A Minimal Relational Ontological Foundation for Physics

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Date: January 2026
Version: 1.0

Abstract

We present a minimal relational ontological framework intended as a foundation for physical description. The framework does not modify empirically validated predictions of existing physical theories in their tested regimes, but instead addresses the lack of a shared ontological ground between General Relativity and Quantum Mechanics.

The approach eliminates fundamental assumptions of time, space, dynamics, and probability, replacing them with a relational structure in which stable physical entities arise as equivalence classes of relational configurations. Time, space, probability, and dynamics are introduced strictly as bookkeeping structures over repeated realizations.

General Relativity and Quantum Mechanics are treated as effective descriptions that emerge under specific structural and representational conditions, rather than as fundamental ontological theories. The framework is explicitly falsifiable through well-defined deviations in strong-gravity regimes, where it makes predictions that differ from those of General Relativity while remaining consistent with all existing observations.

No claim of unification or completion is made.

1. Introduction

General Relativity and Quantum Mechanics constitute the two most empirically successful physical theories currently available. Despite their predictive accuracy, they rest on fundamentally different conceptual foundations. General Relativity treats spacetime geometry as primary, while Quantum Mechanics relies on probabilistic structure, superposition, and measurement postulates.

The tension between these theories is often presented as a technical problem requiring new dynamical laws or quantization procedures. However, this work adopts the position that the conflict is primarily ontological rather than empirical. The theories do not merely employ different mathematics; they presuppose incompatible notions of what constitutes physical reality.

Attempts at reconciliation frequently proceed by modifying one theory to resemble the other, for example by quantizing spacetime or geometrizing quantum dynamics. Such approaches risk importing unexamined assumptions rather than resolving them.

This paper pursues a different strategy. Instead of proposing new dynamics or modifying existing theories, we seek a minimal ontological foundation capable of supporting both General Relativity and Quantum Mechanics as effective descriptions, without privileging either as fundamental.

The goal is not to unify these theories, but to clarify the structural conditions under which each becomes applicable, and to provide a common ground in which their coexistence does not entail contradiction.

This paper explicitly does not attempt to:

- derive the full formalism of either theory,
- propose new interaction terms or fields,
- resolve all open problems in quantum gravity.

Its scope is restricted to foundational structure.

2. Ontological Requirements

Any acceptable ontological foundation for physics must satisfy a small set of non-negotiable requirements.

First, it must be minimal. Each primitive assumption must be necessary, and no structure should be introduced solely to recover known results.

Second, it must avoid assuming as fundamental those concepts whose status is under question. In particular, time, space, dynamics, and probability must not be taken as primitive, as their foundational roles differ sharply between existing theories.

Third, the framework must be empirically compatible. It must allow existing successful theories to remain valid in their tested regimes, even if they are reinterpreted as effective descriptions.

Fourth, it must be falsifiable. The framework must make clear claims whose failure would rule it out, rather than accommodate all possible outcomes.

Force-based ontologies and geometry-first ontologies are insufficient at the foundational level. Forces presuppose interaction laws without explaining their origin, while geometric ontologies presuppose spacetime structure whose operational meaning is theory-dependent.

A viable foundation must therefore precede both force and geometry, providing a substrate from which they can emerge as bookkeeping descriptions rather than primitives.

3. Relational Ontological Foundation

The foundational assumption of this framework is that physical reality is composed of relational possibilities rather than objects embedded in space and time.

A relational possibility is defined as a structurally specified configuration that may or may not be realized. No assumption is made about when or where such a configuration occurs.

A preorder relation is introduced on the set of relational possibilities, encoding structural compatibility. This relation does not represent causation, distance, or interaction strength. It only specifies whether relational configurations can coexist without contradiction.

Stable physical entities are not taken as substances. Instead, identity is defined as an equivalence class of relational possibilities that can be repeatedly realized without structural change. Stability is a relational property, not an intrinsic one.

This definition of identity is intentionally non-substantival. What persists is not an object, but a pattern of relations that remains structurally invariant under repeated realization.

At this ontological level, there is:

- no time,
- no space,
- no dynamics,
- no probability.

These concepts are introduced only later, as bookkeeping structures required to describe patterns of realization.

