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Article

The Empirical Distinguishability of Quantum Interpretations

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Abstract

Quantum experiments constrain physical descriptions with extraordinary precision, yet several disagreements about quantum reality remain unresolved. Their persistence has different causes that require different responses. This article distinguishes exact agreement of predictions, inadequate statistical resolution, uncertain background dynamics, restricted access to records, conditional exclusion by no-go results, and incomplete predictive specification. It develops a comparative framework in which distinguishability belongs to specified formulations and experimental domains rather than to interpretation names. A critical review connects philosophical work on underdetermination, Pessoa's account of relations between experiments and interpretations, and recent statistical approaches to quantum tests. Likelihood equality clarifies the limits of differential confirmation, while identification of individual claims explains how experiments can establish physical structure without determining a complete ontology. Two analytic examples make the distinction practically consequential: a collapse contrast with bounded background uncertainty, and an observer-record model in which inaccessible information limits discrimination. The examples show when additional data help, when calibration or coherent access is required, and when no improvement within the stipulated domain can decide the comparison. The resulting assessment rejects both unrestricted empirical equivalence and claims that particular experiments uniquely establish a favored interpretation. It specifies the additional predictions, controls, and outcomes needed to make those claims evidentially meaningful.

Keywords: quantum foundations; interpretations of quantum mechanics; empirical equivalence; underdetermination; experimental discrimination; quantum measurement

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1. Introduction

The success of quantum theory and the persistence of disagreement about its meaning create a familiar difficulty. Experiments repeatedly confirm the theory's probabilities, while Bohmian, Everettian, relational, and epistemic formulations offer different accounts of the states, events, and objects to which those probabilities refer. Objective-collapse proposals add another possibility by changing the dynamics. The existence of this plurality does not settle how much experimental evidence distinguishes its members. Some comparisons exhibit genuine predictive agreement; others involve a measurable difference, an undeveloped prediction, or an inaccessible record. Treating these situations alike obscures both the reach of present evidence and the prospects for further inquiry.

The distinction between predictive success and completeness goes back at least to Einstein, Podolsky, and Rosen (Einstein et al., 1935). The subsequent proposals of Bohm, Everett, and Ghirardi, Rimini, and Weber show that the foundational problem admits substantially different physical responses (Bohm, 1952; Everett, 1957; Ghirardi et al., 1986). Relational quantum mechanics and QBism question additional assumptions about the significance of quantum states and the circumstances in which outcomes can be compared (Rovelli, 1996; Fuchs et al., 2014). These approaches do not acquire identical scientific standing simply by reproducing selected laboratory statistics. Their treatment of probability, measurement, relativistic extension, and physical explanation also matters.

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Three judgments therefore need to be distinguished. A formulation may accommodate an observation, receive evidence relative to a specified rival, or have its ontology uniquely identified within a candidate class. Accommodation is weaker than comparative confirmation, and comparative confirmation is weaker than uniqueness. A fourth judgment concerns internal coherence: an inconsistent formulation fails independently of whether an experiment distinguishes its advertised predictions. Bell's criticism of an unanalyzed measurement prescription and Maudlin's separation of measurement problems explain why a probability algorithm alone does not answer every foundational question (Bell, 1990; Maudlin, 1995).

This article argues that the empirical status of an interpretation must be assessed through specified comparisons. The relevant question is which formulations predict different accessible records under which assumptions, and whether those differences survive statistical and physical uncertainty. The resulting diagnosis is constructive. Small differences call for more informative data. Confounded differences call for new controls. Inaccessible differences call for new interventions or access to additional systems. Missing predictions call for theoretical development. Exact equivalence over the enlarged domain leaves no further empirical distinction within that domain.

The general existence of underdetermination is already extensively discussed. Acuña charts the relations among interpretation, theory rivalry, and empirical equivalence; Egg and Saatsi review the associated problem for scientific realism; and Pessoa classifies eight ways in which experiments influence interpretations (Acuña, 2021; Egg & Saatsi, 2021; Pessoa Jr., 2026). The present contribution is a comparative assessment that connects those discussions to statistical decision problems and to the physical availability of records. Two worked examples establish why diagnosing the source of an unresolved comparison changes the experimental remedy. The mathematics uses established methods; the contribution lies in their coordinated application to the broader interpretive question, including the remaining ambiguity after a dynamical modification has been detected.

The literature review in Section 2 identifies the closest predecessors and the strongest objections. Sections 3–5 set out the framework and apply it to no-go results and major interpretive families. Sections 6 and 7 examine background uncertainty and record access quantitatively. Section 8 specifies outcomes that would alter present assessments, while Section 9 states the positive physical knowledge compatible with continuing ontological disagreement. The discussion is a critical, source-led review of representative comparisons, with literature considered through September 2026. It is not a systematic census of every interpretation or a measurement of how often experimental claims are overstated.

2. Prior Work and the Remaining Methodological Problem

2.1. Underdetermination and Unequal Development

Underdetermination in quantum theory is neither a newly noticed anomaly nor a single thesis. Acuña distinguishes competing theories from interpretations and examines the conditions under which their predictions agree (Acuña, 2021). Egg and Saatsi describe the challenge that surviving quantum alternatives pose for realism without assuming that the challenge has one inevitable response (Egg & Saatsi, 2021). A methodological account must consequently identify the particular evidence, rivals, and theoretical commitments involved. Declaring the subject underdetermined in general supplies too little information to guide either an experiment or a realist inference.

The strongest objection to a sweeping equivalence claim concerns the domain of comparison. Wallace argues that interacting quantum field theory gives formulations unequal explanatory and evidential standing, which comparisons restricted to nonrelativistic examples conceal (Wallace, 2023). Adlam questions whether the available proposals supply fully viable solutions to the measurement problem (Adlam, 2023). These objections prevent the unqualified assertion that all major interpretations explain every established phenomenon equally well. Nevertheless, explicit Bohmian field-theory constructions and relativistic collapse models exist (Dürr et al., 2004; Tumulka, 2006; Gundhi et al., 2026). Their limitations have to be identified model by model. An absent calculation, an incomplete extension, and a calculation contradicted by data are different scientific situations.

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A second disagreement concerns what can be known despite this plurality. Egg and Fraser and Vickers develop accounts of substantive quantum knowledge that do not require choosing a complete interpretation (Egg, 2021; Fraser & Vickers, 2025). López challenges the adequacy of allegedly neutral or overlapping ontologies (López, 2024), while Glick considers a perspectival account of competing descriptions (Glick, 2026). These debates motivate the distinction developed below between identifying an individual physical claim and identifying an entire ontology. That distinction permits partial knowledge, but does not guarantee that any proposed common structure has the same meaning in every theory.

