

From Matter Waves to Anchored Events: Anchored Causality Theory and Quantum Brownian Measurement

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Abstract

Anchored Causality Theory (ACT) holds that a quantum system is never a particle: it is one wave, a quantum field with internal structure, from start to finish, and the particle is what happens, the mark a detector makes. The main accounts of quantum mechanics keep a particle somewhere, at the detector or on a hidden path, or they keep every outcome, each in a world of its own; ACT does neither. A bath, not an observer, makes the mark: the detector's surroundings keep a record, and when the record has passed beyond recovery one event occurs, with the Schrödinger equation unchanged. This paper works out the bath's part for matter waves. Wave mechanics began as a realist attempt to understand the wave character of matter, but neither de Broglie's nor Schrödinger's program produced a mechanism by which an extended wave yields one localized event. Born's rule removed that question from dynamics, and decoherence explains the suppression of interference without supplying the occurrence of an outcome. Objective-collapse models restored that demand, at the cost of autonomous stochastic localization dynamics. ACT is an alternative in which the event-rate structure is inherited from a physical quantum Brownian motion bath rather than postulated, while the actuality of one resulting history is postulated explicitly. Global dynamics are unmodified; the environment's record structure supplies the event hazard and constrains the realized instrument class. We give a two-condition event law: an admissible fragment-readable record architecture makes an event eligible, while accessible irreversible phase loss fixes the hazard $h(t) = \dot{\Phi}_{\text{irr}}(t)$, with no new constant and no adjustable threshold, within a stated regime boundary: the event rate is read off the same coupling that draws the decoherence curve, and in the nondemolition case the two curves are one. Irreversibility is defined through recoverable phase distinguishability, and scoped to CP-divisible dynamics. Two models are worked through: an exactly solvable pure-dephasing model in which the Born weights are forced by ensemble consistency and an explicit outcome-neutrality hypothesis, which checks in the model the general result of the companion paper, where six stated premises on the law of chance force them for every released record; and a Caldeira–Leggett Brownian-particle model exhibiting the noise–dissipation pairing. A selection theorem shows that fragment-accessible records support only classical post-processings of the localization instrument; its role is ontological rather than empirical. A detector is any body that keeps an irreversible record of the mode it couples to; no observer enters. The framework posits an exclusive outcome register and the actuality of one record history, and adds one event-law identification; in the record-algebra class of the companion paper the first is a theorem and the identification is the nondemolition case of a general law, so that one primitive commitment remains.

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1 Introduction: wave mechanics as a realist program

Wave mechanics began as a realist attempt to understand the wave character of matter. When de Broglie proposed in 1924 that matter carries a wave character, and when Schrödinger constructed the equation governing that wave in 1926, neither was offering a bookkeeping device for experimental statistics [27, 78]. Both were addressing the question *what is the electron physically?*

That question immediately generated a second one, and it is the second that concerns us. If matter is described by an extended wave, what physically occurs when a detector registers a single localized event?

This paper’s answer to both questions is Anchored Causality Theory’s, and it can be given at once. The electron is never a particle: it is one wave, a quantum field with internal structure, from start to finish. The particle is what happens, the mark a detector makes, and a bath, not an observer, makes it; one history of marks is actual, and the Schrödinger equation is never changed (Section 5). The main accounts keep a particle somewhere, at the detector or on a hidden path, or they keep every outcome, each in a world of its own; ACT does neither (Section 6). What this paper supplies is the bath’s part for matter waves: when the mark is made, and in what instrument.

The two founding programs approached the second question differently, and neither is well described as proposing a wave-to-particle transition.

De Broglie retained a corpuscle. His pilot-wave theory, and the more ambitious double-solution program that followed, sought a realist account in which an extended wave structure and a localized element coexist, the former guiding the latter [28]. The particle was never eliminated; what was at stake was the physical standing of the wave, and the relationship between the two. After the 1927 Solvay conference de Broglie set the program aside, returning to it only after Bohm’s independent reconstruction [15].

Schrödinger’s hope was more radical: that the particle might be nothing but a wave packet, so that localized behaviour would emerge from a sufficiently concentrated solution [78]. This did not survive contact with the theory. Free packets disperse, and the N -particle wavefunction lives on a $3N$ -dimensional configuration space rather than in physical space—so whatever ψ is, it is not a classical wave in the laboratory.

What the two programs share is not a mechanism but a demand: that the appearance of a localized event should have a physical account rather than an axiomatic one. That demand is the subject of this paper.

2 The localization problem

The Schrödinger equation governs continuous evolution accurately and completely within its domain. What it does not do is identify the physical occurrence of one outcome. For a system prepared in a superposition of pointer alternatives $\{|o_k\rangle\}$ and coupled to a detector, unitary evolution carries

$$\left(\sum_k c_k |o_k\rangle\right) \otimes |D_0\rangle \longmapsto \sum_k c_k |o_k\rangle \otimes |D_k\rangle, \quad (1)$$

and stops. Every correlated component appears on the right with the status it had on the left. Throughout, “superposition” denotes the coherent component structure of a single quantum state. The components $c_k |o_k\rangle$ are not thereby independently actual record histories; actuality enters only through the event process developed below. Where a Fourier or normal-mode representation is physically natural, it may characterize that component structure; nothing in the present account asks the decomposition itself to deliver exclusivity. Three levels are therefore distinguished throughout: the component structure of the evolving state; the distinct record

alternatives defined by a record-supported instrument; and the single actual record outcome added to the realized history at an anchoring event.

The gap is therefore not a defect in the Schrödinger equation. That equation is a law of *continuous evolution*; what is missing is a complementary *law of events* specifying when a definite occurrence happens, in what basis, and with what probability. These are the three questions any completion of the dynamical program must answer, and they organize everything that follows: WHEN does an event occur, WHAT alternatives does it select among, and WHICH outcome obtains. Standard quantum mechanics supplies such a law as a postulate applied at moments designated measurements, with the designation left primitive. On the account developed here the designation is not primitive: a measurement is a detector anchoring a mode of the field, and a detector is any body that keeps an irreversible record of the mode it is coupled to, whether or not anything reads it (Section 5).

3 The retreat from dynamical explanation

The wavefunction becomes statistical. Born’s 1926 rule assigned $|\psi|^2$ the status of a probability density for finding a particle [16]. Its success is not in dispute. But note the effect on the founding question: “how does the wave become a particle?” is replaced by “what is the probability of finding a particle at x ?” The transition ceases to be an event requiring explanation.

Collapse becomes a postulate. The projection rule was added as an independent axiom, applied at measurement, with no dynamical account of its occurrence.

Measurement becomes primitive. Complementarity recast the question of what physically occurs between preparation and registration as a category error. The measurement problem continued to be discussed—by Einstein, by Bell, by Wigner—but the dominant formalism no longer required a dynamical answer. The reading on which an observer completes a measurement descends from this period; Section 5 sets out the experiments in which the observer is removed and the record remains.

Decoherence explains suppression, not occurrence. Tracing over an environment that monitors a system observable suppresses off-diagonal elements of the reduced density matrix in an einselected pointer basis, and quantum Darwinism explains how the resulting records become redundant across environment fragments [60, 96, 77, 99, 14]. None of this is disputed here. But it is an ensemble-level statement: writing

$$\rho_S(t) \longrightarrow \sum_k p_k P_k \rho_S(0) P_k, \quad (2)$$

one obtains an *improper* mixture: the reduced state is diagonal in the pointer basis, but precisely because the global state remains pure, that diagonality cannot be read as ignorance over an already actual k . Nothing in Eq. (2) asserts that one k obtains.

Where the present proposal departs from quantum Darwinism. Because what follows leans heavily on einselection and on fragment-accessible records, the point of departure should be stated before the machinery. Both are retained here in full: the pointer basis is environmentally selected, and redundancy across dynamically independent fragments is what makes the selected alternatives objective and robust. The comparison intended is with the strongest available formulation, in which pointer states, quantum jumps, Born’s rule and objective classical reality are all addressed within an unmodified unitary global evolution [100], rather than with the earlier statements of the programme alone. What such an account does not supply—and cannot

Framework	Source of noise / event-rate structure	Energy treatment
Standard quantum theory	Unspecified; projection at measurement	Unitary between measurements
Standard CSL	Autonomous collapse noise field, parameters λ_0, r_C	Secular growth, Eq. (3)
Dissipative CSL	Effective finite-temperature noise sector; additional phenomenological parameter	Relaxes to a finite asymptote
This work	Physical QBM bath already present; actuality of one history postulated	Unconditioned exchange with physical bath; event-level ledger open

Table 1: Contrast in the origin of the noise and event-rate structure. Section 11 demonstrates the noise–dissipation pairing explicitly.

supply without a further commitment—is the occurrence of one alternative rather than another; the disagreement is not with the derivations but with whether anything beyond them is required. Quantum Darwinism explains why observers agree about which alternatives are available; it is silent on which obtains. The proposal below takes that same record structure and assigns it two further jobs: fixing the rate at which events occur, and constraining the instrument class within which one alternative is actualized. The physics invoked is not new. The ontological role given to it is.

4 Objective collapse restores the question

GRW and its continuous successor CSL deserve credit rather than treatment as foils [47, 73, 48]: they reasserted that something physically happens when a state becomes definite, dynamically and without an observer. Diósi and Penrose pursued gravitationally induced versions [33, 74], and the program has matured into an empirical one [8, 35, 25].

The structural cost is autonomous stochastic localization dynamics — in CSL, an explicit noise field. CSL carries a phenomenological rate λ_0 and coherence length r_C , neither constrained by the system Lagrangian, and the noise enters without a dissipation partner, so energy is injected at rate

$$\frac{dE}{dt} \sim \frac{\lambda_0 \hbar^2}{2mr_C^2}. \quad (3)$$

Dissipative CSL addresses this by introducing an effective finite-temperature noise sector, with momentum-dependent operators and an additional phenomenological parameter, so that the mean energy of an isolated system relaxes to a finite asymptote [81].

An essential qualification. The comparison in Table 1 should not be read as a claim that the present theory reproduces what CSL does more economically. It does not reproduce it at all. CSL modifies the dynamics of *isolated* systems: localization occurs whether or not an environment is present. The theory developed here does nothing of the kind. Events occur only through irreversible record-forming interactions with an environment; an isolated system evolves unitarily forever. The two are answers to different questions, and the avoidance of CSL-type heating follows partly from this different aim rather than from a superior solution to the same problem. What the comparison does establish is that *if* one is willing to locate definiteness in environmental interaction rather than in a universal spontaneous process, then the dissipative structure comes for free.

5 What is proposed

The proposal developed here is called *Anchored Causality Theory* (ACT): an event is an *anchoring*—the moment at which a system enters the causal order of records—and the theory’s content is a law for when anchorings occur and in what instrument.

What a particle is. On this account there is no wave–particle duality left to interpret. The field is what exists; what the word *particle* has always named operationally—a click, a developed grain, a droplet, a track—is an anchored event: the mark a detector makes when the bath carries the record of one mode beyond recovery. The wave does not turn into a particle; it leaves one. Mott’s treatment of α -ray tracks is the canonical case: one spherical wave, and a straight chain of ionization events, each a condensation in a supersaturated vapour [69]. The comparison is closer than a metaphor and is worth stating once. Anchoring is to the bath what nucleation is to a supersaturated medium: nothing has happened while the nucleus can still dissolve back (the record remains coherently recoverable); past the critical size—release, Section 9—it grows and stays; the untransformed fraction is the survival law $S(t) = e^{-\Phi_{\text{irr}}(t)}$ of Section 10, Eq. (16); and the rate is set by the medium, here the detector architecture, with no new constant. The phase change is in the record, not in the field, which never changes phase. Nothing below depends on the analogy.