4. Repetition, Counting, Frequency, and Probability

At the ontological level defined in Section 3, no notion of time, sequence, or dynamics is assumed. Nevertheless, relational possibilities may be realized repeatedly. Repetition is defined purely structurally: a relational configuration is said to repeat if successive realizations are structurally equivalent, independent of any temporal metric.

Counting is introduced as a bookkeeping operation over repetitions. It does not presuppose time or duration, only distinguishability of realizations. Given a stable identity defined as an equivalence class of relational possibilities, one may count the number of times this identity is realized relative to others.

Frequency is defined as the ratio of counts within a given bookkeeping domain. Importantly, frequency is not an intrinsic property of the identity, but a relational statistic derived from repeated realizations.

Probability is then defined as expected frequency in the limit of large repetition. This definition avoids introducing probability as a primitive or subjective concept. Probability does not describe what will occur, but how often structurally equivalent identities are realized under comparable conditions.

At no point does probability enter the ontology. It is an accounting tool required to summarize regularities in repetition. This distinction is essential for later interpretation of quantum phenomena.

5. Time as Ordering

Time is not introduced as a fundamental flowing quantity. Instead, it is defined as an ordering relation over realizations.

Given repeated realizations of relational possibilities, one may introduce an order relation that distinguishes “earlier” and “later” realizations. This ordering is sufficient to define sequences, correlations, and conditional descriptions, without invoking duration or an external clock.

The framework therefore rejects the notion of time as an independent background parameter. What is fundamental is only the ordering of realizations, not the rate at which they occur.

Effective temporal metrics arise only when realization rates vary across relational contexts. Such metrics are secondary constructs used to compare different orderings, not ontological primitives.

This approach allows time to function consistently across both quantum and relativistic descriptions, without requiring it to be quantized or geometrized at the foundational level.

6. Space as Relational Difference

Space is introduced as a bookkeeping structure that quantifies relational difference between stable identities.

No assumption is made that identities are embedded in a pre-existing spatial manifold. Instead, spatial relations emerge as structured measures of difference between relational configurations.

Distance is not a primitive length, but a parameter summarizing how relational compatibility changes between identities. Motion is described as an ordered change in relational difference across successive realizations.

In this view, spatial structure is descriptive rather than constitutive. It encodes how relational configurations differ, not where objects are located.

This interpretation allows spatial geometry to emerge as an effective description in regimes where relational differences vary smoothly, while remaining agnostic about geometry at the ontological level.

7. Measurement

Measurement is defined as the establishment of a new stable relational identity through coupling.

A measurement interaction does not reveal a pre-existing value, nor does it require a fundamental collapse process. Instead, it corresponds to a transition in the relational bookkeeping: previously distinct relational possibilities become correlated in such a way that a new equivalence class is formed.

This process alters the accounting of realizations, frequencies, and probabilities, but does not modify the underlying ontology. What changes is not reality itself, but the set of stable identities used to describe it.

This interpretation eliminates the need for collapse as a physical mechanism, while preserving the empirical content of measurement outcomes. Measurement is a structural event in the relational network, not a special dynamical intervention.

8. Mathematical Formalization

The relational ontological foundation can be expressed using minimal formal structure.

8.1 Basic Structure

Let R denote the set of relational possibilities. A preorder relation $\preceq \subseteq R \times R$ is defined on R, encoding structural compatibility. This relation is:

- Reflexive: $r \preceq r$ for all $r \in R$
- Transitive: if $r_1 \preceq r_2$ and $r_2 \preceq r_3$, then $r_1 \preceq r_3$

The relation is not necessarily antisymmetric, allowing distinct relational possibilities to be mutually compatible.

8.2 Equivalence and Identity

An equivalence relation ~ is induced on R by:

$$r_1 \sim r_2 \Leftrightarrow (r_1 \preceq r_2) \wedge (r_2 \preceq r_1)$$

This relation is reflexive, symmetric, and transitive. Stable identities are defined as equivalence classes:

$$i = [r] = \{r' \in R : r' \sim r\}$$

Let $I = R/\sim$ denote the quotient space of stable identities.

8.3 Projection

A canonical projection map exists:

$$\Pi : R \to I \Pi(r) = [r]$$

This projection associates each relational possibility with its corresponding stable identity. It is surjective by construction.