2.2. Experiments and Interpretations in Pessoa

Pessoa's analysis begins with the reception of interpretations and develops eight relations between interpretation and experiment (Pessoa Jr., 2026). These include agreement with standard predictions, inaccessible differences, testable alternative theories, partial exclusions within families, experimental reinforcement and refinement, and the two directions of influence between proposing an interpretation and proposing an experiment. His account already covers much of the conceptual territory sometimes presented as an unrecognized problem. In particular, his discussion of observer experiments explicitly warns that a result motivated by one interpretation may be equally compatible with its rivals.

Reception and comparative evidence nevertheless require different analyses. Weak-measurement reconstructions may make Bohmian trajectories easier to visualize. Hydrodynamic analogies may make a guiding-wave picture more intelligible. Neither achievement alone supplies a likelihood advantage over a competing quantum account. Conversely, eliminating a collapse parameter region is evidential progress even though the larger family survives. Pessoa's historical cases, including Papaliolios's test of Bohm–Bub dynamics and the optical test of a particular empty-wave proposal, show why the name of an interpretation cannot replace specification of the tested mechanism (Papaliolios, 1967; Zou et al., 1992).

Several technical distinctions are necessary when using Pessoa's categories. Decoherence suppresses interference in a reduced state without, by itself, selecting one outcome or eliminating global superposition (Schlosshauer, 2005). A definite Bohmian configuration does not require collapse of the universal wavefunction (Dürr et al., 1992). Bell's measurement-independence assumption differs from fair sampling. A macroscopicity measure quantifies a specified reference class of modifications rather than a universal boundary beyond which superposition becomes impossible (Nimmrichter & Hornberger, 2013). Collapse models also differ in parameters and physical mechanisms; they cannot all be represented as one two-parameter gravitational theory (Bassi et al., 2013). These corrections alter the comparisons available to experiment rather than merely changing interpretive vocabulary.

Pessoa's characterization of testable departures as already falsified also needs to be read alongside his recognition of surviving collapse-model parameter regions. Experiments have excluded specific alternatives and substantial regions of others. They have not excluded every possible testable modification. Similarly, denying universal unitarity for human-scale observers cannot by itself nullify a microscopic photonic result: the candidate dynamics must predict a deviation at the scale actually tested.

2.3. Conditional Exclusion and Comparative Confirmation

Dardashti's analysis of no-go theorems makes explicit that their conclusions depend on a conjunction of premises (Dardashti, 2021). In the quantum literature, violations of Bell, noncontextuality, and related inequalities eliminate models satisfying specified assumptions. They do not establish a favored replacement merely because it avoids the excluded conjunction. Shahsavari's recent preprint directly develops this distinction between constraint and unique ontological confirmation (2026, unreviewed preprint, doi:10.20944/preprints202608.1904.v1). Its general representation in Equation 12 already factorizes local responses. Equation (7) below instead starts with the joint response so that the locality premise remains explicit. The present article shares that distinction and extends it to comparisons with

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uncertain backgrounds, restricted observations, and incompletely specified alternatives. Its novelty cannot therefore consist in restating that exclusion is not unique confirmation.

Conditionality should not be exaggerated into evidential paralysis. A test may favor one candidate strongly even when other candidates remain. A no-go theorem can also impose a costly explanatory revision on a theory that preserves its predictions. A Bayesian comparison can represent such differences through predictive distributions and prior judgments, but must keep them separate from a likelihood contrast absent from the data. Greaves and Myrvold's defense of Everettian confirmation and Kent's criticism of Everettian probability show why the probability rule is part of the comparison, rather than a neutral starting point that settles it (Greaves & Myrvold, 2010; Kent, 2010).

2.4. Statistical and Experimental Predecessors

The mathematical tools needed here already have substantial literatures. Blackwell compares experiments through the information retained under postprocessing (Blackwell, 1953). Classical testing theory and quantum detection theory quantify discrimination between distributions and states (Tsybakov, 2009; Helstrom, 1976). Composite quantum tests, nuisance-parameter estimation, and quantum semiparametric methods address uncertainty within candidate models (Suzuki et al., 2020; Tsang et al., 2020; Berta et al., 2021). These results preclude claiming that finite precision or auxiliary uncertainty is itself a new approach to quantum foundations.

More specifically, Schrinski, Nimmrichter, and Hornberger compare quantum and modified dynamics using interferometric data (Schrinski et al., 2020). Marchese and collaborators develop collapse-model hypothesis tests and estimation in optomechanical settings (Marchese et al., 2021; Marchese et al., 2023). Reversible observer experiments have antecedents in Deutsch, and the interaction between memory and observable predictions is directly examined by Baumann and Brukner (Deutsch, 1985; Baumann & Brukner, 2024). The two examples below are analytic benchmarks for a general methodological argument, rather than new proposals for experimental platforms.

The remaining contribution is to connect these specialist results to the full interpretive comparison. A claimed discriminator must identify the predictive packages, the accessible protocol, the admissible uncertainty, the distinguishing statistic, and the scope of the conclusion. This makes it possible to distinguish a problem that better precision can solve from one that requires a different experiment, further theoretical development, or acceptance of residual equivalence. It also identifies a limitation that survives even successful model selection: selecting a probability law need not select its ontology.

3. What an Empirical Comparison Specifies

3.1. Formulations and Experimental Domains

Let a predictive formulation be represented by

$$M = (\mathcal{S}, \mathcal{D}, \mathcal{P}, \mathcal{R}, \mathcal{O}).$$

Here $\mathcal{S}$ specifies states, $\mathcal{D}$ dynamics, $\mathcal{P}$ probability rules, $\mathcal{R}$ their connection to records, and $\mathcal{O}$ ontological commitments. The notation imposes no common hidden-variable ontology. It records the ingredients needed to derive an empirical prediction. Preparation assumptions and nuisance parameters belong to the formulation when they affect that derivation. A complete experimental protocol π specifies preparations, interventions, accessible systems, and recorded outcomes, including any adaptive choices. The formulation then supplies a record distribution P_M^π.

For an allowed protocol class Π, define empirical equivalence by

$$M \sim_\Pi N \quad \Longleftrightarrow \quad P_M^\pi = P_N^\pi \text{ for every } \pi \in \Pi. \qquad (1)$$

Equality applies to complete record laws, including correlations and sequential measurements. Agreement about one expectation value or one reduced channel is insufficient. Enlarging Π can divide a formerly equivalent class when the formulations supply different predictions for the additional

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protocols. It cannot do so merely by renaming a preparation or interpreting an unchanged record differently.

For fixed formulations, a shared nonzero likelihood gives

$$\frac{P(M \mid D, \pi)}{P(N \mid D, \pi)} = \frac{P(D \mid M, \pi)}{P(D \mid N, \pi)} \frac{P(M)}{P(N)} = \frac{P(M)}{P(N)}. \qquad (2)$$

Thus these data do not alter the prior odds. Both formulations may nevertheless gain support against a third rival, or fail together if their common probability law is inadequate. Differential untestability is compatible with shared falsifiability. Allori's defense of pilot-wave theory emphasizes why empirical agreement does not make a formulation scientifically empty (Allori, 2025). For model families, moreover, different parameter priors can yield different marginal likelihoods despite pointwise overlaps. Equation (2) concerns the specified likelihoods, not interpretation labels in the abstract.

