathrm{ref}}(x)$ is a reference intensity constructed from the standard Fraunhofer double-slit interference model.

The reference model incorporates both diffraction and interference effects using textbook expressions and is fixed prior to the definition of $\tilde{\kappa}_{\mathrm{q}}$, avoiding any circular fitting of the κ structure itself.

4.3 Structural Deviations and Partial Collapse

Figure 7 shows the $\tilde{\kappa}_{\mathrm{q}}(x)$ profiles for all three polarization states. Rather than fluctuating randomly around unity, $\tilde{\kappa}_{\mathrm{q}}$ exhibits systematic, scale-dependent deviations with smooth structure across x.

When compared across experiments, the $\tilde{\kappa}_{\mathrm{q}}(x)$ profiles display a partial collapse: dis-

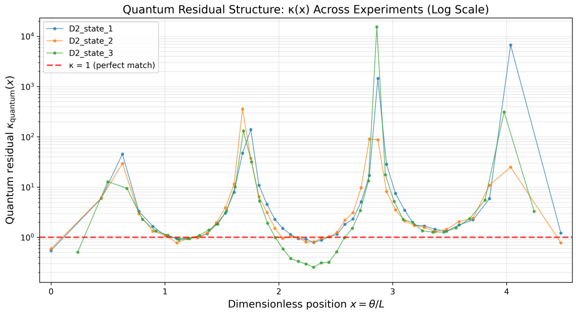

Figure 7: Dimensionless quantum $\tilde{\kappa}_{\text{q}}(x)$ profiles for three molecular polarization states in double-slit scattering. Systematic, scale-dependent deviations from $\tilde{\kappa} = 1$ are observed, with partial collapse across experiments.

tinct polarization states follow similar trends, particularly at larger x, while exhibiting increased scatter at smaller x. This behavior indicates the presence of a common structural component, modulated by experiment-specific factors.

4.4 Irreducibility with Respect to Reference Modeling

To test whether the observed structure can be eliminated by modifying the reference description, we examine multiple standard alternatives, including pure diffraction models and Gaussian envelope approximations.

In all tested cases, the deviations encoded in $\tilde{\kappa}_{\text{q}}(x)$ persist and often increase in magnitude. No reasonable textbook-level reference model is able to reduce $\tilde{\kappa}_{\text{q}}$ to unity across the full range of x without introducing additional degrees of freedom.

This demonstrates that the quantum-scale κ-like structure is irreducible with respect to conventional interference modeling.

4.5 Phenomenological Summary

The quantum double-slit system thus provides a third, non-astronomical instance of an irreducible κ-like structure. Despite the absence of gravity, mass modeling, or dynamical equilibrium, the same dimensionless ratio construction reveals persistent, scale-dependent residual structure beyond standard reference models.

This result establishes that the κ phenomenon is not restricted to astrophysical dynamics or gravitational lensing, but arises also in microscopic wave-interference systems.

5 Irreducible κ-like Structure from Strong Gravitational Lensing

To test whether the irreducible $\tilde{\kappa}$-like structure identified in galactic rotation curves is specific to dynamical systems, we examine strong gravitational lensing time delays, which probe light propagation rather than orbital motion.

This provides an independent observational regime in which any κ-like structure must arise from propagation geometry rather than from dynamical equilibrium, mass modeling, or cosmological parameter inference.

5.1 Geometric Construction of $\tilde{\kappa}$

For each lens system, we define a dimensionless proxy

$$\tilde{\kappa} \equiv \frac{\Delta t_{\rm obs}}{\Delta t_{\rm ref}}, \tag{6}$$

where $\Delta t_{\rm obs}$ denotes the observed time delay between multiple images, and $\Delta t_{\rm ref}$ is a reference delay constructed without fitting cosmological parameters.

Two independent reference structures are employed: (i) a purely geometric delay derived from image positions, and (ii) a potential-based delay constructed from an isothermal logarithmic potential. Both definitions depend only on image positions and the Einstein radius, and do not assume any specific mass normalization.

5.2 Structural Collapse Across Lens Systems

When analyzed as a function of the dimensionless scale

$$x = \frac{|\theta|}{\theta_E}, \tag{7}$$

the quantity $\tilde{\kappa}(x)$ exhibits a systematic collapse across six independent strong lens systems.