8.4 Counting and Frequency

Realizations are organized as a multiset over I. For each identity $i \in I$, define:

$$N(i) \in \mathbb{N}$$

as the multiplicity of i in the multiset of realizations.

Frequency is defined as:

$$f(i) = N(i) / \Sigma_j N(j)$$

where the sum is taken over all realized identities in the bookkeeping domain.

8.5 Compatibility Function

For relational contexts requiring quantitative compatibility assessment, a compatibility function may be defined:

$$C : I \times I \to \mathbb{R}$$

This function quantifies structural compatibility between stable identities. It is not a metric and need not satisfy triangle inequality. Its properties are determined by the relational structure of R and the equivalence relation ~.

8.6 Structural Invariance

The key requirement is that all physically observable quantities must be expressible in terms of:

- Equivalence classes in I
- Counting functions N(i)
- The compatibility structure C

No reference to specific representatives $r \in R$ should appear in physical predictions. This ensures representation-independence at the ontological level.

9. Emergent Dynamics

Although no fundamental dynamics is postulated, effective dynamical descriptions arise when realization frequencies vary systematically across relational contexts.

Let f(i) denote the frequency of realization of identity i. When f(i) varies smoothly over a structured subset of identities, it becomes possible to describe changes in frequency as if they were generated by an effective dynamical law.

Such laws do not govern motion in an ontological sense. Instead, they summarize how realization patterns change under repeated ordering. Apparent trajectories correspond to sequences of identities with correlated realization frequencies.

This interpretation reverses the usual explanatory order: motion is not fundamental, but inferred from regularities in realization. Dynamics is therefore an emergent bookkeeping description, valid only insofar as these regularities persist.

10. Gravitation

Gravitation is introduced without assuming force or spacetime curvature as fundamental concepts.

The compatibility function $C : I \times I \to \mathbb{R}$ introduced in §8.5 quantifies structural compatibility between stable identities. Gradients in C correspond to systematic variations in realization frequency.

In regimes where these gradients are smooth and vary slowly, they may be represented by an effective potential V, yielding equations of motion formally equivalent to Newtonian gravity or geodesic motion in curved spacetime.

The parameter τ appearing in dynamical equations is an ordering parameter (as defined in §5), not fundamental time. The resulting dynamics is therefore an effective description of how realization frequencies are distributed, not a law governing underlying motion.

10.1 Weak-Field Limit

In weak compatibility gradients, where $|\nabla C|$ is small and varies slowly, the framework reproduces Newtonian gravitational dynamics to first order. Specifically, variations in realization rate give rise to an effective potential:

$$V(x) \propto \int \nabla C \cdot dx$$

Objects follow trajectories that maximize cumulative realization frequency, which in the smooth limit corresponds to geodesic motion.

10.2 Strong-Field Behavior

The framework predicts deviations from General Relativity in strong compatibility gradients, as detailed in §11. These deviations arise not from modifications to geometry, but from the fundamental requirement that realization rates remain finite bookkeeping quantities.

This interpretation reproduces the empirical content of gravitational phenomena while assigning them a fundamentally relational origin.

11. Time Dilation, Strong-Gravity Regimes, and Observational Implications

In the present framework, effective time is defined through the local realization rate associated with a given relational context. Let τ denote an abstract ordering parameter over realizations. The locally experienced effective time t is defined via:

$$dt = \kappa(x)\, d\tau$$

where $\kappa(x)$ represents the local realization rate.

Variations in $\kappa(x)$ lead to effective time dilation. In regimes where compatibility gradients are weak and vary smoothly, this formulation reproduces the standard predictions of General Relativity to first order. In particular, gravitational redshift and differential clock rates emerge as consequences of spatial variation in realization rate, not as modifications of temporal ontology.

11.1 Divergence in General Relativity and Its Interpretation

In classical General Relativity, gravitational time dilation and redshift diverge as one approaches the event horizon of a black hole, as encoded in the vanishing of the metric component g_{tt}. Within the present framework, this divergence is interpreted not as a necessary physical effect, but as a consequence of extrapolating an effective description beyond the regime where its underlying bookkeeping assumptions remain valid.

Specifically, the divergence arises from treating the realization rate as unboundedly reducible. The relational framework does not assume this. Since realization rates are bookkeeping quantities associated with the establishment of stable relational identities, they are required to remain finite.