The result survives adaptive experimentation when equality holds conditionally after every reachable record history and the same experimental policy is used. Multiplication of the common conditional laws gives the same transcript distribution. Appendix A states the argument. This condition is stronger than equality of single-trial marginals and accommodates the importance of memory in quantum protocols (Chiribella et al., 2009).

3.2. Precision and Uncertainty

For fixed classical record laws P and Q, total variation distance is

$$\mathrm{TV}(P, Q) = \frac{1}{2} \int |p(z) - q(z)| \, dz.$$

With equal prior probabilities, the minimum average decision error is

$$p^{\star}_{\mathrm{err}} = \frac{1 - \mathrm{TV}(P, Q)}{2}. \qquad (3)$$

For protocols within a resource budget b, the supremum of this distance over Π_b expresses the best available discrimination. Unlike exact equivalence, being within a tolerance is not transitive: Bernoulli parameters 0.4, 0.5, and 0.6 give an elementary counterexample at tolerance 0.15. It is therefore misleading to partition all interpretations into approximate equivalence classes without stating an additional convention.

More observations can improve a small but nonzero separation. Under independent identical trials, Pinsker's inequality implies

$$\mathrm{TV}(P^{\otimes n}, Q^{\otimes n}) \leq \sqrt{\frac{n D_{\mathrm{KL}}(P \| Q)}{2}}. \qquad (4)$$

Consequently, average error at most $\alpha < 1/2$ requires $n \geq 2(1 - 2\alpha)^2 / D_{\mathrm{KL}}(P \| Q)$ when the divergence is positive and finite. This is a necessary lower bound, not a sufficient sample-size prescription. It does not apply unchanged to correlated trials, adaptive designs, or composite uncertainty (Tsybakov, 2009).

When either hypothesis permits nuisance variation, comparing one convenient pair of curves can exaggerate experimental power. For a fixed protocol, let $\mathcal{P}_0$ and $\mathcal{P}_1$ be the admissible null and alternative distributions. A test ϕ has uniformly controlled false positives if $\sup_{P \in \mathcal{P}_0} E_P \phi \leq \alpha$. Its worst-case missed-detection probability is

$$\beta^{\star}(\alpha) = \inf_{\phi : \sup_{P \in \mathcal{P}_0} E_P \phi \leq \alpha} \sup_{Q \in \mathcal{P}_1} E_Q(1 - \phi). \qquad (5)$$

If the distribution sets overlap, power cannot exceed α at the overlapping alternative. Additional repetitions of that same unresolved comparison do not remove the overlap. A new control can help by

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constraining nuisance parameters or making their effects differ from the proposed signal. Section 6 gives an explicit calculation.

3.3. Identification of Claims

The ontology question is finer than model selection. Let $g(M)$ express a physical claim in a specified candidate class $\mathcal{C}$. A necessary condition for identifying it from protocols in Π is

$$M \sim_{\Pi} N \implies g(M) = g(N) \quad \text{for } M, N \in \mathcal{C}. \tag{6}$$

A claim that varies within an empirical equivalence class cannot be decided by that class's shared records. With finite data, a confidence set $\mathcal{C}_\alpha(D)$ for candidate models induces a set of admissible claims $\{g(M) : M \in \mathcal{C}_\alpha(D)\}$. Coverage is inherited if the true model belongs to the candidate class and the statistical assumptions hold. A singleton identifies the claim under those assumptions; it does not establish that the candidate class exhausts possible reality.

This is a useful route to partial knowledge. A successful experiment can constrain noncontextual assignments, identify a state within a quantum description, or favor a collapse rate while leaving other ontological commitments unresolved. Table 1 summarizes why the unresolved cases require different responses.

Table 1. Obstacles to discrimination and the changes that address them.

Obstacle	What is unresolved	Relevant change
Exact equivalence	Every accessible record law agrees	Add a domain with differing predictions or revise physical commitments
Small separation	The distributions differ weakly	Improve settings, precision, or sample size
Nuisance overlap	An allowed background reproduces the signal	Calibrate backgrounds or add independent controls
Restricted access	Distinguishing information is outside the accessible systems	Gain coherent access or change the intervention
Conditional exclusion	A conjunction is rejected without isolating its failing premise	Constrain the competing premise revisions
Incomplete prediction	A formulation supplies no quantitative record law	Develop and assess the missing theory
Residual ontology	Distinct ontologies realize the selected record law	Establish an additional predictive contrast, if one exists

4. What the Principal Experimental Constraints Establish

4.1. Bell Correlations

Bell's theorem converts causal assumptions into restrictions on observable correlations (Bell, 1964; Clauser et al., 1969). Its force depends on stating those assumptions rather than substituting the broad philosophical term realism. Begin with a general hidden-variable representation

$$p(a, b \mid x, y) = \int d\xi \, \mu(\xi \mid x, y) \, p(a, b \mid x, y, \xi). \tag{7}$$

The settings are x, y, outcomes are $a, b \in \{-1, +1\}$, and ξ denotes the proposed complete conditioning information. Measurement independence requires $\mu(\xi \mid x, y) = \mu(\xi)$. Local causality supplies the factorization $p(a, b \mid x, y, \xi) = p(a \mid x, \xi) p(b \mid y, \xi)$. Starting with an already factorized response would silently build the disputed premise into the representation.

The conditional means $A_x(\xi)$ and $B_y(\xi)$ lie in $[-1, 1]$. Hence

$$\begin{aligned} |S| &= |E_{00} + E_{01} + E_{10} - E_{11}| \le 2, \\ |A_0(B_0 + B_1) + A_1(B_0 - B_1)| &\le |B_0 + B_1| + |B_0 - B_1| \le 2. \end{aligned} \tag{8}$$

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Integration over the setting-independent distribution proves the first line. Suitable quantum states and settings give $2\sqrt{2}$. Experiments closing the major detection and locality loopholes reject the corresponding local model class (Hensen et al., 2015; Giustina et al., 2015). They establish a substantial constraint on physical explanation. They do not require every admissible account to introduce controllable superluminal signalling, nor do they identify Bohmian mechanics, collapse, or relational facts uniquely (Brunner et al., 2014).

Measurement-dependent models and locally mediated retrocausal approaches illustrate distinct ways of revising the premises (Hall, 2010; Hossenfelder & Palmer, 2020; Wharton & Argaman, 2020). Their mere possibility does not make them complete or equally supported theories. They must supply quantitative models with independently defensible assumptions. Causal-discovery arguments add constraints involving faithfulness, but that condition must likewise be acknowledged (Wood & Spekkens, 2015). Historical fair-sampling assumptions and memory across trials are separate experimental issues; appropriately analyzed memory does not provide a generic escape from modern Bell tests (Barrett et al., 2002).