What a detector is. The same account removes the observer. A detector is a device built to couple a signal into a continuum, with amplification; but what makes it a detector is not that it is read. Detectors and observers anchor events because they are coupled to the bath, not because they observe, and which record is written is fixed by what is physically coupled—the detector actually present—not by anyone’s choice (Section 12). The point can be put as a thought experiment, and the experiment has been performed. Take the double slit, which works for electrons, for atoms and for large molecules, and remove the detector; put a plain slab beside one path, with nothing reading it. The fringes die anyway, and they die in proportion to how lossy the slab is: electron waves passing above a plate of doped silicon lose their fringes near it, while beside gold, a million times less lossy, they barely change [85, 63]. Nothing observed anything. The slab kept a record it cannot give back. Interaction is not the criterion; a record is, and this is the sense in which decoherence is built into the account rather than added to it: the same dissipation that keeps the record is the decoherence. The detector/observer effect is the bath’s effect.

The physical picture is a single chain,

composite quantum field $\longrightarrow$ QBM interaction with a detector $\longrightarrow$ stable record formation $\longrightarrow$
anchoring $\longrightarrow$ one causal history,

and the technical content of the paper is what this architecture supplies to the three questions of Section 2: the selection theorem of Section 12 addresses WHAT, the event law of Section 9 addresses WHEN, and the trace rule on the record-conditioned state addresses WHICH. The weights of that rule are forced, in general, by six stated premises on the law of chance (the companion paper [84], Appendix A; the ontology paper [83], Appendix A), and Proposition 2 checks them in the exactly solvable model of Section 10.

Ontological commitment. ACT is an *unraveling-selection* theory, not a modification of unconditioned dynamics.

1. The global system–bath evolution is unitary and is not modified. No noise field is added to the Schrödinger equation.
2. A master equation admits many stochastic unravelings [18, 93]. The proposal is that exactly one is physically realized, and that the environment’s record structure—not the experimenter’s choice of what to measure in the bath—constrains which. The selection result of Section 12 fixes the admissible class rather than a unique member; what it does not fix is recorded in Section 15.
3. Along the realized history the *conditioned* state jumps: at an anchoring event

$$\rho \longrightarrow \frac{\mathcal{I}_r(\rho)}{\text{Tr } \mathcal{I}_r(\rho)},$$

for $\{\mathcal{I}_r\}$ the completely positive instrument the records support (Section 9), and the unrealized components cease to be part of that history. For an efficient instrument this is $\rho \rightarrow M_\alpha \rho M_\alpha^\dagger / \text{Tr}(M_\alpha^\dagger M_\alpha \rho)$, and where the records are sharp it reduces further to $\rho \rightarrow P_k \rho P_k / p_k$.

4. The *ensemble* is untouched. In the QND pure-dephasing model developed in Section 10, averaging over the event statistics reproduces the exact unconditioned reduced dynamics. Extension to general multilevel instruments requires an instrument-resolved record functional and is not established here (Sections 9 and 15).

Stated without formalism: anchoring does not reduce the wave, it adds a determination. What was indeterminate—which record obtains—becomes determinate, and stays so. Nothing contracts: under unmodified unitary evolution the set of decohered alternatives only grows, and it is the actual history that extends. The unrealized correlated components remain in the global state. Recoherence involving them is precluded not by fiat but by the irreversibility of the record, made precise in Section 9; accordingly the present construction applies only where the record dynamics prevents physically accessible recoherence. The ontological treatment of exact global recurrence—where the unitary dynamics would return the record—lies outside its scope, as does the corresponding regime of the event law (Section 10.2).

One broader ontological premise of the wider program should be visible here, precisely because nothing in this paper depends on it: on the anchored-causality picture a pre-anchored quantum state has structure but not yet a temporal causal history — entry into the causal order of records is what anchoring adds. That premise motivates the name and frames the program; the derivations below are stated entirely within ordinary laboratory time and are independent of it.

The companion paper. This paper states the ontology, works the quantum Brownian motion case in two exactly solvable models, and proves the selection theorem. A companion paper [84] works at the level of the algebra the records generate: it proves that the record algebra is commutative for arbitrary system Hamiltonian and coupling, so that the exclusivity of outcomes is a theorem in that class; it defines release of a record as commutation with the system’s physically accessible future, through every return path the interaction network provides, and proves the bound that ties release to the irreversibility measure of Section 9; and it states the general event law as the instrument path measure, of which the law of this paper is the

nondemolition case. Where a result of this paper is given its general form there, the text says so; nothing here depends on the companion results.

6 Relation to other proposals

Because the commitment of Section 5 places this work in a populated neighbourhood, the comparison is made before the mathematics rather than after it.

Modal interpretations. Modal interpretations assign definite values to some observables while the quantum state evolves unitarily [90, 32]. The closest relative is the minimal modal interpretation, in which the definite properties of an open system are given by the spectral decomposition of its reduced density operator. The similarity to the present proposal is real: unitary global dynamics, actual properties for open systems, no added noise.

Two differences are substantive. First, the preferred decomposition here is not the spectral decomposition of ρ_S —which is unstable under small perturbations and ill-defined at degeneracies—but is fixed by the architecture of environmental records (Section 12 and Appendix A). Second, and more importantly, modal interpretations leave the *event process* underdetermined: dynamics for the possessed values can be supplied—Bacciagaluppi and Dickson construct a family of empirically equivalent stochastic jump dynamics of Bell–Vink type [3]—but nothing in the interpretation selects one, nor ties the transition rate to anything physical. The present theory is event-based, with a hazard read off the environment’s record production.

Bell-type stochastic beables. Bell’s beable model for lattice quantum field theory [11] is the nearest structural analogue, and it does supply explicit jump times and rates—so event timing as such is not what distinguishes the present proposal from it. The difference is the *source* of the rate. Bell’s jump rates are read off the Hamiltonian and the current on a lattice, and are nonzero whether or not any record forms; here the rate is the production rate of irreversible *environmental records* (Section 9), and vanishes for environments that decohere without recording.

Consistent and decoherent histories. The histories program supplies a consistency criterion for assigning probabilities to sequences of events [50, 72, 44], and Brun established the direct correspondence between quantum-trajectory unravelings and sets of decoherent histories [20]. That correspondence makes the relationship precise: the present theory picks one unraveling, hence one set of histories, and asserts that one history in that set is actual. The histories program does neither, which is why it faces the set-selection problem [36]—many mutually incompatible consistent sets, with no principle choosing among them. The record-architecture criterion here is offered as such a principle, restricted to sets realizable by fragment-accessible records.

Everettian quantum mechanics (Many Worlds). Everett’s relative-state formulation [38], in its modern decoherence-based development [91], shares the present proposal’s equation, and a real wave that never collapses. The two part at the outcome, and there they are opposites. Everett keeps no particle, but every outcome: in Many Worlds every outcome happens, each in a world of its own, with a copy of the observer in each, and the bath only draws the borders between those worlds, decoherence having been brought in later to say where they fall [60, 96]. Here the bath makes the mark, and one history of marks is actual. In the formalism the two differ by one statement, the postulate of Section 14 that one record history is actual; in what they say happens, that statement is the difference between every outcome and one. No experiment decides between them: every detection is one mark, as both predict. The present account takes that mark at face value; Many Worlds counts every other outcome as a world of its own, which no experiment can reach, and where every outcome happens, what a chance is has to be rebuilt.

The standard objection runs the other way. If the global state is unmodified, the unselected components persist with all their internal structure, and it may be asked what the postulate adds beyond a label—the charge pressed against Bohmian mechanics by Brown and Wallace [19]. It applies here no less than to Bohmian mechanics, since both leave the unselected components in place, where the modified dynamics of GRW with flashes suppresses their amplitude. The reply is the primitive ontology [1]: what is concrete on this account are the anchoring events. The global state is real structure—one field whose components are the possibilities for anchoring, weighted by their amplitudes, and the object that fixes the event law’s rate and instrument class—but a component holds possibilities for events, not events. Two senses of “real” are kept apart. The components are real as the structure of the one field: they carry amplitude, they interfere while no record is released, and what a record leaves unrecorded can anchor later. An alternative is real as fact only when a released record has made it actual; after an event the unselected alternatives keep the first kind of reality and never acquire the second. Every component carries its own records, but only one history of them is actual, and only its records are marks. Whether a component with no events in it could still hold someone who sees an outcome is a substantive question, answered here in the negative, as it is in flash-ontology theories. That answer is a commitment, defended, not derived.

Where no experiment can choose, Occam’s razor does, and it counts what must be assumed to account for what is observed: one outcome in every run, with Born frequencies. Many Worlds adds nothing to the equation, but to account for the one outcome it holds that every outcome occurs, each in a world of its own with a copy of the observer, and no experiment in one world can reach another; and it rebuilds what a chance is. The present account adds the postulate of Section 14, that one record history is actual, so the outcome a run shows is the only one that occurs (with exclusivity a second, for a reader who does not grant the companion theorem). Whether the unselected components hold observers who saw other outcomes is the question no run can reach, and there the razor counts against positing them. Against Many Worlds the count comes down to one comparison: of each run, the present account asserts one outcome, the one the run shows; Many Worlds asserts that outcome and every other besides, the others in worlds no run can reach. The flagship sets out the count for every account [83].

Flash and primitive ontologies. The primitive-ontology category is that of GRW with a flash ontology [88, 1], in which the spacetime events—rather than a field or a continuous trajectory—are what the theory is fundamentally about in spacetime. The present proposal shares that category, with one qualification: it is not a pure flash ontology in the sense that would make the quantum state nomological or otherwise less than real. Here the global state is real wave structure, alongside which exactly one record history is actual; what the events do is constitute that history, not exhaust what there is. With that said, anchorings are the events, and between them there is no fact of the matter as to which alternative obtains—an absence of fact, not an unknown fact. The difference from GRWf is dynamical rather than ontological. GRWf obtains its flashes from a spontaneous localization term added to the Schrödinger equation, with a rate and a width fixed by new constants; here the events are obtained from a record process already present in the environmental dynamics, introducing no new constant and leaving the unconditioned evolution untouched. The difference has an empirical side, stated in Section 15: GRWf is in principle empirically distinguishable from unmodified quantum mechanics, and the present proposal, within its stated regime, is not.

Event ontologies. The reading of a quantum event as the passage from possibility to fact has a lineage that this proposal joins rather than founds: Heisenberg’s *potentia* [54]; Haag’s events as fundamentally irreversible transitions inside a growing causal net [51, 52]; the event-enhanced quantum theory of Blanchard and Jadczyk [12]; Kastner’s transactional actualisation [61]; Belavkin’s nondemolition principle, which identifies the output of a continuously monitored

system as a classical past [9]; Kent’s late-time records, which show that a one-history ontology over unmodified unitary dynamics can be Lorentz covariant [62]; the ETH approach of Fröhlich and collaborators, in which an event occurs when the algebra of the future acquires a non-trivial centre, with the loss of access grounded in radiation escaping to infinity [40, 13, 41, 42, 23]; and Zhang’s event anchoring, an event defined by local classicalization, redundant recording and irreversibility against recovery, with single-outcome event generation left open as a separate problem [95]. The present proposal is of the same type and should be judged against these. What it adds is the combination: the Schrödinger evolution left exactly as it is, where ETH evolves stochastic states; a boundary stated against the system’s *accessible* future rather than the full future algebra or a final hypersurface; an event rate read off irreversible record production; and the selection theorem of Section 12, which says that the fragment records of a position-diagonal coupling can support a localization instrument and never a coherent momentum kick. The open piece Zhang’s account names, single-outcome event generation, is what Sections 9 and 14 supply. The deltas are set out in full, with the record-algebra results, in the companion paper [84].