11.2 Realization-Rate Saturation

The framework therefore predicts that in sufficiently strong compatibility gradients, the realization rate $\kappa(x)$ reaches a finite lower bound. This saturation of realization rate implies:

- finite gravitational redshift,
- finite time dilation,
- absence of true divergence at or near horizons.

Importantly, this saturation is not introduced to resolve singularities or to modify spacetime geometry. It follows from the requirement that realization rates remain finite accounting quantities within the relational bookkeeping scheme.

Time does not "stop" in strong-gravity regimes. Rather, the rate at which realizations can be accounted for reaches a minimum.

11.3 Observational Regimes and Consistency with Existing Data

The predicted saturation occurs in regimes that are currently only weakly constrained by observation. Existing data do not exclude this behavior.

Event Horizon Telescope (EHT):EHT observations probe the photon sphere and exterior lensing structure of compact objects. They do not directly test near-horizon redshift divergence. Finite saturation occurring inside the photon sphere is therefore consistent with current EHT images.

Gravitational Wave Ringdown (LIGO/Virgo/KAGRA):Ringdown signals are sensitive to the near-horizon structure of compact objects. Present observations are consistent with General Relativity but do not yet exclude weak or rapidly damped deviations associated with finite realization-rate saturation. No definitive evidence for or against saturation is currently available.

Extreme Mass Ratio Inspirals (EMRIs):EMRIs, particularly as targeted by future space-based detectors such as LISA, provide a critical test domain. The framework predicts that realization-rate saturation would manifest as systematic deviations from GR-based waveform templates in the late inspiral phase.

11.4 Status of the Prediction

At present, the saturation of realization rate is a phenomenological prediction, not a fitted result. No numerical value for the saturation scale is specified within the framework. The theory constrains where such saturation may occur relative to observable structures (e.g.

below the photon sphere and above scales already excluded by ringdown observations), but does not yet compute its magnitude.

This is an intentional limitation. The framework provides the structural conditions under which saturation arises, while leaving its quantitative determination to future theoretical development and empirical constraint.

11.5 Falsification Conditions

The framework is falsified if any of the following are established:

1. Empirical confirmation of unbounded gravitational redshift arbitrarily close to horizons.
2. Strong-gravity observations conclusively incompatible with any finite realization-rate saturation.
3. Demonstration that finite realization rates necessarily violate weak-field gravitational tests already confirmed experimentally.

Conversely, observation of finite near-horizon effects would support the framework while remaining compatible with all currently tested regimes.

12. Relation to General Relativity

General Relativity is recovered within the present framework as an effective description valid in regimes where compatibility gradients are smooth and realization rates vary slowly. In such regimes, the bookkeeping structures introduced to describe relational differences and ordering reproduce the operational content of spacetime geometry.

The framework does not reinterpret General Relativity as incorrect, nor does it modify its field equations in tested domains. Instead, it assigns General Relativity a secondary status: spacetime geometry is not fundamental, but an effective representation of how realization rates and relational differences are distributed.

Crucially, the framework departs from General Relativity only in regimes where the latter extrapolates beyond its empirically tested domain. In particular, near-horizon behavior is treated differently. Where General Relativity predicts unbounded time dilation and redshift, the present framework predicts saturation of realization rates.

This difference is not semantic but physical, and it provides a clear criterion for empirical distinction. Until such regimes are probed with sufficient precision, General Relativity remains an excellent effective theory.

13. Relation to Quantum Mechanics

Quantum Mechanics is interpreted as a probabilistic bookkeeping framework describing the frequencies of realization of relational identities when multiple relational possibilities contribute to the same stable identity.

Superposition corresponds to the coexistence of relational possibilities prior to stabilization. Probability amplitudes do not describe physical waves or hidden variables, but encode bookkeeping structures required to account for interference consistently and representation-independently.

Measurement is not treated as a fundamental collapse process. Instead, it is the formation of a new stable relational identity through coupling, which alters the accounting of realizations without modifying the underlying ontology.

13.1 Derivation of the Born Rule

The Born rule—that probability is proportional to the square of the amplitude—is not postulated but emerges as a consequence of representation-independence in the presence of interference.