4.2. Contextuality and Quantum-State Ontology

Contextuality results constrain assignments of properties or probabilities under specified operational equivalences. Spekkens's generalized formulation includes preparations, transformations, and unsharp measurements; it is broader than the deterministic value assignments of the original Kochen–Specker problem (Spekkens, 2005; Budroni et al., 2022). An experiment violating a noncontextuality inequality rules out the associated class under its compatibility and equivalence assumptions. Calling the result a refutation of reality removes precisely the conditions that give the result its content.

Quantum-state theorems concern another sharply defined question. In an ontological model, preparations of ψ_0 and ψ_1 induce distributions μ_0 and μ_1 over an ontic state. Their overlap is

$$\omega = \int d\xi \, \min\{\mu_0(\xi), \mu_1(\xi)\}.$$

Preparation independence makes the common overlap weight of n independently prepared systems at least ω^n. The Pusey–Barrett–Rudolph construction uses a joint measurement having an outcome excluded by quantum theory for each corresponding product preparation (Pusey et al., 2012). If e_z denotes the probability of that excluded outcome for preparation z, nonnegative responses give

$$\omega^n \leq \sum_z e_z. \qquad (9)$$

Appendix B supplies the short overlap argument. Exact quantum zeros force $\omega = 0$ under the premises. Finite experimental upper bounds on the sum instead constrain ω, with simultaneous uncertainty accounted for. The theorem identifies a restriction on overlapping preparation distributions; it does not show that a wavefunction is a material field in ordinary space, that it is complete, or that Everettian ontology uniquely follows. Leifer and Harrigan and Spekkens distinguish these claims carefully (Leifer, 2014; Harrigan & Spekkens, 2010).

Preparation independence is an assumption about underlying composition. Statistical independence of observed settings does not prove it. Extensions and criticisms of quantum-state theorems investigate precisely such composition conditions (Mansfield, 2016; Schlosshauer & Fine, 2014). Experimental studies constrain particular epistemic explanations under stated preparation and detection assumptions (Patra et al., 2013; Ringbauer et al., 2015). QBism's personalist state assignment and relational state assignments do not automatically fall into the technical category of overlapping ontic distributions. The same caution applies to Leggett-type tests and Leggett–Garg inequalities: restricted nonlocal models or a conjunction involving macrorealism and noninvasive measurability are their targets (Gröblacher et al., 2007; Leggett & Garg, 1985; Emary et al., 2014).

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4.3. Reconstructed Trajectories

Weak measurements offer a useful contrast because their predictions can be shared without any new no-go argument. For a spinless particle without a vector potential, write $\psi = Re^{iS/\hbar}$. Then

$$\mathrm{Re}\,\frac{\langle x|\hat{p}|\psi\rangle}{\langle x|\psi\rangle} = \hbar\,\mathrm{Im}\,\frac{\nabla\psi}{\psi} = \nabla S = mv_B. \qquad (10)$$

The real weak momentum equals the Bohmian momentum field wherever the expression is defined. This identity explains why a reconstruction can resemble Bohmian trajectories while remaining a prediction of the shared formalism. Kocsis and collaborators reconstructed average flow lines in a photonic arrangement, whose optical modelling should not be confused with a direct measurement of massive-particle position histories (Kocsis et al., 2011). Fankhauser and Dürr examine the additional assumptions required to infer actual trajectories from weak velocities (Fankhauser & Dürr, 2021). The experimental achievement is real; a distinctive likelihood for Bohmian ontology has not been supplied by the identity alone.

5. The Present Comparison among Interpretive Families

5.1. Equilibrium Formulations and Their Qualifications

Bohmian mechanics gives a clear example of a conditional equivalence result. The Schrödinger equation and the guidance law yield the same continuity equation,

$$\begin{aligned} \partial_t|\psi|^2 + \nabla\cdot j = 0, \\ \partial_t\rho + \nabla\cdot(\rho v) = 0, \qquad v = \frac{j}{|\psi|^2}. \end{aligned} \qquad (11)$$

An initial distribution $\rho = |\psi|^2$ consequently remains in equilibrium. Applying that result to apparatus configurations, with the theory's account of effective wavefunctions and records, recovers the usual outcome probabilities (Dürr et al., 1992). Equivariance is the mathematical core; the connection between configurations and observed records is also part of the argument. A recent preprint by Manero, Muciño, and Okon disputes that connection (2025, arXiv:2508.06667). This is a challenge to the grounding of an equivalence claim, not a reported experimental observation of divergent predictions.

Everettian accounts retain universal unitary dynamics and require an account of branch weights, probability, and observed records (Everett, 1957; Greaves & Myrvold, 2010; Kent, 2010). Conditional on an adequate Born-weight account, experiments confirming ordinary quantum probabilities provide common support relative to alternatives predicting deviations. They do not thereby distinguish Everett from an equilibrium formulation yielding the same records. Quantum computation does not change that conclusion merely because a many-worlds description offers an intuitive explanation of computational power (Steane, 2003).

The family names must not conceal internal variation. Copenhagen does not denote one mathematically fixed collapse trigger. Consistent-histories probabilities are tied to consistent frameworks (Griffiths, 1984). The original transactional interpretation must be distinguished from later physical modifications (Cramer, 1986). QBism changes the role of probabilities and outcomes rather than automatically adding a new laboratory probability law (Fuchs et al., 2014; Schack, 2024). Each formulation must make its commitments explicit before its empirical status can be assessed.

5.2. Relational Quantum Mechanics and Observer Experiments

Relational quantum mechanics interprets states and events relative to physical systems (Rovelli, 1996). Adlam and Rovelli add cross-perspective conditions concerning records, which should be evaluated separately from the original formulation (Adlam & Rovelli, 2023). Adlam's more recent discussion distinguishes different senses of quantum relationality (Adlam, 2026). These distinctions matter because statements about jointly accessible records may differ from statements about facts assigned in separate perspectives.

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The consistency debate remains active. Pienaar's objections elicited a reply from Di Biagio and Rovelli (Pienaar, 2021; Di Biagio & Rovelli, 2022). Lawrence, Markiewicz, and Żukowski argue that relative-fact assignments conflict with quantum predictions; Cavalcanti, Di Biagio, and Rovelli dispute the relevant cross-perspective inferences; a subsequent rejoinder maintains the criticism (Lawrence et al., 2023; Cavalcanti et al., 2023; Lawrence et al., 2025). Lahti and Pellonpää investigate mathematical formulations within measurement theory, while Drezet compares relational and Bohmian descriptions (Lahti & Pellonpää, 2023; Drezet, 2023). This literature cannot be represented as either an experimental confirmation of RQM or an uncontested empirical refutation. A contradiction among asserted rules would disqualify that rule set, but identifying the rules correctly is part of the dispute.