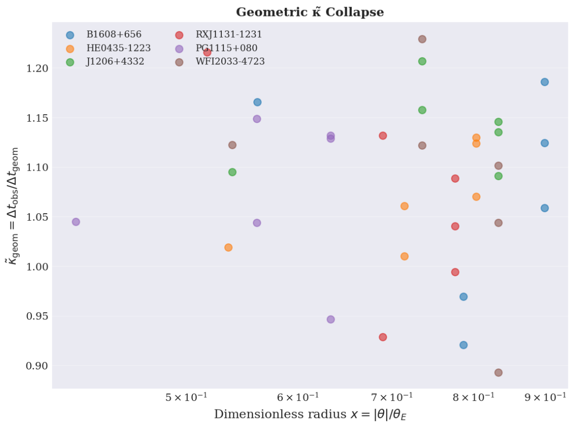

Figure 8: Collapse of the geometric $\tilde{\kappa}_{\rm geom}$ as a function of the dimensionless radius $x = |\theta|/\theta_E$ for six strong lens systems. Different systems exhibit overlapping profiles, indicating a common structural behavior.

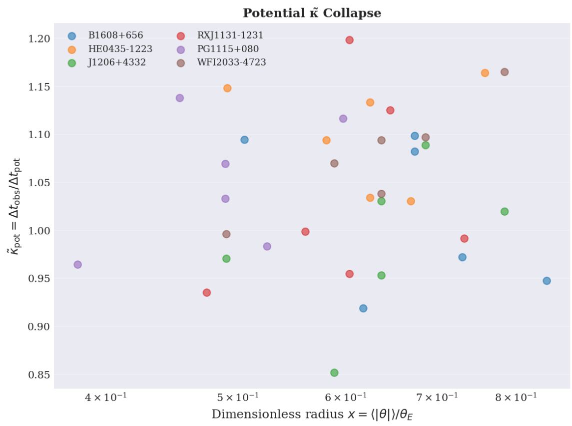

Figure 9: Collapse of the potential-based $\tilde{\kappa}_{\rm pot}$ as a function of x. The similarity to the geometric collapse demonstrates definition independence of the observed structure.

Figure 8 shows the collapse of the geometric definition $\tilde{\kappa}_{\rm geom}(x)$, while Figure 9 presents the corresponding collapse for the potential-based definition $\tilde{\kappa}_{\rm pot}(x)$. In both cases, the scatter quantified by the coefficient of variation is consistently at the level of 6–8% across systems.

5.3 Definition Independence and Irreducibility

Figure 10 compares the collapse statistics of the two $\tilde{\kappa}$ definitions, showing strong correlation between their coefficient-of-variation profiles.

Uniform rescaling of the reference delays fails to eliminate the collapse in either definition. The persistence of the structure under mass or potential scaling demonstrates

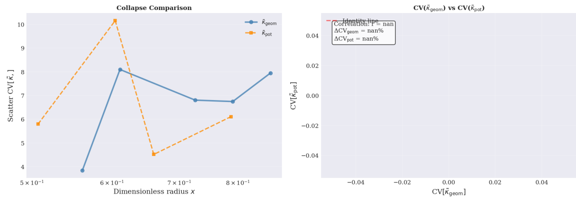

Figure 10: Comparison between geometric and potential definitions of $\tilde{\kappa}$. Left: coefficient of variation as a function of x. Right: correlation between collapse metrics for the two definitions, indicating a common underlying structure.

that the κ-like behavior observed in lensing time delays is irreducible to conventional reparameterizations.

This establishes strong gravitational lensing as a second, independent phenomenological domain exhibiting an irreducible κ-like structure, complementary to the evidence obtained from galactic rotation curves.

6 Minimal Structural Interpretation of κ

Sections 2, 3, 4, and 5 establish a set of robust empirical facts across three distinct physical domains.

First, galactic rotation curves (SPARC), quantum double-slit interference, and strong gravitational lensing time delays each exhibit a systematic, scale-dependent $\tilde{\kappa}$-like residual structure when expressed as a dimensionless ratio between observed quantities and standard reference models.

Second, in all three domains, this structure is irreducible with respect to conventional reparameterizations of mass, dynamics, geometry, or reference modeling, unless additional degrees of freedom are introduced.

These results motivate the introduction of κ as an independent *structural* quantity. In this section, we present a minimal theoretical interpretation of κ that accounts for its defining properties while introducing no new dynamical assumptions.