Indivisible stochastic processes. Barandes’ stochastic–quantum correspondence [5, 4, 6] establishes an exact correspondence between unitarily evolving quantum systems and a class of non-Markovian “indivisible” stochastic processes on a configuration space. It is the closest recent relative of the structure assumed here: one actual trajectory, ordinary probability, and unitary evolution retained as the law governing the process. Two differences bear on what follows. First, the correspondence is a general representation theorem—it holds for any quantum system, with the division times supplied by the mathematics—whereas the claim made here is the physical and defeasible one that event timing and instrument class are fixed by environmental record production. Second, the correspondence demotes the quantum state to a derived mathematical object, while the present proposal retains $|\Psi\rangle$ as the carrier of the dynamics and adds the history variable alongside it. A reader already persuaded by the correspondence may treat the ontological postulate of Section 14 as secured independently, and read what follows as a proposal about where in the physics the division times come from.

Ultradecoherence and detector click dynamics. Nguyen’s ultradecoherence model [71] is the nearest recent work and deserves a precise comparison. There the measurement device is assigned an open decoherence dynamics fast compared with every other relevant timescale; in that limit the device occupies a definite state to within the fast decoherence time, and clicking rates follow from the underlying parameters for von Neumann devices and photon detectors alike. The overlap is substantial: both accounts obtain event rates from open-system dynamics rather than postulating them, and neither modifies the Schrödinger equation. Two things are not supplied there and are the substance of what follows. First, the ultradecoherence limit yields a definite device state and a click rate but does not select which of the mathematically available unravelings is actual, nor introduce a single actual record history. Second, its rate is set by the device’s decoherence timescale, whereas the hazard proposed here is tied to irreversible record production. Where phase leaves the system without a readable record being formed—the eraser configurations of Section 9—the present law does not assign a vanishing rate but ceases to apply: Φ_{irr} is no longer monotone and the hazard is undefined there (Section 15). A record-production functional that assigns zero rate to reversibly encoded correlations is the intended completion, not a present result. The present proposal may accordingly be read as an ontological and record-theoretic layer over a click-generating mechanism of the kind Nguyen supplies, rather than as a competitor to it.

What is and is not claimed as novel. The root of the proposal is the one stated in Section 5: there is no particle, only a wave and the marks a bath makes. The main accounts keep a particle somewhere, at the detector or on a hidden path, or they keep every outcome: Copenhagen brings

the particle back at the detector, through a measurement rule; Bohm keeps it all along, on a path the wave steers; the collapse models squeeze the wave down to one place, with a new law and new constants (with flashes, GRW’s events are of ACT’s kind, and the law is the difference); Everett keeps no particle, but every outcome, one mark to a world. Those who say plainly that there are no particles, only fields, part ways with ACT at the detector: Hobson lets the field collapse there and leaves the cause open [56]; Zeh, who gave up the collapse as well as the particle, was left with every outcome [94]. ACT takes the third road: no particle, no collapse, one history, and the bath makes the mark; the event ontologies above come nearest to it. It follows from the above, and from Section 12, that no new empirical prediction is being offered. Within that root, the proposal’s distinctive technical content is this:

1. the *timing* of events is tied to irreversible *environmental record formation*—not merely supplied, as in Bell-type models, but conditioned on whether a record forms at all. The quantity the law computes is accessible-phase loss, which coincides with a record-production rate only under the architectural conditions of Section 7 and may otherwise bound it from above (Sections 10 and 15);
2. the physically privileged instrument is constrained by accessible record architecture rather than chosen;
3. the ontology is event-based—definiteness is produced at events—rather than a continuous assignment of properties.

Each is absent from at least one of the neighbours above; the record-conditioned form of (1) is absent from all of them.

7 The anchoring environment

The environment proposed comprises fields already known to be present: electromagnetic gauge fields with spectral weight extending to $\omega \rightarrow 0$, phonons in detectors and surrounding matter, and thermal electromagnetic fluctuations, described by the Caldeira–Leggett class of spectral densities [24, 58]. No field content is added.

Two kinds of condition must be separated, because they have different mathematical character:

- **Spectral conditions**, properties of $J(\omega)$ and the bath state, governing whether the decoherence functional diverges, converges, or recurs (Section 10.2).
- **Architectural conditions**, properties of the interaction and of information flow, which do *not* follow from $J(\omega)$: approximate QND coupling in the pointer variable, and readability of the record from small disjoint fragments.

A bath may have an ohmic spectrum and fail the architectural conditions; the architectural conditions cannot compensate for a spectrum that produces only feeble dephasing. Taken together they are *sufficient* for an asymptotically certain, architecture-selected event; finite but large record functionals may still produce measurements of arbitrarily high reliability (Section 10.2). Neither condition implies the other. This paper establishes the spectral condition by explicit calculation and treats the architectural conditions as assumptions of the selection theorem, whose model-independent status is open. One part of the release structure assumed below is supplied by the bath itself: Riedel has shown that Markovian quantum Brownian motion is an iterated entanglement-breaking measurement of the particle’s position by its environment on a preferred timescale [75], so that in this class the fragments carry records the system cannot coherently recover.

Controlled-displacement qualification. One part of the architectural package is weaker than an assumption. Within the approximately QND record window the position-local coupling has controlled form $U = \sum_r |r\rangle\langle r| \otimes U_r$, so the reduced channel into any outgoing fragment F is $\Gamma_F(\rho) = \sum_r \rho_{rr} \sigma_{F|r}$, and every fragment effect pulls back as

$$\Gamma_F^\dagger(E) = \sum_r \text{Tr}(E \sigma_{F|r}) |r\rangle\langle r|. \quad (4)$$

Within this class the confinement of fragment record statistics to the pointer algebra generated by the recorded observable is therefore a consequence of the dilation rather than an independent postulate. Two limits should be stated with it. The statement concerns fragment-accessible *outcome statistics*; it does not by itself establish irreversible loss of conditional coherence, which depends additionally on the accessibility of the distributed record. And it is a statement about the controlled/QND window: once the free system dynamics fails to commute with the recorded observable, off-diagonal corrections enter at first order relative to the record signal.

Gapped fields. A field with a mass gap Δ has no thermally populated modes below Δ , and at laboratory temperatures $k_B T \ll \Delta$ the occupation is exponentially suppressed. Such a field can generate local effective interactions when integrated out, but it does not supply the low-frequency continuum on which unbounded record growth depends: as Section 10.2 shows, a gapped spectral density yields a *bounded* decoherence functional, hence a nonzero probability that no event ever occurs. For the heavy sector of the Standard Model the gap is enormous and the thermal occupation negligible, so the bound is not merely finite but strongly suppressed—which is why such fields are implausible low-frequency anchoring baths. The argument is structural, resting on the shape of a gapped spectral density rather than on a coupling-specific computation; a quantitative exclusion for a named field would require its spectral density and coupling, and is not attempted here. Section 10.2 records why boundedness by itself would not suffice to exclude them.

8 Reduced dynamics

Take the total Hamiltonian in system–bath form, $H = H_S + H_B + H_{SB}$ with $H_{SB} = \hat{O} \otimes \hat{X}$. On the closed-time-path contour, with

$$\Sigma = \frac{1}{2}(\phi_+ + \phi_-), \quad \Delta = \phi_+ - \phi_-, \quad (5)$$

integrating out the environment gives the Feynman–Vernon influence action [39, 24]

$$S_{\text{IF}}[\Sigma, \Delta] = -2 \int_0^t ds \int_0^s ds' \Delta(s) \eta(s-s') \Sigma(s') + \frac{i}{2} \int_0^t ds \int_0^s ds' \Delta(s) \nu(s-s') \Delta(s'). \quad (6)$$

The two kernels enter with different structure: the *dissipation* kernel η couples the difference variable to the average variable and is retarded, while the *noise* kernel ν is quadratic in the difference variable and carries the factor i . Terms linear in Δ encode dissipation; terms quadratic in it encode noise.

Both are determined by one spectral density and the bath state,

$$\eta(\tau) = \int_0^\infty \frac{d\omega}{\pi} J(\omega) \sin \omega \tau, \quad \nu(\tau) = \int_0^\infty \frac{d\omega}{\pi} J(\omega) \coth\left(\frac{\hbar\omega}{2k_B T}\right) \cos \omega \tau, \quad (7)$$

Here J is normalised as in Caldeira–Leggett, so that η and ν have the dimensions required by Eq. (6); the independent-boson model of Section 10 adopts a different normalisation, in which

J carries frequency units, and the two should not be compared term by term. In terms of the retarded response χ_R of the bath coordinate, with $\text{Im } \tilde{\chi}_R(\omega) = J(\omega)/\hbar$ in this convention,

$$\tilde{\nu}(\omega) = \hbar \coth\left(\frac{\hbar\omega}{2k_B T}\right) \text{Im } \tilde{\chi}_R(\omega) \quad (8)$$

up to convention-dependent factors, for a bath in thermal equilibrium.

A theory whose noise is an autonomous postulated field has no obligation to satisfy Eq. (8). A theory whose noise and event-rate structure originate in a thermal environment satisfies it by construction: one function $J(\omega)$ fixes both the fluctuations and the dissipation. Section 11 exhibits this explicitly.

Remark. Equation (8) is a fluctuation–dissipation relation requiring equilibrium. It is not the Wiener–Khinchin theorem, which relates a stationary autocorrelation function to its power spectrum for any stationary process and carries no information about dissipative response.

9 Records, irreversibility, and the event law

Three questions. The account separates three questions that discussions of measurement tend to run together: which alternatives a detector records, when that record becomes irreversible, and which alternative is actual. The first is settled by record architecture (Section 12, Appendix A); the second by the irreversibility measure developed in this section, which supplies the event rate; the third by postulate (Section 14). The first two are constructed from standard open-system and record physics together with the event-law identification; only the third requires the ontic commitment. None of the three mentions an observer: who, if anyone, reads the record is not a variable of the account. The present section addresses the second.

9.1 What counts as a record

Why irreversibility rather than correlation. Steane has recently argued that a single-world reading of quantum theory is sustainable, without modification of the equation of motion, provided certain outcomes are not quantum-erased in the future, and that reasoning from observations must take the possibility of such erasure into account [86]. An argument of that form requires a physical criterion for when erasure is genuinely unavailable rather than merely impractical. The definition developed in this section is offered as a candidate: irreversibility is characterised through recoverable phase distinguishability rather than through system–environment correlation as such, so that configurations in which which-path information remains recombinable do not qualify.

Where a system–environment correlation remains coherently accessible—where which-path information can in principle be recombined—that correlation does not yet constitute an irreversible record of the corresponding alternative, and no anchoring of *that* alternative has occurred. Quantum-eraser configurations illustrate the distinction; detector clicks in those same experiments are separate record-forming events, and anchoring one record does not thereby determine every correlated observable of the system. Making this precise requires a measure that cannot be inflated by operations on the system alone.

A naive criterion based on the surviving off-diagonal element fails: a unitary acting on the system can rotate population imbalance into off-diagonal entries, registering “recovery” where no phase information has returned. The following definition avoids this by testing whether a *relative phase* remains distinguishable.