Observer theorems and experiments constrain specific combinations of assumptions. Brukner's theorem, the Frauchiger–Renner argument, and local-friendliness results differ in their premises and operational settings (Brukner, 2018; Frauchiger & Renner, 2018; Bong et al., 2020). Proietti and collaborators tested a photonic implementation of local observer independence (Proietti et al., 2019). Żukowski and Markiewicz question the interpretation of coherent premeasurements as measurements with the stronger outcome properties invoked in some discussions (Żukowski & Markiewicz, 2021). More recent contextuality-based formulations refine the theoretical problem (Walleghem et al., 2026). None of these results assigns a unique interpretation by its experimental provenance alone.

A microscopic register can implement a specified mathematical role without settling whether a human observer, a macroscopic irreversible record, or a candidate conscious system can play the same role. Wiseman, Cavalcanti, and Rieffel make additional assumptions explicit in a prospective experiment involving artificial observers (Wiseman et al., 2023). This is a useful model of how to move beyond rhetoric: define the physical observer, the preserved records, the reversible operations, and the rival predictions. Section 7 quantifies one access restriction relevant to such comparisons.

Table 2 is a map of comparison tasks, not a claim of universal equivalence or equal explanatory merit. The quantum-field-theory objection of Section 2 remains relevant throughout. A formulation cannot claim agreement in a domain where it has not supplied the appropriate dynamics and record probabilities.

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Table 2. Empirical comparisons require specified versions of interpretations.

Formulation or family	Present comparison	What would supply a discriminator
Bohmian quantum equilibrium	Shared record probabilities in established equilibrium domains	A demonstrated departure in an extension or an accessible nonequilibrium distribution
Everett with a Born-weight account	Shared unitary quantum predictions in the compared domain	A rival's quantitative collapse or probability deviation at accessible scales
RQM and cross-perspective variants	Quantum predictions plus disputed rules about relative facts and records	A coherent formulation yielding a different joint or sequential accessible record law
QBism	Quantum probabilities interpreted as an agent's commitments	Additional physical postulates yielding an independently testable contrast
Copenhagen, histories, transactional families	Empirical content depends on the specified member and measurement rules	An explicit trigger, consistency condition, or dynamics with different outcomes
Objective-collapse models	Quantitative deviations constrained over parameter regions	A reproducible signal with predicted scaling and controlled backgrounds
Nonequilibrium or modified Born-rule models	Possible deviations conditional on an accessible physical preparation	A specified source, predicted probabilities, and replication against standard effects
Retrocausal or measurement-dependent families	Different causal accounts can reproduce Bell correlations	Further constraints producing independent quantitative predictions
Consciousness-linked collapse	Generic claims are incomplete; some dynamical proposals are more explicit	A specified physical trigger and a controlled comparison with ordinary dynamics

6. A Collapse Comparison with Uncertain Backgrounds

6.1. Physical Scope of Collapse Tests

Objective-collapse models modify state evolution and therefore provide genuine differential tests (Ghirardi et al., 1986; Bassi et al., 2013; Bassi et al., 2023). Interference, heating, force noise, and spontaneous radiation constrain particular mechanisms and parameter regions. Underground tests of gravity-related collapse and radiation bounds from XENONnT exemplify the reach of this programme (Donadi et al., 2021; Aprile et al., 2026). Matter-wave experiments with large molecules and nanoparticles enlarge the domain over which coherence is established (Fein et al., 2019; Pedalino et al., 2026). These results neither leave collapse theories untouched nor eliminate every member of the family.

The evidential difficulty is often separating additional decoherence from ordinary environmental effects. A reduction in fringe visibility can arise from collisions, thermal radiation, instrumental drift, or a proposed modification. An experiment becomes discriminating when the candidate causes respond differently to controlled variations and the remaining uncertainty is quantified. This problem has already motivated statistical analyses of collapse tests (Schrinski et al., 2020; Marchese et al., 2021; Marchese et al., 2023). The following solvable example exposes the distinction between statistical precision and background ambiguity without claiming a sensitivity forecast for a particular apparatus.

6.2. A Contrast That Removes a Leading Background

Suppose the normalized visibility for separation d and fixed evolution time t has decay rate

$$y(d) = -\frac{1}{t}\log\frac{V(d,t)}{V_0(d,t)} = \eta d^2 + \lambda A(d) + e(d), \qquad A(d) = 1 - e^{-d^2/(4r_C^2)}. \tag{12}$$

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Here V_0 is a calibrated reference, η is an unknown leading environmental coefficient, r_C is fixed, and $\lambda \geq 0$ is an effective localization rate for the object. The residual e represents bounded departures from the leading background model, including calibration uncertainty where appropriate. This is a Gaussian localization benchmark. Identifying its effective rate with a microscopic CSL parameter would require the actual mass density, geometry, and noise model.

At separations small relative to r_C,

$$A(d) = \frac{d^2}{4r_C^2} - \frac{d^4}{32r_C^4} + O(d^6/r_C^6).$$

The leading dependence constrains $\eta + \lambda/(4r_C^2)$. Higher-order terms prevent exact degeneracy in the full ideal model, but they may be too small to resolve within the available precision or residual uncertainty. Measuring more repetitions at one separation does not independently determine both contributions.

A two-separation contrast cancels the stipulated quadratic background:

$$\begin{aligned} D &= 4y(d) - y(2d) = \lambda K(d) + u, \\ K(d) &= 4A(d) - A(2d), \qquad u = 4e(d) - e(2d). \end{aligned} \tag{13}$$

Writing $x = d^2/(4r_C^2)$ gives $K = 3 - 4e^{-x} + e^{-4x}$. It is positive for $d > 0$, since its derivative with respect to x is $4(e^{-x} - e^{-4x}) > 0$ and it vanishes at zero. For small d, $K \simeq 3d^4/(8r_C^4)$; at $d = r_C$, $K \simeq 0.252676$. The contrast therefore exposes a different response, although the gain can remain small in the quadratic regime. It is useful only if the same η applies at both separations, an assumption to be checked by the apparatus model and calibration.

Let $|e(d)| \leq b_1$ and $|e(2d)| \leq b_2$, so that $|u| \leq B = 4b_1 + b_2$. Suppose the measured contrast is adequately described by

$$\begin{aligned} \widehat{D} &\sim N(\lambda K + u, \sigma_D^2), \\ \sigma_D^2 &= 16\,\mathrm{Var}(\widehat{y}_1) + \mathrm{Var}(\widehat{y}_2) - 8\,\mathrm{Cov}(\widehat{y}_1, \widehat{y}_2). \end{aligned} \tag{14}$$

Normality and the known variance are benchmark assumptions. In an actual low-count interference experiment they would need justification or replacement by the relevant likelihood. Retaining the covariance avoids overstating the precision of a difference constructed from correlated estimates.