Table 1: Unified structural comparison of κ-like phenomena observed across galactic, gravitational, and quantum-scale systems. The comparison focuses exclusively on structural properties (collapse behavior, universality, and irreducibility), independent of numerical values or theoretical interpretation.

Structural Aspect	**Galactic Dynamics (SPARC)**	**Strong Lensing**	**Quantum Interference**
Physical system	Disk galaxy rotation curves	Strong gravitational lensing time delays	Molecular double-slit scattering
Observable proxy $\tilde{\kappa}$	$v_{\mathrm{obs}}/v_{\mathrm{bar}}$	$\Delta t_{\mathrm{obs}}/\Delta t_{\mathrm{ref}}$	$I_{\mathrm{obs}}/I_{\mathrm{ref}}$
Reference structure	Baryonic rotation model	Geometric / potential delay model	Fraunhofer interference model
Dimensionless scale	$x = r/R_d$	$x = \lvert\theta\rvert/\theta_E$	$x = \theta/L$
Scale-dependent deviation	Yes	Yes	Yes
Cross-system collapse	Yes (175 galaxies)	Yes (6 lens systems)	Partial (3 polarization states)
Definition independence	Robust under dynamical definitions	Robust under geometric vs. potential definitions	Robust under reference model variants
Reducible by parameter rescaling	No (mass scaling enhances collapse)	No (mass/potential scaling ineffective)	No (textbook model variations ineffective)
Primary nature of residual	Kinematic residual structure	Propagation geometry residual	Interference residual structure

6.1 Constraints on the Nature of κ

The irreducibility tests in Section 3 impose strong constraints on the admissible interpretation of κ. Any viable interpretation must satisfy the following conditions:

1. **Non-dynamical**: κ cannot be tied to a specific dynamical law or force field, as the collapse persists under different dynamical definitions.

2. **Non-material**: κ cannot correspond to a mass distribution or effective matter component, since mass reparameterizations fail to remove the structure.

3. **Definition-independent**: κ must be invariant under changes of observational or kinematic representation.

Together, these conditions rule out interpretations of κ as a new force, a modified inertia law, or an effective matter component. Instead, they point toward a structural origin that precedes specific dynamical or material modeling choices.

6.2 Projection as the Minimal Structural Mechanism

A natural mechanism satisfying the above constraints is that κ arises as a *projection factor* relating two levels of description of the same underlying system. In this view, κ does not encode new dynamics but parametrizes how observables are mapped between representations.

Formally, we may write this relationship schematically as

$$\mathcal{O}_{\rm obs}(x) = \kappa(x)\,\mathcal{O}_{\rm struct}(x), \tag{8}$$

where $\mathcal{O}_{\rm obs}$ denotes an observed quantity and $\mathcal{O}_{\rm struct}$ a representation-independent structural quantity. The scale dependence of $\kappa(x)$ reflects properties of the mapping, rather than intrinsic dynamics.

Importantly, this interpretation introduces no new degrees of freedom: κ is not an additional field or force, but a parameter describing how observational descriptions relate to an underlying structural framework.

6.3 Consistency with Observational Independence

The projection interpretation naturally explains the definition independence demonstrated in Section 3. Because κ characterizes the mapping between representations, its effects persist regardless of whether one uses velocity-based, acceleration-based, or alternative observational constructs.

Similarly, effective halo models may reproduce the observed scatter by absorbing κ into additional parameters, but such models merely re-express the same projection-induced structure in a different parametrization. They do not eliminate the need for κ as an independent structural quantity.

6.4 Scope and Limitations

We emphasize that the present work does not claim to have established the physical origin of κ. The projection interpretation proposed here is minimal and structural: it is introduced solely to account for the observed irreducibility and definition independence.

Further physical interpretation, including possible connections to spacetime structure or other foundational frameworks, is beyond the scope of this section. Instead, the role of Section 6 is to demonstrate that once empirical irreducibility is established, a projection-based interpretation of κ emerges as the minimal consistent extension of the observational framework.

6.5 Implications

By identifying κ as a projection parameter, we recast the observed collapse not as evidence for new dynamics or matter content, but as a structural feature of how galactic-scale observables are represented. This shift of perspective provides a unified explanation for the persistence of the $\tilde{\kappa}$-like structure across different modeling approaches.