Definition 1 (Recoverable phase distinguishability). Fix alternatives $|j\rangle, |k\rangle$ and let

$$|\psi_\theta\rangle = \frac{1}{\sqrt{2}}(|j\rangle + e^{i\theta}|k\rangle), \quad (9)$$

with $\rho_\theta(t)$ the global state evolved from $|\psi_\theta\rangle\langle\psi_\theta| \otimes \rho_E$. Let $\mathcal{A}_{\text{acc}}$ be the *physically accessible local algebra*—determined by the detector architecture, causal locality, and the specified environmental partition—and let $\mathcal{E}_{\text{acc}}$ denote restriction to it. Define

$$\mathcal{D}(t) = \frac{1}{2} \left\| \mathcal{E}_{\text{acc}}[\rho_0(t)] - \mathcal{E}_{\text{acc}}[\rho_\pi(t)] \right\|_1, \quad \Phi_{\text{irr}}(t) = -\ln \frac{\mathcal{D}(t)}{\mathcal{D}(0)}. \quad (10)$$

The algebra is defined by the physics of the coupling and partition, not by an agent’s choices; an experimenter may exploit $\mathcal{A}_{\text{acc}}$ but does not fix it. No optimization over recovery operations appears, and none is needed: a unitary acting within the retained subsystem leaves the trace distance invariant, and any CPTP operation can only decrease it. (If one wishes to model phase information being concentrated from several fragments into a smaller readout, the output system must be named explicitly and $\mathcal{E}_{\text{acc}}$ redefined accordingly.) Because the two states differ only in relative phase, $\mathcal{D}$ cannot be inflated by rotating populations.

Monotonicity and its scope. $\Lambda(t) = \dot{\Phi}_{\text{irr}}(t) \geq 0$ requires $\mathcal{D}$ to be non-increasing, and contractivity of the trace distance delivers this only given a CPTP map carrying the accessible state at time s to that at time t for all $s < t$ —that is, *CP-divisibility* of the accessible reduced dynamics [76]. A fixed accessible set and CPTP evolution from the initial time are not sufficient; where divisibility fails, trace-distance backflow signals information returning to the accessible set [17]. Accordingly:

Scope of the event law. The construction below applies to CP-divisible (or otherwise monotone) record-forming regimes only. Where the accessible dynamics is not CP-divisible, Φ_{irr} may decrease and the hazard is undefined; such regimes lie outside the present law and require a generalized record functional. The companion paper supplies the reason for the boundary: these are the regimes in which a released record exists at all, carried by fresh, non-returning fragments, and within them a time-local jump unravelling with non-negative rates exists exactly when the reduced dynamics is CP-divisible [53, 84]. The asymmetry deserves its own sentence: the ontology is proposed generally, while the present derivations are established in Markovian/CP-divisible record-forming regimes, principally within approximately QND and linear-Gaussian windows — a regional derivation of a law proposed universally.

9.2 The event law

The law is stated at the level of a general instrument, so that the object it uses is the same object the selection theorem of Section 12 delivers. In the three-question vocabulary of Section 2: this law is the WHEN answer — the gate sets eligibility, the rate sets timing — the selection theorem of Section 12 is the WHAT answer, and the trace rule resolving the law over outcomes is the WHICH answer.

Event law. Let $\{\mathcal{I}_r\}$ be the instrument supported by the environmental records—a family of completely positive maps with $\sum_r \mathcal{I}_r$ trace preserving. Define the architectural indicator

$$g_{\mathcal{I}}(t) = \begin{cases} 1, & \mathcal{I} \text{ is supported by an admissible record architecture at } t, \\ 0, & \text{otherwise,} \end{cases} \quad (11)$$

where admissibility is the architectural condition of Section 7—approximate QND coupling in the pointer variable together with fragment readability. The total event hazard is

$$h(t) = g_{\mathcal{I}}(t) \Lambda(t) = g_{\mathcal{I}}(t) \dot{\Phi}_{\text{irr}}(t), \quad (12)$$

resolved over outcomes by the trace rule—forced at the general level by six stated premises on the law of chance, by Zurek’s argument [97, 98] in Barnum’s no-signalling form [7] (the companion paper [84], Appendix A), and checked independently for the binary QND model in Proposition 2—as

$$h_r(t) = h(t) \text{Tr}[\mathcal{I}_r(\rho_t)], \quad \rho_t \longrightarrow \frac{\mathcal{I}_r(\rho_t)}{\text{Tr}[\mathcal{I}_r(\rho_t)]}. \quad (13)$$

Admissibility is *not* implied by $\dot{\Phi}_{\text{irr}} > 0$: a bath may take phase irreversibly out of the accessible algebra while supporting no readable record, in which case $g_{\mathcal{I}} = 0$ and no event occurs however fast the dephasing.

What the gate means. In the present two-condition approximation $g_{\mathcal{I}}$ represents *structural* admissibility of the active record channel—whether the interaction architecture is of a kind that generates fragment-readable records—and not a quantitative measure of how much redundancy has so far accumulated. The latter is precisely what the unified functional of Section 15 would supply. The distinction matters for timing: a graded measure that rose only as redundancy accrued would generally open later than a structural indicator, so multiplying the instantaneous phase-loss rate by $g_{\mathcal{I}}$ plausibly *overestimates* the event probability at early times. The present hazard should accordingly be read as an upper-bound approximation to genuine record-production timing, consistent with the inequality anticipated in Section 15. What the gate is relative to is the physics of the coupling and the apparatus, the detector specification that quantum-trajectory theory also needs [92]. The companion paper gives it its definition—release of the record relative to the system’s accessible future, with readability as the permanence-side coordinate—and the structural indicator used here is the form that definition takes in the record-forming regimes of this paper.

Survival with the gate. Integrating Eq. (12),

$$S(t) = \exp\left[-\int_0^t g_{\mathcal{I}}(s) \dot{\Phi}_{\text{irr}}(s) ds\right], \quad (14)$$

which reduces to $S(t) = e^{-\Phi_{\text{irr}}(t)}$ only when the gate is open throughout. Where the gate is closed the ensemble still dephases while no event occurs, and the dephasing is then *not* generated by event statistics: the improper mixture of Eq. (2) remains improper and no outcome is actual. This is the *nonrecording decoherence* configuration—phase information leaves the accessible system monotonically without becoming a readable classical record—and it is the formal content of the claim that decoherence alone does not produce definiteness.

A quantum eraser is a distinct case and should not be conflated with it: there the phase information remains recoverable or returns, so Φ_{irr} does not accumulate monotonically and the

configuration falls outside the CP-divisible scope of Definition 1 rather than inside it with the gate closed.

Efficient special case. When each $\mathcal{I}_r$ has a single Kraus operator—an *efficient* instrument, $\mathcal{I}_\alpha(\cdot) = M_\alpha \cdot M_\alpha^\dagger$ with $\int d\alpha M_\alpha^\dagger M_\alpha = \mathbb{I}$ —Eq. (13) becomes $h_\alpha = h \text{Tr}(M_\alpha^\dagger M_\alpha \rho_t)$ with update $M_\alpha \rho_t M_\alpha^\dagger / \text{Tr}(\cdot)$. Note that Theorem 1 delivers the fine-grained localization family $\{M_y\}$ in efficient form, but the fragment-conditioned operations it licenses, $\mathcal{I}_r(\rho) = \int dy \mu_r(y) M_y \rho M_y^\dagger$, are generally *not* efficient—which is why the law is stated for CP maps.

Status of the general form. Equation (13) is the *proposed* general law. Exact ensemble recovery is demonstrated in Section 10 for the binary QND case only, and the extension is not automatic: in a multilevel measurement the pair coherences generally decay at different rates, $\rho_{jk}(t) = e^{-\Phi_{jk}(t)} \rho_{jk}(0)$ with $\Phi_{12} \neq \Phi_{13} \neq \Phi_{23}$, and a first-event process carrying a single scalar survival function cannot in general reproduce every Φ_{jk} simultaneously. Uniform dephasing or a suitable symmetry is required for the scalar law to suffice. The companion paper states the general law as the instrument path measure, of which Eq. (12) is the nondemolition corollary, and shows that outside the QND window $\dot{\Phi}_{\text{irr}}$ is not the rate: for a driven two-level atom with a photodetected output the extrapolated law gives the wrong lifetime and no antibunching, while the path-measure law gives Carmichael’s waiting-time density [84]. The law is accordingly used here only within its stated window.

This is not merely a gap in the present treatment. Sharp projective families are provably inadequate in general multilevel settings: Appendix B shows that the pair rates achievable by any static family of coarse projective jump channels are nonnegative combinations of cut pseudometrics and therefore obey the triangle inequality, whereas collisional kernels with quadratic onset violate it at small separations. The CP-map form of Eq. (13) is thus forced rather than merely convenient—smeared, record-shaped operations are what a multilevel law requires—but supplying the corresponding rate structure is the open problem of Section 15.

A complete general trajectory also requires a compatible no-event CP propagator describing the conditioned evolution between events. This is fixed explicitly in Model I, where $\sum_k L_k^\dagger L_k = \Lambda \mathbb{I}$ makes the no-event evolution uniform and leaves the normalized conditional state coherent; for the multilevel CP-map framework it remains part of the extension.

Trace preservation of $\sum_r \mathcal{I}_r$ guarantees $\sum_r h_r = h$, so the outcome resolution does not alter the total rate. When the records are sharp— $\mathcal{I}_k(\cdot) = P_k \cdot P_k$ with $P_j P_k = \delta_{jk} P_k$ —Eq. (13) reduces to

$$h_k(t) = h(t) p_k(t), \quad p_k = \text{Tr}[P_k \rho_S], \quad \rho_S \rightarrow P_k \rho_S P_k / p_k, \quad (15)$$

which is the form used in the worked model of Section 10. Stating the law this way unifies the hazard, the outcome rule, the selection theorem and the treatment of partial or imperfect measurements: the theorem constrains $\{M_\alpha\}$, and the event law then acts on whatever instrument that constraint leaves.

Equation (12) is not an arbitrary stipulation: it is the unique law consistent with the three requirements below. Those requirements are themselves substantive commitments—particularly (ii)—rather than neutral desiderata, so what follows is an identification of the law’s content given them, not a derivation of the law from nothing.

Proposition 1 (Uniqueness of the hazard, gate open). *Assume (0) a persistently admissible record architecture over the interval considered, so that $g_{\mathcal{I}} \equiv 1$ there; (i) an absolutely continuous first-event process, absorbing at its first event, with survival function $S(t)$ and instantaneous conditional event rate depending only on the current reduced record state, so that $h(t) = -\frac{d}{dt} \ln S(t)$; and (ii) ensemble consistency—the averaged process reproduces the exact coherence decay, requiring $S(t) = e^{-\Phi_{\text{irr}}(t)}$. Then $h(t) = \dot{\Phi}_{\text{irr}}(t)$ uniquely on that interval.*

Proof. By (i), $S(t) = \exp[-\int_0^t h(s) ds]$. Equating with (ii) gives $\int_0^t h = \Phi_{\text{irr}}(t)$ for all t ; differentiating, $h = \dot{\Phi}_{\text{irr}}$ almost everywhere on that interval, and pointwise wherever both derivatives exist. $\square$

Scope of assumption (ii). Proposition 1 is a uniqueness statement conditional on its hypotheses, and the load is carried by (ii). That ensemble consistency *requires* $S(t) = e^{-\Phi_{\text{irr}}(t)}$ is established below in the binary QND construction of Section 10, where the exact coherence decay is available in closed form. It is not established for general multilevel instruments, and Appendix B shows that the obvious extension fails. Outside that construction, Eq. (12) should be read as a proposed law whose uniqueness is demonstrated in a controlled case, not as a theorem of the general theory.

The cumulative hazard is $H(t) = \Phi_{\text{irr}}(t)$ and the survival probability

$$S(t) = e^{-\Phi_{\text{irr}}(t)}. \quad (16)$$

No new constant appears: the event rate is read off the same coupling that draws the decoherence curve, with no free constant, and in the nondemolition case the two curves are one—where CSL introduces λ_0 and r_C . No threshold is postulated: $\Phi_{\text{irr}} \sim 1$ is the e -folding point of a waiting-time distribution.