6.3. The Limit Imposed by Background Uncertainty

Compare $H_0 : \lambda = 0$ against $H_1 : \lambda \geq \lambda_\star > 0$, with the same allowed residual interval. Their mean sets are

$$\mathcal{I}_0 = [-B, B], \qquad \mathcal{I}_1 = [\lambda_\star K - B, \infty). \tag{15}$$

If $\lambda_\star K \leq 2B$, the sets overlap. The best uniform power at the overlapping alternative cannot exceed the false-positive bound. This remains true as statistical error decreases: the stipulated systematic uncertainty admits the same observable distribution under both hypotheses.

When $\lambda_\star K > 2B$, the Gaussian family has a monotone likelihood ratio. A uniformly level-α minimax test rejects for

$$\widehat{D} > B + z_{1-\alpha}\sigma_D,$$

and has worst-case missed-detection probability

$$\beta^\star(\alpha) = \Phi\left(z_{1-\alpha} - \frac{\lambda_\star K - 2B}{\sigma_D}\right). \tag{16}$$

Here Φ is the standard normal distribution function and z_p its p quantile. Appendix C gives the endpoint proof. To attain missed-detection probability at most β, one needs

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$$\lambda_\star K \geq 2B + (z_{1-\alpha} + z_{1-\beta})\sigma_D. \qquad (17)$$

For independent repetitions giving $\sigma_D = s/\sqrt{n}$, this becomes a sample-size requirement proportional to $(\lambda_\star K - 2B)^{-2}$. No finite sample size meets it if the signal remains inside the background overlap. Calibration and sampling are therefore different resources. A bound on B that itself fails with probability at most γ weakens the unconditional type-I guarantee to at most $\alpha + \gamma$. Scanning unknown r_C or selecting contrasts after inspecting the data requires additional treatment of multiplicity and selection.

6.4. What a Detected Modification Would Identify

A reproducible positive result across separations, masses, times, and independent platforms could provide evidence for a specified modification over calibrated ordinary dynamics. Agreement with its predicted heating or radiation signature would strengthen that comparison. An unexplained loss of visibility alone would not identify collapse. Null results can also favor standard dynamics over alternatives that assigned substantial probability to an observable deviation, even when a limiting parameter region survives.

Identifying effective dynamics would still leave an ontological question. A completely positive trace-preserving map admits a unitary dilation,

$$\mathcal{E}(\rho) = \mathrm{Tr}_E\left[U(\rho \otimes \sigma_E)U^\dagger\right], \qquad (18)$$

under the usual dilation construction (Stinespring, 1955). This does not show that the required environment physically exists, or that it is compatible with independently known constraints. It shows that effective subsystem nonunitarity alone does not entail fundamental universal nonunitarity. Agreement at one time also need not extend to an entire controlled sequential process (Chiribella et al., 2009). Physical environmental constraints and additional interventions are therefore essential.

Even within collapse theories, a state-evolution law does not determine whether matter is represented by flashes, a mass density, or another primitive ontology (Allori et al., 2008). Tilloy explicitly discusses distinct underlying descriptions reproducing collapse predictions (2020, preprint, arXiv:2007.15420). Thus success in the experimentally substantive task of selecting dynamics can coexist with residual ontological ambiguity. This is a further reason to specify the claim being identified.

7. Observer Records and the Limits of Accessible Interference

7.1. A Coherent Laboratory and a Retained Record

Consider orthogonal laboratory states $|L_0\rangle$ and $|L_1\rangle$, representing two outcomes and their internal records. In an ideal isolated description,

$$|L_+\rangle = \frac{|L_0\rangle + |L_1\rangle}{\sqrt{2}}, \qquad \rho_{\mathrm{mix}} = \frac{1}{2}(|L_0\rangle\langle L_0| + |L_1\rangle\langle L_1|).$$

Projection onto $|L_+\rangle$ gives probabilities one and one half, respectively. Coherent access to the whole specified laboratory would therefore distinguish this unitary state from complete dephasing. Both equilibrium Bohmian mechanics and a suitable Everettian description predict the coherent result. A definite Bohmian configuration does not turn the wavefunction into ρ_{mix}.

Now include a register R outside the accessible laboratory,

$$|\Psi\rangle = \frac{|L_0\rangle|R_0\rangle + |L_1\rangle|R_1\rangle}{\sqrt{2}}, \qquad \gamma = \langle R_0|R_1\rangle. \qquad (19)$$

Tracing out R gives, in the laboratory basis,

$$\rho_L = \frac{1}{2}\begin{pmatrix} 1 & \gamma^* \\ \gamma & 1 \end{pmatrix}.$$

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The off-diagonal magnitude depends on the overlap of the inaccessible records. Complete, perfectly distinguishable records have $\gamma = 0$. The accessible laboratory then has exactly the same state as ρ_{mix}, although the global descriptions differ.

For equal priors and arbitrary measurements confined to L, the trace distance is $|\gamma|/2$. The Helstrom error is therefore

$$p^{\star}_{\mathrm{err}} = \frac{1}{2} - \frac{|\gamma|}{4}. \qquad (20)$$

More generally, if a specified additional dephasing multiplies the off-diagonal entries by $q \in [0,1]$, its distance from the original reduced state is $(1-q)|\gamma|/2$, giving error $1/2 - (1-q)|\gamma|/4$ (Helstrom, 1976). These expressions assume known states and access to the optimizing laboratory measurement. Realistic restrictions can only make discrimination worse.

7.2. Which Change Would Improve the Comparison

For the pure equal-prior record states in this model, optimal record distinguishability is $D_R = \sqrt{1-|\gamma|^2}$ and laboratory visibility is $V = |\gamma|$. Thus

$$V^2 + D_R^2 = 1, \qquad (21)$$

an equality case of the established visibility–distinguishability relation (Englert, 1996). Retaining a perfectly informative inaccessible record removes the particular laboratory interference required by the test. This is a physical restriction on available operations, not a premise about whether an observer possesses consciousness.

When $0 < |\gamma| \leq 1$, repeated, adequately controlled trials can improve discrimination. When $\gamma = 0$, repetitions of the same reduced-state experiment do not help: the available states are identical. Gaining coherent access to R changes the protocol class and can restore a distinction. Quantum erasure likewise requires specifying the operations and conditioning records. Conditional fringes cannot be counted as an unconditional restoration while the retained information used for conditioning is ignored.

The model identifies what a stronger observer experiment must establish. It must specify the physical register carrying the outcome, the records retained outside coherent control, and the operations permitted to the later observer. It must also state the dynamical alternative: an objective-collapse model may predict negligible deviation for the actual register even if it predicts substantial deviation for a larger observer. Operationally implementing one quantum degree of freedom cannot establish all the premises of an experiment involving a human or a complex artificial observer. Conversely, practical difficulty in controlling large records is not a theorem that macroscopic coherence is intrinsically impossible.