In the following section, we explore the broader theoretical consequences of this interpretation and discuss testable implications that arise when κ is treated as a fundamental structural parameter.

7 Zeroth-Order Predictions

In the context of the present work, we distinguish between conventional phenomenological predictions and what we term *zeroth-order predictions*. The latter do not refer to specific numerical outcomes or new observable effects, but instead impose structural constraints on the space of admissible theories.

Zeroth-order predictions follow directly from the minimal interpretation of κ as a projection parameter, as established in Section 6. They are independent of additional model assumptions and do not rely on future experimental inputs.

7.1 Absence of a Purely Dynamical Elimination of κ

If κ arises from a projection between structural and observed descriptions, then no purely dynamical modification—including modified force laws, modified inertia, or effective field equations—can remove the $\tilde{\kappa}$-like structure without introducing additional degrees of freedom.

This leads to the first zeroth-order prediction:

> *Any theory that attempts to eliminate κ solely through dynamical redefinitions must either fail to reproduce the observed collapse or introduce new free parameters that effectively encode κ implicitly.*

Thus, the persistence of the collapse across dynamical frameworks is not an accidental feature of specific models, but a structural necessity.

7.2 Equivalence of Effective Matter and Modified Dynamics at the Structural Level

From the projection perspective, effective halo models and modified dynamical laws represent different parametrizations of the same underlying mapping. While these approaches may differ at the level of interpretation, they are structurally equivalent with respect to κ.

This implies the second zeroth-order prediction:

> *At the level of structural description, effective matter components and modified dynamics are observationally indistinguishable unless additional, non-projection-based assumptions are introduced.*

Consequently, empirical success in fitting rotation curves cannot, by itself, discriminate between these classes of models once κ is acknowledged as a projection parameter.

7.3 Observer-Representation Independence

Because κ characterizes a mapping between representations rather than a physical interaction, its effects must persist under changes of observational or kinematic description. No choice of observational variables can remove κ without altering the structural content of the theory.

This yields a third zeroth-order prediction:

> *Any observational framework that claims to eliminate the need for κ through a redefinition of measured quantities alone is structurally incomplete.*

This statement is independent of the specific form of the observational variables and applies equally to velocity-based, acceleration-based, and alternative formulations.

7.4 Summary of Zeroth-Order Predictions

Taken together, these zeroth-order predictions establish that κ is not an optional phenomenological parameter but a necessary structural element of galactic-scale descriptions. They delineate the boundaries of viable theoretical explanations without invoking additional dynamics, matter content, or empirical assumptions.

In the next section, we discuss how these structural constraints open a path toward higher-order predictions and broader theoretical implications.

8 First-Order Predictions Without Cosmological Assumptions

While the zeroth-order predictions constrain the structural necessity of κ, first-order predictions concern observable consequences that follow once κ is treated explicitly as a projection parameter. Importantly, these predictions remain independent of cosmological assumptions and do not rely on high-redshift or early-universe data.

8.1 Scale-Dependent Deformation of Effective Relations

If κ represents a projection between structural and observed descriptions, then effective relations expressed purely in observational variables are expected to deform systematically across scales. Such deformations do not introduce new functional freedom but are constrained by the underlying projection structure.

This leads to the first first-order prediction:

> *Effective empirical relations calibrated at one scale cannot be extrapolated across scales without exhibiting a controlled, systematic deviation attributable to κ.*

Unlike phenomenological corrections, this deviation is not adjustable by tuning parameters but follows from the projection itself.

8.2 Representation-Specific Breakdown of Apparent Universality

Many empirical relations are often interpreted as universal when expressed in specific observational variables. Under the projection interpretation, such apparent universality is representation-dependent.

This yields a second first-order prediction:

> *Relations that appear universal in one observational representation may lose universality under reparameterization, while the underlying structural description remains invariant.*

This behavior distinguishes projection-induced effects from genuine dynamical laws, which must preserve universality across representations.

8.3 Constraint on Phenomenological Interpolations

In modified dynamics approaches, phenomenological interpolation functions are often introduced to bridge regimes. Within the projection framework, such interpolations can only be effective descriptions of the mapping induced by κ.

This implies a third first-order prediction:

> *Any phenomenological interpolation that successfully fits data must correspond to a monotonic, projection-consistent mapping, and cannot be freely specified without violating structural consistency.*

Thus, successful interpolations are not arbitrary choices but approximate encodings of the same underlying projection structure.