Setup:Consider multiple relational possibilities r_1, r_2, ..., r_n that project to the same stable identity:

$\Pi(r_1) = \Pi(r_2) = \ldots = \Pi(r_n) = i$

If these possibilities are indistinguishable after projection but contribute differentially to the realization of i, we require a representation that can account for both constructive and destructive interference.

Representation Requirements:

1. Combination of contributions must be associative (grouping should not affect results)
2. Contributions can be enhancing or suppressing (interference)
3. Final probability must be independent of how contributions are grouped (representation-independence)

Why Linear Summation Fails:

If we assign weights directly and sum them, regrouping changes the result. Consider three possibilities with contributions +5, -3, +2:

- Direct sum: |5| + |-3| + |2| = 10
- Grouped: |5-3| + |2| = 2 + 2 = 4

This violates representation-independence.

Why Squared Norm Succeeds:

If contributions combine linearly in a representation space (forming a “total contribution” B), and probability is defined as:

$P \propto |B|^2$

Then for B = 5 - 3 + 2 = 4:

- Direct: $|4|^2 = 16$
- Grouped: $|(5-3) + 2|^2 = |4|^2 = 16$

The result is invariant under regrouping.

Generalization:

For any set of contributions that combine linearly, the only rule that ensures:

- Additivity for mutually exclusive outcomes
- Invariance under regrouping of contributions
- Smooth behavior under continuous variation

is proportionality to squared norm: $P(i) \propto |\Sigma c_j|^2$

This is precisely the Born rule. It emerges not as a postulat but as the unique representation-independent way to compute probabilities when interference is present.

13.2 Status of Quantum Mechanics

The framework does not attempt to derive the full Hilbert space formalism of Quantum Mechanics. It only claims that, when interference and representation independence are required, the standard probabilistic structure of Quantum Mechanics emerges as the unique consistent bookkeeping scheme.

Quantum Mechanics therefore remains valid and complete within its domain of applicability, while its conceptual tensions are relocated from ontology to representation.

14. Falsifiability

The framework is explicitly falsifiable. It makes concrete claims that can be tested independently of interpretational preference.

The framework is ruled out if any of the following are established empirically:

1. Demonstration of unbounded gravitational time dilation or redshift arbitrarily close to horizons.
2. Precise observation of strong-gravity phenomena incompatible with any finite saturation of realization rates.
3. Experimental necessity of fundamental wavefunction collapse as a physical process.
4. Incompatibility between finite realization rates and empirically verified weak-field gravitational phenomena.
5. Discovery of a representation-independent interference phenomenon that cannot be described by squared-norm probability rules.

Conversely, confirmation of finite near-horizon effects would support the framework while remaining compatible with existing observations.

Falsifiability is therefore not an auxiliary feature, but a structural property of the proposal.

15. Discussion

The framework presented here is deliberately minimal. It does not attempt to provide a complete dynamical theory, nor does it introduce new fundamental entities or forces. Its purpose is to clarify the ontological status of concepts that are treated inconsistently across existing theories.

By separating ontology from bookkeeping, the framework allows Quantum Mechanics and General Relativity to coexist without contradiction. Their apparent incompatibility is shown to arise from competing foundational assumptions rather than empirical conflict.

Several open questions remain. In particular, the detailed structure of the compatibility function and its relation to known interaction patterns is not specified. This omission is intentional, as premature specification would compromise the framework's generality.

The derivation of the Born rule (§13.1) demonstrates that key quantum-mechanical features emerge from representation-theoretic requirements rather than physical postulates. This suggests that other aspects of quantum formalism may similarly emerge from structural consistency conditions.

The predicted saturation of realization rates in strong-gravity regimes (§11) provides a concrete empirical distinction from General Relativity, testable by future gravitational wave observations and extreme-mass-ratio inspiral studies.

The framework should therefore be understood as a foundation upon which further theoretical development may proceed, not as a final theory.

16. Conclusion

A minimal relational ontological foundation has been presented in which physical reality consists of relational possibilities whose stable equivalence classes define identity.

Time, space, probability, dynamics, and gravitation are shown to arise as bookkeeping structures over repeated realization, rather than as fundamental constituents of reality.

Within this framework, Quantum Mechanics and General Relativity emerge as effective descriptions applicable under specific structural conditions. Their empirical success is preserved, while their ontological tension is resolved by reassigning them to different representational roles.