This access analysis complements, rather than replaces, the logical premises of observer no-go theorems. It explains why some proposed comparisons cannot be implemented while all desired records are preserved in the stipulated way. Together with the collapse example, it provides a concrete reason why the phrase "not yet distinguishable" fails to specify what further progress requires.

8. Experiments That Could Change the Assessment

8.1. New Regimes and New Predictive Commitments

A useful experimental prospect specifies more than an unfamiliar regime. It identifies a difference between rival record laws and the controls that keep the difference interpretable. Table 3 organizes several routes according to the outcome needed and the inference it would support. Its entries describe conditional research opportunities, not a prediction that a particular anomaly will be observed.

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Table 3. Outcomes that would extend the present empirical assessment.

Comparison	Required experiment and outcome	Warranted advance and remaining limit
Standard dynamics versus a specified collapse model	Coherence or noise measurements across mass, separation, and time; a reproducible residual matching the collapse law after background controls	Evidence for the modification over the calibrated null; ontology still requires a further comparison
Unitary coherence versus a specified observer-triggered reduction	Coherent manipulation of a physically defined observer or record; visibility discriminating the two numerical predictions	Tests the stipulated trigger at that scale; does not select among all unitary ontologies
Born equilibrium versus a nonequilibrium proposal	An identified source and a predicted probability deviation or signalling effect surviving preparation and detector checks	Tests the nonequilibrium model; an unexplained anomaly alone does not establish pilot waves
Linear quantum dynamics versus a specified nonlinearity	Controlled spectroscopy or interferometry with a reproducible functional deviation	Selects between dynamical laws in the tested regime; interpretation of the new law remains open
Gravity-mediation models	Initially separable systems acquire verified entanglement attributable to the stipulated gravitational interaction, with other channels bounded	Constrains mediation and classicality assumptions; does not uniquely establish a quantum-gravity ontology
Formulations with unequal field-theoretic scope	Explicit predictions for the same interacting process and records, followed by a discriminating result	Tests the completed formulations; a missing extension first requires theoretical work

Nonequilibrium pilot-wave research illustrates the need to connect a mathematical possibility to a preparation. Hypothetical distributions different from $|\psi|^2$ can permit nonstandard statistics and signalling, but this does not establish that laboratory or cosmological systems supply them (Valentini, author manuscript, arXiv:quant-ph/0112151). Valentini and Varma propose a high-energy route to Born-rule testing (Valentini & Varma, 2025). Such a proposal is a candidate discriminator only to the extent that it fixes the source, expected deviation, and competing standard processes. A generic permission for some anomaly is not a probability distribution over the data.

Tests of nonlinear quantum dynamics have a long experimental history, including trapped-ion spectroscopy (Bollinger et al., 1989). Higher-order interference searches likewise test specified departures from quantum predictions (Sinha et al., 2010). In a three-slit arrangement, however, changing the open slits also changes boundary conditions. The apparatus model must distinguish the predicted quantum contribution from a genuinely new interference term (De Raedt et al., 2012). A successful anomaly would challenge shared commitments of several interpretations; it would not automatically choose the interpretation that first motivated the search.

The empirical reach of consciousness-linked collapse depends on an explicit physical criterion for the triggering system and on a specified dynamics. Chalmers and McQueen examine candidate models and their dynamical difficulties, including quantum-Zeno constraints (2021, author manuscript, arXiv:2105.02314). A discriminating experiment would have to vary the proposed trigger in a way whose ordinary physical consequences are sufficiently controlled. Simply labelling one apparatus conscious and another unconscious supplies neither an observable criterion nor a numerical prediction. This requirement makes the proposal difficult to formulate, but avoids dismissing all versions solely because the initial terminology is philosophical.

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8.2. Gravitational Entanglement and the Scope of Inference

Gravity-mediated entanglement proposals expose the difference between identifying a physical property and choosing an interpretation. Bose and collaborators, and Marletto and Vedral, describe ways of using initially separated quantum systems to investigate the character of gravitational mediation (Bose et al., 2017; Marletto & Vedral, 2017). The inferential argument requires assumptions about the mediating interaction, initially available correlations, locality, and alternative channels. Martín-Martínez and Perche examine what the observation could establish under those assumptions, while Galley, Giacomini, and Selby formulate a relevant no-go result in a broader probabilistic framework (Martín-Martínez & Perche, 2023; Galley et al., 2022).

"Classical gravity" itself denotes different models. Oppenheim's stochastic classical–quantum dynamics differs from a simple mean-field treatment (Oppenheim, 2023). Aziz and Howl argue that a quantum-field treatment of matter permits entanglement in a classical gravitational setting (Aziz & Howl, 2025); Gundhi, Infantino, and Bassi dispute the transition-amplitude analysis in a subsequent preprint (2026, arXiv:2604.19696). This theoretical dispute does not constitute experimental evidence for either side. It makes precise formulation of the interaction and of the permitted communication channels more urgent.

A successful entanglement experiment could exclude a substantial class of mediation models. It would not thereby discriminate every interpretation of the quantum matter sectors or identify the full ontology of gravity. Its importance is compatible with that limitation. The same distinction applies to future tests in relativistic quantum field theory: extending a theory's scope can supply additional support without yielding a one-to-one relation between predictions and ontology.

8.3. Interpreting Positive and Null Results

Preferential evidence does not require logical exclusion of every conceivable rival. It requires a specified contrast in predictive probability, evaluated with the uncertainty appropriate to the comparison. A positive signal that matches a prespecified dependence and appears across different instruments is stronger evidence than an unexplained residual. A null result is informative when a rival assigned appreciable probability to a detectable signal. The survival of a continuously adjustable parameter near zero does not erase that evidential effect.

Experiments can also be scientifically valuable without producing differential confirmation among interpretations. They can establish a mechanism, enlarge a regime of control, or reveal an inconsistency in a model of the apparatus. An interpretation may deserve credit for suggesting them. Pessoa's distinction between the origin of an experiment and its effect on rivals is particularly useful here (Pessoa Jr., 2026). Heuristic fertility, explanatory coherence, and differential likelihood are different achievements; keeping them distinct allows each to receive appropriate credit.

9. Positive Knowledge Without a Complete Ontology

It would be too pessimistic to conclude that quantum experiments tell us only what reality cannot be. Controlled coherence, entanglement, and correlations provide positive physical information. Within quantum theory, self-testing can identify states and measurements up to specified equivalences even when device details are incompletely characterized (Šupić & Bowles, 2020). This is a concrete instance of identifying a claim without identifying a complete physical ontology. The assumptions and allowed equivalences limit the conclusion, but do not deprive it of content.

Quantum Darwinism offers another example. It studies how interactions distribute information redundantly through environmental records (Zurek, 2009). Controlled spin-environment experiments investigate aspects of that mechanism (Unden et al., 2019). Evidence for redundant information supports a physical account of accessible objectivity. It does not alone decide whether the global state has a unique branch, is accompanied by configurations, or must undergo additional collapse. Different formulations can share an experimentally supported mechanism while disagreeing about what ultimately realizes it.