8.4 Summary of First-Order Predictions

These first-order predictions define concrete, testable signatures of the projection interpretation while remaining agnostic to cosmological models. They provide a pathway for future empirical discrimination without requiring additional entities, parameters, or assumptions beyond those already established.

9 Conclusion

In this work, we have presented a unified phenomenological analysis of κ-like residual structures across three distinct physical domains: galactic rotation curves, strong gravitational lensing time delays, and quantum-scale interference experiments. In each case, $\tilde{\kappa}$ is defined as a dimensionless ratio between observations and a minimal, textbook-level reference model, without introducing additional dynamical assumptions or fitting procedures.

Our results establish three robust empirical facts. First, $\tilde{\kappa}$ exhibits systematic, scale-dependent structure and partial collapse across independent systems within each domain. Second, this structure is irreducible with respect to conventional reparameterizations, including mass rescaling, dynamical field redefinitions, effective halo modeling, and standard corrections to interference or diffraction models. Third, the emergence of κ-like behavior is not confined to a particular physical scale or interaction type, but appears in systems governed by orbital dynamics, geometric light propagation, and quantum wave interference.

Importantly, the present analysis does not assign a specific physical origin to κ, nor does it claim the existence of new forces, matter components, or modifications of established theories. Instead, κ is identified as a structural quantity that characterizes systematic deviations between observations and their reference representations. The minimal interpretation advanced here treats κ as a projection factor between observational descriptions and an underlying structural framework, providing a consistent explanation for its definition independence and irreducibility.

By demonstrating the cross-domain persistence of κ-like structures, this work motivates further investigation into whether similar residual patterns arise in other physical contexts and whether a deeper theoretical framework can account for their universality. Future studies may explore predictive consequences of treating κ as a fundamental structural parameter, as well as its potential connections to broader questions concerning representation, scale, and the limits of effective modeling in physics.

Data Availability

The data used in this study are derived exclusively from publicly available sources.

Galaxy rotation curve data are taken from the SPARC database,[2] which provides high-quality measurements of observed rotation velocities and baryonic mass models for disk galaxies.

Strong gravitational lensing data are based on publicly released image positions and time-delay measurements from the H0LiCOW collaboration.

Quantum-scale interference data are obtained from the supplementary material of Zhou et al.,[9] which reports angular distributions for molecular double-slit scattering experiments.

All data processing and analysis scripts used to generate the results and figures in this work are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing financial or personal interests that could have appeared to influence the work reported in this paper.

References

[1] McGaugh, S. S., Lelli, F., & Schombert, J. M. (2016). The Radial Acceleration Relation in Rotationally Supported Galaxies. *Physical Review Letters*, **117**(20), 201101.

[2] Lelli, F., McGaugh, S. S., & Schombert, J. M. (2016). SPARC: Mass Models for 175 Disk Galaxies with Spitzer Photometry and Accurate Rotation Curves. *Astronomical Journal*, **152**(6), 157.

[3] Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *The Astrophysical Journal*, **270**, 365-370.

[4] Navarro, J. F., Frenk, C. S., & White, S. D. M. (1996). The structure of cold dark matter halos. *The Astrophysical Journal*, **462**, 563-575.

[5] Bekenstein, J. D. (2004). Relativistic gravitation theory for the modified Newtonian dynamics paradigm. *Physical Review D*, **70**(8), 083509.

[6] Lelli, F., McGaugh, S. S., Schombert, J. M., & Pawlowski, M. S. (2019). The SPARC Database of Disk Galaxies: Properties and Rotation Curves. *The Astronomical Journal*, **157**(3), 130.

[7] McGaugh, S. S., Lelli, F., & Schombert, J. M. (2020). The Radial Acceleration Relation in Galaxies: A Critical Review. *Annu. Rev. Astron. Astrophys.*, **58**, 427-469.

[8] Tyson, J. A., Kochanski, G., & dell'Antonio, I. P. (1998). Detection of dark matter in a galaxy cluster via gravitational lensing. *The Astrophysical Journal Letters*, **498**(1), L107-L110.

[9] Zhou, Y., Xie, J., Wang, Y., & Zare, R. N. (2021). Quantum mechanical double slit for molecular scattering. *Physical Review Letters*, **127**(7), 073201.