The framework makes no claim of unification or completeness. It offers instead a disciplined foundation that is empirically compatible, conceptually explicit, and falsifiable.

Acknowledgments

AI Assistance Disclosure

This project was developed with the aid of multiple large language models used as analytical and editorial tools.

The following systems contributed in complementary roles:

- Claude (Anthropic): structural argumentation, mathematical consistency checks
- Nova (OpenAI): ontological analysis, falsifiability stress-testing, strong-gravity regime critique
- Jarvis (OpenAI): logical compression, adversarial review of assumptions
- Gemini (Google DeepMind): cross-framework comparison and redundancy analysis

All scientific responsibility rests entirely with the human author. No AI system is listed as an author, and no results are claimed on the authority of AI output.

Appendix A: Born Rule Derivation (Detailed)

A.1 Motivation

The Born rule states that the probability of measuring outcome i is proportional to $|\psi_i|^2$, where ψ_i is the quantum amplitude associated with that outcome. In standard quantum mechanics, this is introduced as a postulate. Here we show it emerges necessarily from representation-theoretic consistency requirements.

A.2 The Interference Problem

Consider a situation where a single stable identity i can be realized through multiple indistinguishable pathways. In the relational framework:

- Multiple $r_1, r_2, \ldots, r_n \in R$ all satisfy $\Pi(r_j) = i$
- Each is realized with some frequency
- The pathways cannot be distinguished operationally

The question is: how do we compute the total probability for identity i?

A.3 Naive Counting Fails

A naive approach would be to count each pathway separately:

$P\_naive(i) = \Sigma_j P(r_j)$

But this fails to account for interference. Pathways can enhance or suppress each other's contributions, depending on their relative "phase" or orientation in the relational structure.

A.4 Representation with Orientation

To handle interference, we must introduce a representation that allows contributions to have orientation. As established in the main text (§8), we require:

1. An oriented representation space where contributions can be positive or negative (or more generally, have phase)
2. Associative combination: grouping pathways differently shouldn't change physics
3. Linear combination in the representation: $c(r_1 \oplus r_2) = c(r_1) + c(r_2)$

This leads to representing each pathway r_j by a contribution c_j in an oriented space.

A.5 The Grouping-Invariance Argument

Suppose three pathways contribute $c_1 = +5$, $c_2 = -3$, $c_3 = +2$ to the same identity i.

Attempt 1: Sum absolute values

$P_1 = |c_1| + |c_2| + |c_3| = 5 + 3 + 2 = 10$

Now regroup: $(c_1 + c_2)$ and c_3 separately:

$P_1' = |c_1 + c_2| + |c_3| = |2| + |2| = 4$

Result depends on grouping: INCONSISTENT

Attempt 2: Square of the sum

Total contribution: $C = c_1 + c_2 + c_3 = 5 - 3 + 2 = 4$

$P_2 = |C|^2 = 16$

Regrouped: $C' = (c_1 + c_2) + c_3 = 2 + 2 = 4$

$P_2' = |C'|^2 = 16$

Result is independent of grouping: CONSISTENT

A.6 General Proof

Theorem: If probabilities must be:

1. Non-negative
2. Additive for exclusive alternatives
3. Invariant under regrouping of indistinguishable contributions
4. Continuous in the contributions

Then $P \propto |\Sigma c_j|^2$ is the unique solution.

Sketch:

- Requirement (1) eliminates linear forms
- Requirement (3) demands the probability depends only on the total contribution $C = \Sigma c_j$
- Requirements (2) and (4) together with homogeneity demand P(C) = k|C|^n for some k > 0, n > 0
- Additivity for orthogonal contributions (no interference) requires n = 2

Therefore $P \propto |C|^2$, which is the Born rule.

A.7 Connection to Hilbert Space

The above derivation uses only:

- Oriented contributions (which can be represented as complex numbers or vectors)
- Linear combination
- Representation-independence

This is precisely the minimal structure of a Hilbert space. The Born rule emerges because squared norm is the only grouping-invariant, continuous, homogeneous probability measure on such a space.

No additional quantum postulates are needed. The structure is forced by consistency.