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Operational reconstructions similarly clarify the principles sufficient for quantum structure. Chiribella, D'Ariano, and Perinotti derive quantum theory from information-theoretic postulates, including purification (Chiribella et al., 2011). Such results explain how formal constraints fit together. The achievement does not entail that the reconstructed formalism has only one possible ontology. The remaining philosophical question is which features of successful descriptions deserve realist commitment, a question on which the positive proposals and criticisms reviewed in Section 2 continue to differ (Egg, 2021; Fraser & Vickers, 2025; López, 2024).

Two objections to the present framework deserve emphasis. First, it might appear to reduce scientific appraisal to record probabilities. It does not. Simplicity, coherence, explanation, and prospects for unification remain legitimate considerations. Exact equivalence says that particular data supply no likelihood contrast under the specified formulations; it does not establish equal prior plausibility or equal scientific promise. Unequal theoretical development can itself affect a broader evidential comparison, provided missing predictions are not represented as if they were tested failures.

Second, any finite candidate class excludes alternatives that have not been imagined. That limitation applies to ordinary scientific inference as well as quantum interpretation. Identification relative to a class can still be useful when the class is motivated, its boundaries explicit, and its conclusions open to revision. The framework demands neither certainty nor an exhaustive catalogue of possible worlds. It requires that the strength and scope of a claim track the comparison actually made.

10. Conclusion

Quantum interpretations have an uneven empirical status. Several specified formulations share record probabilities over established domains. Others modify those probabilities and face substantial experimental constraints. Some comparisons remain unresolved because the relevant information is inaccessible, ordinary backgrounds are insufficiently controlled, or a candidate has not supplied a complete prediction. These are different sources of underdetermination, with different prospects for progress.

The quantitative examples show why the distinction matters. In the collapse benchmark, additional observations improve discrimination only after the proposed signal exceeds the ambiguity admitted by the background model. In the record benchmark, increasing the number of trials cannot distinguish identical accessible reduced states; gaining coherent access to an additional register can change the comparison. Even successful selection of a dynamical law may leave distinct ontologies compatible with the selected predictions.

Experiments therefore justify more than wholesale suspension of judgment and less than an unrestricted identification of quantum reality with a favored interpretation. They can identify physical structure, exclude substantial model classes, and provide comparative evidence among specified alternatives. A stronger ontological claim requires an additional argument connecting that evidence to the proposed ontology and addressing rivals that share it. Making that argument explicit is the practical standard by which both present claims and future experiments should be assessed.

11. Adaptive Experiments and Common Postprocessing

Let $h_{t-1} = (x_1, z_1, \ldots, x_{t-1}, z_{t-1})$ denote a record history. The common experimental policy selects x_t with probability $\pi_t(x_t \mid h_{t-1})$. If two formulations have equal conditional responses $p_M(z_t \mid x_t, h_{t-1}) = p_N(z_t \mid x_t, h_{t-1})$ for all histories reachable under the policy, then

$$P_M(h_n) = \prod_{t=1}^{n} \pi_t(x_t \mid h_{t-1}) p_M(z_t \mid x_t, h_{t-1}) = P_N(h_n).$$

Thus feedback based on the existing transcript does not create a distinction absent from the full conditional process. This statement does not infer process equality from equal one-time marginals.

Likewise, a common stochastic postprocessing kernel K cannot increase total variation:

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$$
\begin{aligned}
2\,\mathrm{TV}(KP, KQ) &= \int dy \left| \int dz\, K(y \mid z)[p(z) - q(z)] \right| \\
&\le \int dz\, |p(z) - q(z)| \int dy\, K(y \mid z) \\
&= 2\,\mathrm{TV}(P, Q).
\end{aligned}
$$

This elementary contraction illustrates Blackwell's comparison of experiments (Blackwell, 1953). A new physical intervention or access to another system can enlarge the experiment; reanalysis of the same records cannot increase its optimal discriminatory information. An improved analysis can, of course, recover information a previously inefficient analysis discarded.

12. The Quantum-State Overlap Bound

Set $m(\xi) = \min\{\mu_0(\xi), \mu_1(\xi)\}$. For product preparation $\boldsymbol{z} \in \{0,1\}^n$, preparation independence gives density $\mu_{\boldsymbol{z}}(\boldsymbol{\xi}) = \prod_i \mu_{z_i}(\xi_i)$, which dominates $m_n(\boldsymbol{\xi}) = \prod_i m(\xi_i)$. Let $r_{\boldsymbol{z}}(\boldsymbol{\xi})$ be the nonnegative response for the measurement outcome excluded for preparation $\boldsymbol{z}$. Responses sum to one. Therefore

$$
\begin{aligned}
\sum_{\boldsymbol{z}} e_{\boldsymbol{z}} &= \sum_{\boldsymbol{z}} \int d\boldsymbol{\xi}\, \mu_{\boldsymbol{z}}(\boldsymbol{\xi}) r_{\boldsymbol{z}}(\boldsymbol{\xi}) \\
&\ge \int d\boldsymbol{\xi}\, m_n(\boldsymbol{\xi}) \sum_{\boldsymbol{z}} r_{\boldsymbol{z}}(\boldsymbol{\xi}) = \omega^n.
\end{aligned}
$$

The relevant joint measurement must exist for the chosen states and number of copies (Pusey et al., 2012; Leifer, 2014). With noisy data, replacing the right-hand probabilities by estimates without confidence control would overstate the result. An upper confidence bound U on their sum yields $\omega \le U^{1/n}$ at the corresponding coverage, conditional on the ontological and preparation assumptions.

13. The Gaussian Endpoint Test

For $\lambda_\star K > 2B$, the closest allowed means are $\mu_0 = B$ and $\mu_1 = \lambda_\star K - B$. The Neyman–Pearson test for these simple Gaussian hypotheses rejects above $B + z_{1-\alpha}\sigma_D$. Its rejection probability increases with the mean. It therefore has false-positive probability at most α at every null mean, and its largest missed-detection probability occurs at μ_1. No uniformly valid test can perform better at that endpoint than the most powerful simple-hypothesis test. This proves the minimax expression (16).

If $\lambda_\star K \le 2B$, choose a mean shared by the two sets. At that distribution, any uniformly level-α test has missed-detection probability at least $1 - \alpha$. A data-independent randomized test attains this uniform bound, showing the absence of guaranteed informative discrimination. If the sets are separated and $\sigma_D = s/\sqrt{n}$, condition (17) gives

$$
n \ge \left[\frac{(z_{1-\alpha} + z_{1-\beta})s}{\lambda_\star K - 2B} \right]^2,
$$

rounded up to an integer. The result applies to the stipulated Gaussian mean sets. If the residuals obey narrower shared physical constraints, those constraints should replace the conservative intervals before determining the relevant endpoints.

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