10 Worked model I: pure dephasing and the event statistics

10.1 Model

Take the independent-boson model, writing the coupling with an explicit $\hbar$ so that g_j carries frequency units:

$$H = \frac{\hbar\omega_0}{2}\sigma_z + \hbar\sigma_z \otimes \sum_j g_j(b_j + b_j^\dagger) + \sum_j \hbar\omega_j b_j^\dagger b_j, \quad J(\omega) = \sum_j g_j^2 \delta(\omega - \omega_j), \quad (17)$$

so that J has units of frequency and the exponent below is dimensionless. The coupling is QND, $[\sigma_z, H] = 0$, so populations are exactly conserved and the dynamics is pure dephasing. The model is exactly solvable:

$$\rho_{+-}(t) = \rho_{+-}(0) e^{-\Phi(t)}, \quad \Phi(t) = 4 \int_0^\infty d\omega \frac{J(\omega)}{\omega^2} \coth\left(\frac{\hbar\omega}{2k_B T}\right) (1 - \cos \omega t). \quad (18)$$

Accessible algebra. For this calculation we take $\mathcal{A}_{\text{acc}} = \mathcal{B}(\mathcal{H}_S)$: the entire bath is traced out, so Eq. (18) is the accessible dephasing exponent and $\Phi_{\text{irr}} = \Phi$ in regime (1) below. Including some environmental fragments in $\mathcal{A}_{\text{acc}}$ would make the trace distance depend only on the inaccessible complement, and the exponent would differ accordingly; the partition must therefore be stated, and is.

One partition, two roles. Definition 1 requires phase to have left $\mathcal{A}_{\text{acc}}$ before Φ_{irr} accumulates, whereas Theorem 1 requires fragment records to lie within accessible reach for the selection argument to bite. Since these pull in opposite directions, it must be shown that one partition can carry both roles rather than each being met by a different choice of $\mathcal{A}_{\text{acc}}$.

It can, and the reason is visible in the fanout of Appendix A. What a fragment records is the probe *position* distribution: tracing over the complement leaves a reduced fragment state in which only $|\varphi|^2$ appears (Lemma 1). The relative phase between o and o' is held by no fragment individually; it resides in correlations spread across the complement, which no fragment-accessible operation reaches. Admitting fragments to $\mathcal{A}_{\text{acc}}$ therefore adds record-reading power without

restoring accessible coherence. It does modify the exponent, since the trace distance then depends only on the inaccessible complement—but in the redundancy regime where Theorem 1 operates, with many dynamically independent fragments carrying the same record, withdrawing any finite number of them leaves the residual overlap small in the number retained, so Φ_{irr} is asymptotically unaltered.

The two requirements are accordingly satisfiable on a single partition: $\mathcal{A}_{\text{acc}}$ may contain the system together with any fragment set from which the record is read, and Φ_{irr} still accumulates, precisely because the phase has gone where no fragment reads it. What would break the compatibility is a fragment set large enough to reconstitute the which-path coherence—which is the eraser configuration already excluded in Section 9.

What this model does and does not establish. A further distinction must be drawn that the terminology can obscure. Definition 1 measures phase information leaving the accessible algebra. That is not the same as information being converted into a stable, redundant, fragment-readable record: a Markovian bath can absorb phase irreversibly while producing no independently readable fragments, no redundancy, and no broadcast structure. The quantity computed here is therefore a rate of *accessible-phase loss*, which coincides with a record-production rate only when the architectural conditions of Section 7 hold.

Accordingly:

Model I establishes the event statistics *conditional upon* the existence of an admissible record architecture. Its pure-dephasing dynamics determines the temporal hazard; it does not by itself demonstrate fragment readability or redundant record formation. Those architectural requirements enter separately, through Theorem 1.

The two conditions are not arbitrary companions—both arise from the same system–environment dynamics—but they are not yet derived from a single quantity. Section 15 states what such a unification would require.

Scope of this model. Because the coupling commutes with H_S , there is no energy exchange between system and bath in the continuous dynamics. This model therefore tests the event law, the ensemble recovery and the Born weighting, but it does *not* exhibit the noise–dissipation pairing central to Section 4. Section 11 supplies a model that does.

10.2 Three spectral regimes

The factor $(1 - \cos \omega t)$ in Eq. (18) oscillates in each mode; the distribution of modes decides the late-time behaviour, and three cases must be distinguished. They were conflated in earlier presentations of this material.

(1) Infrared-divergent continuum: complete asymptotic dephasing. For $J(\omega) = \eta \omega e^{-\omega/\omega_c}$ at $k_B T \gg \hbar \omega_c$, using $\coth(\hbar \omega / 2k_B T) \simeq 2k_B T / \hbar \omega$ and $\int_0^\infty d\omega (1 - \cos \omega t) / \omega^2 = \pi t / 2$, the *long-time* ($t \gg \omega_c^{-1}$) behaviour is

$$\Phi(t) \simeq \frac{4\pi\eta k_B T}{\hbar} t, \quad (19)$$

monotone and unbounded. At $T = 0$ the same density gives $\Phi(t) = 2\eta \ln(1 + \omega_c^2 t^2)$: slower, still unbounded. Here $\Phi_{\text{irr}} = \Phi$, $S(\infty) = 0$, and an event occurs almost surely.

(2) Infrared-convergent continuum: coherence trapping. If J is continuous but infrared-convergent, the integral is bounded,

$$\Phi(t) \leq 8 \int_0^\infty d\omega \frac{J(\omega)}{\omega^2} \coth\left(\frac{\hbar\omega}{2k_B T}\right) < \infty, \quad (20)$$

and by the Riemann–Lebesgue lemma the oscillatory contribution decays, so

$$\Phi(t) \longrightarrow \Phi_\infty < \infty, \quad \rho_{+-}(t) \longrightarrow \rho_{+-}(0) e^{-\Phi_\infty}. \quad (21)$$

Coherence is *partially* destroyed and then trapped; it does not revive. The consequence for the event law is $S(\infty) = e^{-\Phi_\infty} > 0$: a finite probability that no event ever occurs.

Two sub-cases must be distinguished, because only one of them lies inside the scope declared in Section 9. A super-ohmic density with cutoff, $J(\omega) = \eta \omega^3 e^{-\omega/\omega_c}$, gives at high temperature

$$\Phi(t) = \frac{8\eta k_B T \omega_c}{\hbar} \frac{\omega_c^2 t^2}{1 + \omega_c^2 t^2} \longrightarrow \Phi_\infty = \frac{8\eta k_B T \omega_c}{\hbar}, \quad (22)$$

which is bounded *and monotone*, hence CP-divisible in the relevant sense and fully covered by the event law. A gapped density, by contrast, is bounded but rings: its transient contains intervals with $\dot{\Phi} < 0$, which place it outside the monotone construction even though its asymptotics are the same. The gapped case is retained in Figure 1(b) to illustrate finite asymptotic dephasing, with that caveat attached.

(3) Finite or discrete bath: recurrence, and the limit of the present law. For a finite mode set, Φ is a finite sum of cosines, hence almost periodic: coherence decays and genuinely revives, with recurrence time set by the level spacing.

It does not follow from Definition 1 that no record is established here. The accessible dynamics is not CP-divisible, and Φ_{irr} *rises* during the initial dephasing before falling again. On the rising portion $\dot{\Phi}_{\text{irr}} > 0$, so the hazard of Eq. (12) would be nonzero and an absorbing event would occur—after which the stopped process could not reproduce the later revival. In the six-mode example of Figure 1, Φ reaches 56.7 before the first revival, corresponding to an event probability $1 - e^{-\Phi}$ indistinguishable from unity.

The statement is therefore the negative one:

The present monotone hazard construction does not apply to a finite recurrent bath. Such a bath shows why temporary dephasing cannot be identified with irreversible record production, and a generalized record functional is required to separate the two.

This is a limitation of the current event law, not a result derived from it.

Sufficiency, not necessity. Only case (1) yields a completed measurement with probability one, and it is *boundedness*, not recurrence, that distinguishes the infrared-convergent continuum. But infrared divergence is sufficient for an asymptotically certain event, not necessary for a reliable one. The monotone example of Eq. (22) with $\eta = 0.05$, $k_B T = 50$, $\omega_c = 1$, $\hbar = 1$ gives $\Phi_\infty = 20$ exactly, hence a no-event probability $e^{-20} \approx 2 \times 10^{-9}$: operationally a detector failing twice per billion runs, and one that lies inside the event law’s scope. The hierarchy is therefore

- infrared divergence $\Rightarrow$ an event asymptotically with probability one;
- finite $\Phi_\infty \Rightarrow$ event probability $1 - e^{-\Phi_\infty} < 1$;
- finite but *large* $\Phi_\infty \Rightarrow$ measurements of arbitrarily high reliability.

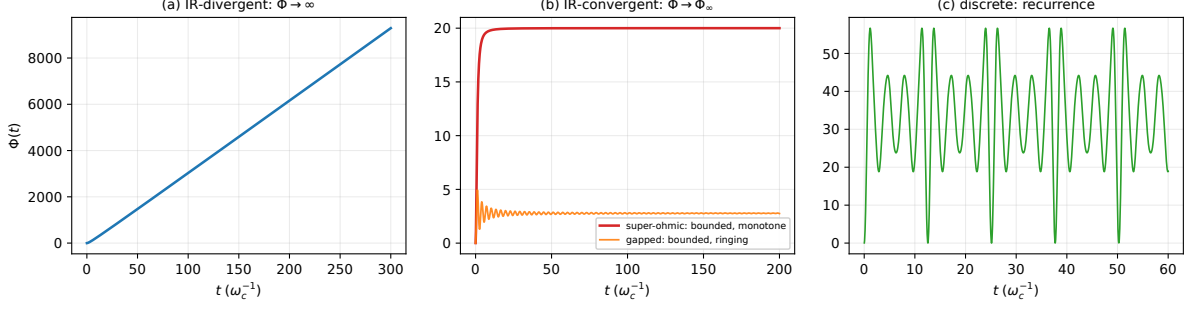


Figure 1: The three regimes of Eq. (18) ($\hbar = k_B = 1$, $\eta = 0.05$, $\omega_c = 1$, $T = 50$; gap $\Delta = 2$; discrete bath of six modes), on linear scales. **(a)** Infrared-divergent (ohmic) continuum: Φ grows without bound. **(b)** Infrared-convergent continuum: the super-ohmic density $J = \eta\omega^3 e^{-\omega/\omega_c}$ rises monotonically to $\Phi_\infty = 8\eta k_B T \omega_c / \hbar = 20$ and lies inside the event law’s scope, while the gapped density settles to $\Phi_\infty = 2.774$ but rings on the way, placing its transient outside the monotone construction. **(c)** Discrete bath: genuine recurrence, returning to $\Phi \approx 0$; outside the present law entirely. Panels are separated because the divergent case otherwise compresses the bounded ones beyond legibility.

Boundedness alone is accordingly not an exclusion theorem. Gapped fields of the heavy Standard-Model sector remain implausible baths for the reasons given in Section 7—an enormous gap, negligible thermal occupation at laboratory temperatures, and no low-energy continuum—which strongly suppress the relevant low-frequency bath weight. As in Section 7, the argument is structural; a coupling-specific quantitative exclusion is not established here.

10.3 Event dynamics, ensemble recovery, and Born weights

The records here are sharp, so the instrument is $\{P_\pm\}$ with $P_\pm = \frac{1}{2}(1 \pm \sigma_z)$. The outcome *weights*, however, are left open: we do not assume that the conditional probability of outcome k given an event is p_k , since assuming it and then recovering it would be circular. Write that conditional probability as an unknown, possibly time-dependent, $q_k(t)$, with total hazard $h(t) = \Lambda(t)$ fixed by Eq. (12).