Appendix B: Observational Implications

B.1 Near-Term Tests (2025-2030)

Gravitational Wave Astronomy:

Current LIGO/Virgo/KAGRA observations of binary black hole mergers provide ringdown signals that are consistent with General Relativity. However, these observations do not yet have sufficient signal-to-noise ratio in the late ringdown phase to distinguish between GR and models with finite near-horizon saturation.

The framework predicts:

- Ringdown frequencies consistent with GR
- Possible weak damping deviations in late-time ringdown
- No change to inspiral waveforms in weak-field regime

Action items:

- Template development for saturation-modified ringdown
- Fisher matrix analysis for parameter estimation
- Comparison with stacked ringdown observations

B.2 Medium-Term Tests (2030-2040)

LISA Mission:

The Laser Interferometer Space Antenna (LISA), planned for launch in the mid-2030s, will observe:

- Supermassive black hole mergers
- Extreme mass ratio inspirals (EMRIs)

EMRIs are particularly sensitive to near-horizon structure because the small body completes many orbits in the strong-field regime before merger.

The framework predicts:

- Deviations from GR-based waveform templates in the late inspiral phase
- Specific phase accumulation differences proportional to time spent in strong-gravity regime
- Magnitude depends on saturation scale (currently unspecified)

Required work:

- Numerical calculation of saturation-modified geodesics
- Waveform generation for EMRIs under finite κ_{min}
- Parameter estimation studies

B.3 Long-Term Tests (2040+)

Next-Generation Ground-Based Detectors:

Einstein Telescope and Cosmic Explorer will provide:

- Much higher signal-to-noise ratios
- Sensitivity to higher-frequency ringdown modes
- Ability to stack many observations for statistical tests

Precision Black Hole Spectroscopy:

If realization-rate saturation exists, it would modify the quasi-normal mode spectrum of black holes. With sufficient precision, this would be detectable as:

- Frequency shifts in overtones
- Modified damping times
- Correlations between mass, spin, and deviation magnitude

B.4 Quantum Tests

While the framework’s primary empirical distinction from GR appears in strong gravity, the Born rule derivation (§13, Appendix A) also makes testable claims:

Claim: Any interference phenomenon, regardless of physical substrate, must follow squared-norm probability rules if it satisfies representation-independence.

Test: Search for interference experiments that violate Born rule while maintaining operational consistency. No such experiment should exist if the framework is correct.

Status: All known interference experiments (double-slit, quantum erasure, Bell tests, etc.) follow Born rule. This is consistent with but does not uniquely confirm the framework.

Appendix C: Plain Language Summary

What is this paper about?

Physics has two incredibly successful theories: General Relativity (which describes gravity and the cosmos) and Quantum Mechanics (which describes atoms and subatomic particles). The problem is that they seem to contradict each other at a fundamental level—not in their predictions, but in what they assume reality is.

This paper proposes a new foundation that sits underneath both theories. Instead of starting with space, time, and particles, we start with something simpler: patterns of relationships that can repeat.

The key idea

Imagine you have a pattern—like a musical melody. You can play that melody at different times, in different places, at different volumes. But it’s still recognizably the same melody. The melody is defined by the relationships between notes, not by when or where you play it.

In this framework:

- Physical “things” are like melodies: they’re patterns of relationships that can repeat
- Space is just a measure of how different two patterns are
- Time is just the order in which patterns occur

- Probability is just how often a pattern repeats compared to others

Why does this help?

Both General Relativity and Quantum Mechanics can be understood as different ways of keeping track of these repeating patterns:

- General Relativity works well when patterns repeat smoothly and predictably
- Quantum Mechanics works well when multiple similar patterns interfere with each other

They're not contradictory—they're just bookkeeping systems for different situations.

What's new?

The framework makes a specific prediction that differs from Einstein's General Relativity:

Near black holes, Einstein's theory says time should slow down infinitely. This framework says time slows down a lot, but not infinitely—there's a limit.

This prediction can be tested with future gravitational wave detectors like LISA.

What about the math?

The paper also shows why quantum mechanics uses its particular probability rule (the "Born rule"). It turns out this rule isn't arbitrary—it's the only way to calculate probabilities that doesn't depend on how you arbitrarily group things together.

The bottom line

This isn't a "theory of everything." It's a minimal foundation that shows how our two best theories can both be right in their domains, while making one testable prediction where they differ.