Proposition 2 (Outcome weights are forced within an outcome-neutral first-event process). *Let the coupling be QND, so the exact populations p_k are constant; let events occur at total rate $h(t)$ with survival $S(t) = e^{-\int_0^t h}$ and unknown conditional outcome law $q_k(t)$; and assume the first-event process is outcome-neutral, meaning that conditioning on no event having occurred by time t does not bias the pointer populations, so that the normalized no-event state still carries population p_k . Then ensemble agreement with the exact dynamics requires $q_k(t) = p_k$ at every t with $h(t)S(t) \neq 0$.*

Proof. Let $r_k(t)$ denote the pointer population of the normalized no-event state. Decomposing the ensemble population of outcome k into the surviving and already-fired parts gives, in general,

$$p_k = S(t) r_k(t) + \int_0^t ds h(s) S(s) q_k(s), \quad (23)$$

and outcome-neutrality is the statement $r_k(t) = p_k$, whence

$$p_k = S(t) p_k + \int_0^t ds h(s) S(s) q_k(s). \quad (24)$$

Differentiating and using $\dot{S} = -hS$,

$$0 = -h(t)S(t) p_k + h(t)S(t) q_k(t), \quad (25)$$

so $q_k(t) = p_k$ wherever $hS \neq 0$. $\square$

Why outcome-neutrality is not question-begging. The hypothesis constrains the first-event *clock*, not the outcome weights: it says the waiting-time process does not preferentially remove one pointer alternative from the surviving ensemble, and it leaves $q_k(t)$ entirely free. It does not follow from a scalar total rate alone—jump families with $\sum_k L_k^\dagger L_k \not\propto \mathbb{I}$ can reproduce the same $h(t)$ on a given state while reweighting the no-event state—which is why it is stated rather than left implicit. A reader who prefers the converse order may take Eq. (26) as defining the model and read Proposition 2 as showing that no other outcome law is consistent with it.

The weights are therefore forced, within the outcome-neutral scalar-hazard construction, by QND population conservation together with exact ensemble agreement—and forced even against a time-dependent alternative law, which is stronger than excluding a constant one. In this controlled model the trace-rule resolution of Eq. (13) is therefore recovered rather than assumed. The general ground of the weights is elsewhere: the companion paper’s Appendix A forces them for every released record from six stated premises on the law of chance, and the descent exhibited here, in which the conditioned weights form a martingale, is the check that the single-history law and the master equation agree. We may write

$$h_k(t) = h(t) p_k, \quad L_\pm = \sqrt{\Lambda} P_\pm, \quad (26)$$

as consequences. Since $\sum_k L_k^\dagger L_k = \Lambda \mathbb{I}$, the no-event evolution decays uniformly: the normalized conditional state evolves by H_S alone and remains fully coherent until an event occurs. That uniformity is exactly the outcome-neutrality hypothesised in Proposition 2, so the construction and the proposition are mutually consistent.

The stopped process then gives

$$\rho_S(t) = S(t) \rho_S^{\text{coh}}(t) + [1 - S(t)] \sum_k P_k \rho_S(0) P_k, \quad S(t) = e^{-\Phi_{\text{irr}}(t)}, \quad (27)$$

whose off-diagonal element is $\rho_{+-}(t) = \rho_{+-}(0) e^{-\Phi_{\text{irr}}(t)}$, reproducing Eq. (18) in regime (1). The stopped event ensemble exactly reproduces the reduced dephasing generated by the underlying system–bath dynamics; no additional dephasing term is imposed by the event ontology, and nothing is double-counted.

The first-event distribution then follows:

$$P(k) = \int_0^\infty h_k(t) S(t) dt = p_k (1 - e^{-\Phi_{\text{irr}}(\infty)}), \quad P(k | \text{event}) = p_k. \quad (28)$$

In monotone instances of regime (2), a finite $\Phi_{\text{irr}}(\infty)$ leaves a residual no-event probability $e^{-\Phi_{\text{irr}}(\infty)}$. Regime (3) lies outside the present construction and is not covered by Eq. (28).

First events and subsequent ones. Proposition 1 treats a process absorbing at its first event, and the results above accordingly describe the first anchoring event of a measurement episode. A continuing realized history requires the process to restart: the hazard recomputed from the post-event conditional state, the instrument re-derived from the record structure then obtaining, and the accessible algebra updated once a durable record has formed—a renewal-type construction. Nothing in the present formalism obstructs this, but it is not developed here, and the phrase “one conditioned history” should be read as an ontological commitment (Section 5) rather than as a claim that the multi-event mathematics has been carried out.

10.4 Numerical verification

All quantitative claims are checked numerically (see Data Availability); Figure 1 is produced by the same script. In regime (1) the long-time slope converges to the predicted $4\pi\eta k_B T/\hbar = 31.416$

(numerical slopes $30.72 \rightarrow 31.19$ over $t \in [20, 100]$), and the $T = 0$ result matches $2\eta \ln(1 + \omega_c^2 t^2)$ to five decimal places. In regime (2) with $\Delta = 2$, Φ settles to $\Phi_\infty = 2.774$, with tail variation 5×10^{-2} over $t \in [200, 400]$ —settling, not reviving—leaving residual coherence $e^{-\Phi_\infty} = 0.062$. This value is exactly half the analytic bound 5.548, as it must be: the bound replaces $(1 - \cos \omega t)$ by its maximum 2, and the oscillatory average tends to unity for any infrared-convergent density, so saturation of the half-bound is a consistency identity rather than an independent check. In regime (3) the six-mode bath returns to $\Phi \approx 0$, a genuine revival, having first reached $\Phi = 56.7$ —so a monotone hazard would have fired with probability indistinguishable from unity before the revival, which is why that regime is excluded from the present law. For the Caldeira–Leggett model the coefficient audit confirms that $-i\gamma/(2\hbar)$ is required for $\langle p \rangle$ to damp at γ and $m\gamma k_B T/\hbar^2$ for $\langle p^2 \rangle$ to equilibrate at $mk_B T$, and the ratio Eq. (32) then evaluates to 50.00 against $\frac{1}{2}(\Delta x/\lambda_{\text{th}})^2 = 50.00$. Equation (28) returns $P(k \mid \text{event}) = p_k$ to six decimals with total event probability 1.000000; $\sum_k L_k^\dagger L_k = \Lambda \mathbb{I}$ holds exactly; and the fragment invariance of Lemma 1 is exact to machine precision.

11 Worked model II: Caldeira–Leggett and the noise–dissipation pairing

Model I deliberately switches off energy exchange. The pairing claim of Section 4 therefore requires a second model in which the coupling does not commute with H_S .

Take a particle of mass m bilinearly coupled to an ohmic bath,

$$H = \frac{p^2}{2m} + V(x) + x \otimes \sum_j c_j q_j + H_B, \quad J(\omega) = m\gamma\omega, \quad (29)$$

whose high-temperature master equation is [24]

$$\partial_t \rho = -\frac{i}{\hbar}[H_S, \rho] - \frac{i\gamma}{2\hbar}[x, \{p, \rho\}] - \frac{m\gamma k_B T}{\hbar^2}[x, [x, \rho]], \quad (30)$$

in the convention where the classical limit is $m\ddot{x} = -V'(x) - m\gamma\dot{x} + \xi(t)$. The friction coefficient is fixed by requiring $\langle p \rangle$ to damp at rate γ : since $\text{Tr}(p[x, \{p, \rho\}]) = -2i\hbar\langle p \rangle$, a coefficient $-i\gamma/\hbar$ would give damping at 2γ , and the factor of $\frac{1}{2}$ in Eq. (30) is required for consistency with $J(\omega) = m\gamma\omega$. The diffusion coefficient is fixed in the same convention by equipartition: with $\text{Tr}(p^2[x, \{p, \rho\}]) = -4i\hbar\langle p^2 \rangle$ and $\text{Tr}(p^2[x, [x, \rho]]) = -2\hbar^2$, the stationary momentum variance under Eq. (30) is $\langle p^2 \rangle = mk_B T$ only for the coefficient $m\gamma k_B T/\hbar^2$; the more familiar $2m\gamma k_B T/\hbar^2$ belongs to the convention in which momentum damps at 2γ . The third term is noise, dephasing a superposition of separation Δx at rate

$$\Gamma_{\text{dec}} = \frac{m\gamma k_B T}{\hbar^2} (\Delta x)^2. \quad (31)$$

Status of Eq. (30). The bare high-temperature Caldeira–Leggett generator is not completely positive, and is used here solely to display the linked damping and diffusion coefficients in their most transparent form—not as a fundamental generator valid for all states and times. Nothing in the argument depends on that, since only the ratio Eq. (32) is used; the minimal Lindblad correction of Diósi [34] or the exact Hu–Paz–Zhang equation [58] may be substituted without affecting it.

The point is that both coefficients descend from the single quantity $m\gamma$ appearing in $J(\omega)$, as required by Eq. (8). Their ratio is fixed with no freedom:

$$\frac{\Gamma_{\text{dec}}}{\gamma} = \frac{mk_B T (\Delta x)^2}{\hbar^2} = \frac{1}{2} \left(\frac{\Delta x}{\lambda_{\text{th}}} \right)^2, \quad \lambda_{\text{th}} = \frac{\hbar}{\sqrt{2mk_B T}}, \quad (32)$$

verified numerically (see Data Availability). One cannot dial the decoherence rate without dialling the damping.

This is precisely the structure that an autonomous collapse field lacks. Standard CSL supplies a localization rate λ_0 with *no* damping partner, which is why Eq. (3) follows; dissipative CSL restores a partner by introducing a finite-temperature noise sector with an additional parameter [81]. Here the partner is not introduced—it is a consequence of the environment being a physical thermal bath.

Applied to this model, the event law takes the pointer variable to be position, with Λ the irreversible growth rate of the position decoherence functional. The three-regime analysis of Section 10.2 was derived for the exact pure-dephasing model and does not transfer automatically here, since a dissipative particle’s alternatives are not fixed: position and momentum evolve together and the separation Δx changes with time. The defensible statement is the local one: *for two approximately fixed position alternatives over the timescale considered*, Eq. (31) gives a monotonically increasing decoherence exponent, permitting the same hazard construction in that window. A full treatment of position, momentum and dissipation together—needed both to remove this restriction and to locate the regime boundary of Section 12 quantitatively—is open.

12 Outcome selection

It remains to say why the pointer decomposition, rather than some mathematically equivalent alternative unraveling, is the physical one.

Theorem 1 (Selection; proved in Appendix A). *Let a probe in wavepacket φ acquire the value of a system observable $\hat{O}$ through $U = \exp(-i\hat{O} \otimes \hat{p}_E)$, and let the probe be read by a position-diagonal environmental fanout acting on the probe’s position before free evolution converts momentum information into position information. Then every conditioned system operation obtainable from fragment records alone has the form*

$$\rho_S \mapsto \int dy \mu(y) M_y \rho_S M_y^\dagger, \quad M_y = \varphi(y - \hat{O}), \quad \mu(y) \geq 0, \quad (33)$$

a classical post-processing of the localization instrument $\{M_y\}$. Moreover, provided (i) the translated wavepackets are pairwise non-proportional on the spectrum of $\hat{O}$ — $\varphi(y - \cdot)$ and $\varphi(y' - \cdot)$ are not related by a constant factor for $y \neq y'$ in $\text{supp } \mu$ —and (ii) $|\varphi(y - o)|$ is non-constant across the relevant eigenvalues o , no nontrivial momentum-kick instrument $L_q = \tilde{\varphi}(q) e^{-iq\hat{O}}$ is realizable by such records.

The status of this result. The theorem is derived entirely from standard unitary system–probe–environment dynamics. It is therefore *not* a new operational prediction: ordinary quantum mechanics, restricted to the same fragment records, issues the same restriction. Its role here is interpretive but non-arbitrary—it identifies, from the physical record architecture, which of the mathematically available unravelings is treated as actual, consistent with the operational equivalence stated in Section 15.

A class, not a unique instrument. Equation (33) constrains fragment-accessible conditioning to the localization class, but does not fix the weight $\mu(y)$, the resolution, or the coarse-graining. What the record structure delivers is the instrument *class* together with the coarse-grainings physically available within it; the event law of Section 9 then acts on whichever member that leaves. Claims that the record architecture determines a unique instrument are stronger than this result supports.

Regime boundary. The result requires record formation fast compared with probe dispersion, $\tau_{\text{rec}} \ll t_{\text{disp}} \sim m_E \sigma^2 / \hbar$. Outside that regime the conclusion inverts: free flight converts momentum displacement into later position displacement, $\Delta y = \hbar q t / m_E$, so a downstream position-local environment can record momentum—time-of-flight is how momentum is ordinarily measured—and the selected instrument follows the recorded variable. Model-independent uniqueness, extension to general POVMs, and a covariant formulation remain open.

13 The conservation statement

A clear distinction between structural and trajectory-level conservation is essential, and the claim made is the former.

Unlike an autonomous stochastic collapse field, the noise and event-rate structure here are placed within an explicit system–bath framework. The *unconditioned* subsystem energy balance is generated by exchange with a physical bath, whose dissipation partner to the noise is supplied by the fluctuation–dissipation relation, Eq. (8)—demonstrated explicitly in Section 11—rather than posited. A trajectory-level account of the energy associated with an individual anchoring event remains open.

This does not assert that each individual anchoring event conserves energy at the trajectory level. For jump operators commuting with H_S the reduced energy is conserved in ensemble expectation while an individual jump carries the conditional energy from $\sum_k p_k E_k$ to E_k ; a strict trajectory ledger requires a bath-conditioned event map displaying the accompanying change in the bath state, which is open. The looser formulation—that the fluctuation–dissipation relation guarantees energy conservation—should be avoided.

14 What is postulated

The ontic postulate. One record history is physically actual.

This is not derivable from the reduced dynamics. Attached only at release, as it is here, it changes no prediction (Corollary 2 of [84]), and it is justified by the explanatory work it does. It is not a hidden variable of Bohm’s kind: Bohm adds a particle with a definite position at all times; ACT adds no particle, only the fact of which marks were made.

The count should be stated exactly, because it is easy to misstate in either direction. Two structural features are posited in this paper and should be visible as such: *the outcome register is exclusive* — each anchoring event contributes exactly one outcome from the record-supported alternatives, a feature carried here by the event process and the instrument construction, not extracted from the unitary dynamics (the three-level distinction of Section 2) — and *one record history is actual*, the boxed postulate above. To these is added one event-law identification, Eq. (12); Proposition 1 reduces it to a consistency consequence of an absolutely continuous first-event process and ensemble agreement, but those assumptions are themselves choices. In the record-algebra class of the companion paper [84] the first commitment is a theorem—the algebra generated by the records is commutative, its spectrum is the set of histories, and the joint spectral projectors are orthogonal, so that exclusivity follows from the record structure—and the identification is the nondemolition case of the instrument path measure. One primitive commitment then remains, the boxed postulate. This paper states exclusivity as a commitment so that nothing in it depends on that result; a reader who grants the companion theorem counts one, a reader who does not counts two, and the postulate ledger of the companion paper records both counts side by side. The Born weights of the trace rule are not a further commitment

of this paper: the companion paper’s Appendix A forces them under six stated premises on the law of chance — three restating the ontology and the postulate above, one extending the parameter-independence requirement below to every division of the network, one an assumption about the record architecture (any released record can be refined by a fresh released pointer), and one, continuity of a record’s chance in the wave, new — and Proposition 2 is their check in the model. Everything else in the framework is standard open-system physics, arranged.

Entangled records and Bell nonlocality. The postulate has a consequence that should be stated. One actual record history with Born weights reproduces the quantum statistics of Bell experiments, and these violate the Bell–CHSH inequality [10], as loophole-free tests confirm [55, 49, 79, 87]. The framework neither correlates the measurement settings with the source nor admits influences running backward in time, so it is nonlocal in Bell’s sense. Which kind: in Jarrett’s decomposition [59] the record history violates outcome independence and satisfies parameter independence. Parameter independence is not read off the weights here. It is a requirement of the framework, placed on the law of chance; the companion paper’s Appendix A states it for every division of the network and uses it to force the weights, and the weights it forces then satisfy it, as the marginal below shows. When one end’s record is anchored, the other end anchors from what is left of the entangled structure consistent with that record,

$$\rho_{B|a} = \frac{\text{Tr}_A[(P_a^x \otimes \mathbb{I}) \rho_{AB}]}{\text{Pr}(a | x)}, \quad \text{Pr}(b | a) = \text{Tr}[P_b^y \rho_{B|a}], \quad (34)$$

while $\sum_a \text{Pr}(a, b | x, y) = \text{Tr}[P_b^y \rho_B]$ does not depend on the distant setting x , so nothing can be signalled. This is what Shimony called passion at a distance [80]. Standard quantum mechanics with definite outcomes and the collapse models share it; Bohmian mechanics violates parameter independence as well, at the level of its complete state. The joint statistics do not depend on which end is conditioned first, $\text{Pr}(a | x) \text{Pr}(b | a) = \text{Pr}(b | y) \text{Pr}(a | b) = \text{Pr}(a, b | x, y)$, so records at spacelike separation need no time order between them. The interpretive layer of Section 5 is not offered as a way around this nonlocality; its role here is only that no preferred order is required. A covariant formulation of the event law remains open (Section 15), and so does its statement as a stopping time of a filtration generated by the coupling structure.

What the postulate carries remains light. The bath is established physics; the rate is read from the decoherence functional; the instrument is selected by record architecture; the dissipative structure follows from Eq. (8). No new field, constant, or threshold is introduced.

15 Open problems

1. **An instrument-resolved record-production functional.** This is the central open problem, and it subsumes several others. The present framework supplies the event rate from accessible-phase loss and the instrument class from record architecture, as two conditions on the same system–environment dynamics rather than as consequences of one quantity. A unified formulation would replace them with a single object indexed by candidate instrument class, $\mathcal{R}_{\mathcal{I}}(t)$, from which the actualized class follows as the dominant index and the hazard as $\frac{d}{dt} \mathcal{R}_{\mathcal{I}_*}(t)$.

Such a functional must: vanish for reversible entanglement and eraser configurations; vanish when phase leaves the system without a readable record being produced; grow when several dynamically independent fragments encode the same alternatives; identify a stable instrument class; be monotone in genuine outgoing-record regimes; recover the present hazard in the Markovian limit; and reproduce Born weights and the unconditioned master equation. Fragment mutual information is probably the wrong starting point, since entanglement alone can inflate it without producing a locally readable record; distinguishability of *conditional*

fragment states, in the spirit of spectrum-broadcast structure [66], is better suited. Two difficulties should be anticipated: redundancy is normally characterized by a late-time plateau rather than an instantaneous production law, so obtaining a differentiable rate is not automatic; and since record formation is generally slower than decoherence, such a functional may yield a hazard *below* $\dot{\Phi}_{\text{irr}}$, in which case the present law is an upper bound rather than the rate.

A successful construction would also dissolve two current limitations rather than merely scoping them: the finite recurrent bath would fail to anchor because its fragments are not dynamically independent, and the instrument switch at $\tau_{\text{rec}} \sim t_{\text{disp}}$ would follow from a change in the dominant index rather than being imposed as a regime condition.

A complete formulation should also make explicit how the component structure of the pre-event state is related to the distinct alternatives of the record-supported instrument. The present account obtains that correspondence from environmental selection (Theorem 1); whether Fourier or normal-mode structure plays a more fundamental role in it remains open. The companion paper states the general law at the level of the instrument path measure, of which the present hazard is the nondemolition case, and gives the gate its definition as release; the functional described in this item is the readability-side quantity, which the companion paper locates but does not construct [84].

2. **Trajectory-level energy accounting:** the bath-conditioned event map of Section 13.
3. **Architectural conditions.** Within the controlled-displacement class of Section 7, diagonality of the fragment record statistics follows from the dilation rather than being assumed (Eq. 4). What remains assumed in Theorem 1 is the physical availability and locality of the record fragments, together with the regime in which the controlled/QND approximation holds; neither can be stated as an inequality on $J(\omega)$. Determining which detector models satisfy them is open.
4. **Model-independent uniqueness** for the selection theorem, with POVM extension and covariant formulation.
5. **Position, momentum and dissipation treated together** in a QBM bath, required for a quantitative regime boundary.

On empirical content. The present formulation is deliberately operationally equivalent to the corresponding unconditioned dynamics within its stated regime. Its contribution is a mathematically specified event ontology: accessible irreversible phase loss, conditional on a record-capable architecture, fixes the event hazard—an identification which, as item 1 above records, may yet prove to be an upper bound on the rate of record production itself—while record architecture constrains the actualized instrument class.

Four senses of empirical standing should be kept distinct; they are taken here from the strongest down. The physics the mechanism runs on is experimentally grounded: decoherence rates controlled by which-path distinguishability, coherence recoverable until records spread, and pointer information redundantly imprinted across environments are measured facts, and the two conditions of the event law are built from them. The mechanism is substantially falsifiable at the level of its supports: the law ties eligibility and rate to concrete, calibrated architecture, so definite outcomes in a configuration whose complete record remains accessibly reversible, or anchoring statistics decoupled from calibrated irreversible dephasing where the regime conditions hold, would refute the identification rather than merely disfavor it. What is *not* presently claimed is a unique deviation from the predictions of unconditioned quantum mechanics — the equivalence above is by construction — and what is not presently available is a direct empirical test of the one-history postulate itself; on those two rungs the framework stands where every

no-new-prediction interpretation stands. The theory’s empirical content lives in the first two senses, within the stated regime.

What the laboratory has settled. The experiments that bear on the mechanism are catalogued, with what each corroborates and what it does not establish, in the registry that accompanies this paper [82]; the companion paper reads them against the candidate placements of an event [84]. They fall into four families, and together they walk the chain of Section 5. A passive dissipative body with no readout destroys interference in proportion to its loss, and a record is what counts, not an interaction [85, 63]. The rate of record formation is a laboratory number set by the coupling: a cavity field prepared in two coherent components decoheres faster for larger separation, with decoherence and damping tied by one coupling [22, 29], and engineered reservoirs dial the rate in a trapped ion [70, 89]. The coupling selects which alternatives can be recorded and never the outcome, and the selection is unitary: a Stern–Gerlach magnet fixes the axis [45], a change of reservoir changes the pointer basis [89], and the split beams recombine [67]; what a coupling separates can be brought back together while no record has been released—a cavity returns the excitation it took [21], which-path information carried by a scattered photon is regained by selecting on the photon [26], erasing a record not yet released lets the marks be sorted into subsets that show fringes [64], emission returned by a mirror or along a delay line alters the source’s own decay [37, 2], and a quantum jump has been caught and reversed in flight [68]—so that an event placed at first interaction, at decoherence of the reduced state, or at the first appearance of a carrier, by a rule that makes the unselected alternatives unavailable to the later dynamics, would assert facts the dynamics later undoes, and release is the earliest placement the data allow; later placements, and accounts with no events at all, survive as well. And every detection is one mark, with Born weights, and no event leaves two: one photon at a beam splitter fires one detector and never both while the same photons interfere [46], and resonance fluorescence is antibunched [65, 31]. These experiments place almost the whole of the mechanism on measured ground, exclude, for event rules of that kind, the three neighbouring placements of the event, and leave one bit, actuality, to the postulate of Section 14. The excess radiation the collapse models predict would, had it appeared, have refuted this account together with unmodified quantum mechanics; it has not appeared [35].

16 Conclusion

De Broglie restored wave character to matter while retaining a corpuscle. Schrödinger supplied the wave’s equation of motion and hoped the corpuscle could be dispensed with. Born supplied the statistical interpretation, and in doing so converted the question of the physical transition into a question about measurement, where the dominant formalism no longer required a dynamical answer. Decoherence explained the environmental suppression of alternatives without explaining the occurrence of one. GRW and CSL restored the demand for a real localization event, at the cost of autonomous collapse dynamics.

What is proposed here is a record-conditioned event law arising from quantum Brownian motion in an environment already present. The claim is not that de Broglie’s or Schrödinger’s mechanisms are revived; theirs were intrinsic to the particle, and this one is environmental. Nor is it that new phenomena are predicted; they are not. The claim is that the demand those programs made—that the appearance of a localized event have a physical account—can be met with machinery that did not exist in 1927, and that the resulting account supplies what comparable proposals leave open: a candidate law for when events occur, and a constraint on the record-supported instrument class within which they are actualized.

The resulting picture is not one in which possibilities are removed. Anchoring does not reduce the wave; it adds a determination. What was indeterminate—which record obtains—becomes determinate, and stays so, while the components through which no history passes remain what

they were: the structure of one field, the possibilities for anchoring, weighted by their amplitudes. The wave is what exists; the particle is what happens. A bath, not an observer, makes the mark, and one history of marks is actual. The companion paper [84] carries the algebra: exclusivity as a theorem, release as the criterion, the general event law, and the laboratory’s placement of the event.

Statements and Declarations

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Data Availability. No external or third-party datasets were used. The numerical data underlying Fig. 1 and the reported verification checks are generated by the archived scripts listed below and are reproducible by running them. All quantitative claims are reproduced by the verification scripts `ACT_FoP_MatterWaves_Verification.py` (spectral regimes, Caldeira–Leggett coefficient ratio, event statistics, Fig. 1), `ACT_FoP_Born_TimeDependent_Check.py` (Proposition 2), and `ACT_FoP_CutCone_Check.py` (Appendix B), archived at <https://anchoredcausality.org> and deposited in Zenodo at <https://doi.org/10.5281/zenodo.21844369>.

Code Availability. All code is openly available in the Zenodo deposit <https://doi.org/10.5281/zenodo.21844369> under the MIT License; the scripts require only `numpy` and `matplotlib`.

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A Proof of the selection theorem

Setup. Let $\hat{O}$ have eigenbasis $\{|o\rangle\}$, and let a probe prepared in $\varphi(y)$ acquire the value through $U = \exp(-i \hat{O} \otimes \hat{p}_E)$:

$$|\Psi\rangle = \sum_o c_o |o\rangle \otimes |\varphi_o\rangle, \quad \varphi_o(y) = \varphi(y - o). \quad (35)$$

The two rival instruments are

$$M_y = \varphi(y - \hat{O}), \quad L_q = \tilde{\varphi}(q) e^{-iq\hat{O}}. \quad (36)$$

Fanout. Let the environment read the probe through

$$V = \int dy |y\rangle\langle y| \otimes V_y, \quad (37)$$

acting on the probe's position variable, so that

$$|\Psi'\rangle = \sum_o c_o |o\rangle \otimes \int dy \varphi(y-o) |y\rangle \otimes V_y |E_0\rangle. \quad (38)$$

Lemma 1 (Phase-only probe information is absent from fragment records). *For any fragment F , the reduced state ρ_F depends on φ only through $|\varphi|^2$; hence $\varphi(y) \mapsto e^{iqy}\varphi(y)$ leaves every ρ_F invariant.*

Proof. Tracing Eq. (38) over system, probe and the complement of F , and using $\langle y'|y\rangle = \delta(y-y')$,

$$\rho_F = \sum_o |c_o|^2 \int dy |\varphi(y-o)|^2 \rho_F(y), \quad \rho_F(y) = \text{Tr}_{\bar{F}} [V_y |E_0\rangle\langle E_0| V_y^\dagger]. \quad (39)$$

Only $|\varphi|^2$ appears, and $|e^{iqy}\varphi(y)|^2 = |\varphi(y)|^2$. $\square$

Proof of Theorem 1. Let $\{E_r\}$ be any POVM on fragment records, so that $0 \leq E_r \leq \mathbb{I}$ and $\sum_r E_r = \mathbb{I}$, and let $M_F = E_r$ be one of its effects. The unnormalized conditioned system state is

$$\begin{aligned} \text{Tr}_{P,E} [\langle \mathbb{I}_S \otimes M_F | \Psi'\rangle\langle \Psi'|] &= \sum_{o,o'} c_o c_{o'}^* |o\rangle\langle o'| \int dy \int dy' \varphi(y-o) \varphi^*(y'-o') \langle y'|y\rangle \text{Tr} [M_F \sigma_{yy'}] \\ &= \sum_{o,o'} c_o c_{o'}^* |o\rangle\langle o'| \int dy \varphi(y-o) \varphi^*(y-o') \mu(y), \end{aligned} \quad (40)$$

with $\mu(y) = \text{Tr} [M_F \rho_F(y)] \geq 0$. Writing $\mu_r(y) = \text{Tr} [E_r \rho_F(y)]$ for the weight induced by effect E_r , and noting that each $\rho_F(y)$ of Eq. (39) is a normalized state, the condition $\sum_r E_r = \mathbb{I}$ gives $\sum_r \mu_r(y) = 1$ for every y . The resulting family is therefore a genuine classical post-processing rather than merely a nonnegative reweighting. This is exactly

$$\rho_S \mapsto \int dy \mu(y) M_y \rho_S M_y^\dagger, \quad (41)$$

a classical post-processing of $\{M_y\}$.

For the second statement we argue by Kraus rank rather than by phase-invariance alone, since invariance of the weights does not by itself exclude an accidental coincidence for some special φ .

The map $\rho \mapsto L_q \rho L_q^\dagger$ has Kraus rank one. The fragment-conditioned map Eq. (41) is a positive mixture $\int dy \mu(y) M_y \cdot M_y^\dagger$ of operators M_y that are diagonal in the $\hat{\mathcal{O}}$ eigenbasis with entries $\varphi(y-o)$. Its Choi operator is $\int dy \mu(y) |m_y\rangle\langle m_y|$ with $|m_y\rangle$ the vectorization of M_y ; this has rank one if and only if the vectors $\{|m_y\rangle : y \in \text{supp } \mu\}$ are mutually parallel, i.e. the functions $\varphi(y-\cdot)$ are pairwise proportional almost everywhere on $\text{supp } \mu$. That is excluded by the non-proportionality hypothesis, which holds for any translated localized wavepacket whose support genuinely moves with y . Hence for μ supported on more than a single point the conditioned map has Kraus rank greater than one and cannot equal $L_q \cdot L_q^\dagger$. For μ concentrated at a single y the map is $M_y \cdot M_y^\dagger$, of rank one, and the exclusion instead uses hypothesis (ii): $L_q = \tilde{\varphi}(q) e^{-iq\hat{\mathcal{O}}}$ has *constant* modulus $|\tilde{\varphi}(q)|$ across the spectrum, whereas M_y has entries $\varphi(y-o)$ of non-constant modulus, so no scalar multiple relates them. This is where a finite spectrum could otherwise admit an accidental coincidence. Lemma 1 supplies the complementary fact that μ carries no q -dependence with which such a coincidence could be engineered. $\square$

Scope. The proof uses (i) position-diagonality of the fanout, Eq. (37); (ii) that the fanout couples to the probe’s position *before* free evolution converts momentum or phase information into position information—the orthogonality $\langle y'|y \rangle = \delta(y - y')$ holds at any time, but the identification of the recorded variable with the initially displaced one does not; and (iii) access restricted to fragments. Relaxing (ii) restores momentum recording by time-of-flight. Relaxing (iii) restores access to complementary global measurements and a correspondingly larger class of unravelings, which is the standard trajectory-theory situation.

B The multilevel cut-cone obstruction

This appendix proves the claim of Section 9 that static families of coarse projective jumps cannot reproduce collisional dephasing kernels with quadratic onset.

Let the pointer index set be $V = \{1, \dots, n\}$. For $S \subseteq V$ define the *cut pseudometric*

$$\delta_S(j, k) = \begin{cases} 1, & |\{j, k\} \cap S| = 1, \\ 0, & \text{otherwise.} \end{cases} \quad (42)$$

Each δ_S is a pseudometric on V ; the *cut cone* is the set of nonnegative combinations $\sum_S w_S \delta_S$, $w_S \geq 0$ [30].

Lemma 2 (Projective families generate cut-cone rates). *Let $\{\mathcal{P}^{(c)}\}_c$ be any static family of partitions of V , channel c applying the projective coarse-graining $\{P_A : A \in \mathcal{P}^{(c)}\}$ at rate $w_c \geq 0$. The induced pair dephasing rates are $\Gamma_{jk} = \sum_c w_c \mathbb{K}[j, k \text{ in different blocks of } \mathcal{P}^{(c)}]$, and Γ lies in the cut cone.*

Proof. A projective channel dephases ρ_{jk} exactly when j and k lie in different blocks, so the stated form of Γ_{jk} follows by summing independent channels. For a partition $\mathcal{P} = \{A_1, \dots, A_m\}$, write $\delta_{\mathcal{P}}(j, k) = \mathbb{K}[j, k \text{ in different blocks}]$. Summing the block cuts, $\sum_{i=1}^m \delta_{A_i}(j, k)$ equals 0 when j, k share a block and exactly 2 when they lie in distinct blocks A_a, A_b ; hence $\delta_{\mathcal{P}} = \frac{1}{2} \sum_i \delta_{A_i}$, a nonnegative combination of cuts. Therefore $\Gamma = \sum_c w_c \delta_{\mathcal{P}^{(c)}}$ is a nonnegative combination of cuts. $\square$

Proposition 3 (Triangle obstruction). *Every Γ in the cut cone satisfies the triangle inequality $\Gamma_{jl} \leq \Gamma_{jk} + \Gamma_{kl}$. Consequently no static family of coarse projective jump channels reproduces a translation-covariant kernel with quadratic onset, $\Gamma(\Delta) \simeq \gamma \Delta^2$ for small $|\Delta|$.*

Proof. Each δ_S is a pseudometric and satisfies the triangle inequality; nonnegative combinations of pseudometrics are pseudometrics, giving the first claim. For the second, take three collinear pointer values with separations u and u . The triangle inequality would require $\Gamma(2u) \leq 2\Gamma(u)$, whereas a quadratic kernel gives

$$\Gamma(2u) - 2\Gamma(u) = \gamma(2u)^2 - 2\gamma u^2 + o(u^2) = 2\gamma u^2 + o(u^2) > 0 \quad (43)$$

for all sufficiently small $u \neq 0$. Hence such a kernel is outside the cut cone. $\square$

Kernels with linear onset, e.g. $\Gamma(\Delta) \propto 1 - e^{-|\Delta|/\xi}$, satisfy the triangle inequality and are the exception; the obstruction concerns the quadratic small-separation behaviour characteristic of collisional decoherence [43, 57]. Adaptive or history-dependent families are not covered. The constructive resolution—smeared, record-shaped operations whose profile is fixed by the environmental correlator—is developed in work by the author currently in preparation.

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