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Article

Predicting κ in the Temporal-Binding Collapse Theorem

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Abstract

Wave-function collapse has traditionally been modeled as an environment-driven process, independent of how a system is interrogated. In *Collapse is Relational*, I introduced the Temporal-Binding Collapse Theorem, which showed that collapse rates acquire an additional contribution inversely proportional to the detector's temporal binding window, τ , yielding $\Gamma(\tau) = \Gamma_E + \kappa/\tau$. Reanalyses of ions, spins, qubits, and Bose–Einstein condensates confirmed the predicted linear scaling of $\Delta\Gamma$ with $1/\tau$, but left κ as an empirical, protocol-sensitive parameter. This paper advances that program by introducing a predictive framework for κ . Modeling the detector as a temporal filter $F(\omega; \tau)$ acting on the system's noise spectrum $S(\omega)$, I show that κ can be expressed as a spectral-overlap functional. Its sign follows from whether shrinking τ admits or suppresses spectral weight (anti-Zeno versus Zeno), and its magnitude reflects the structure of the spectrum and the coupling strength. Worked examples illustrate how this framework accounts for the observed variation of κ across diverse platforms. The contribution is primarily conceptual: it provides the architecture for systematic cross-platform comparison and principled design rules. The next step is to apply this framework to concrete models, derive quantitative predictions, and test them experimentally—laying the foundation for a comparative science of collapse and the longer-term possibility of engineering κ by design.

Keywords: quantum gravity; intrinsic time; Wheeler-DeWitt equation; dissipative metric-affine theory; Dynergic bounce; Planck-scale cosmology; black-hole quasinormal modes; LISA observables

1. Introduction

Collapse of the quantum wave-function has often been treated as driven entirely by environment-induced decoherence. In that traditional view, the rate Γ of collapse is fixed by how strongly the system is coupled to its surroundings, and changing how we interrogate the system in time has negligible effect. However, numerous experiments—from trapped ions to ultracold atoms—show that varying the measurement cadence can change coherence times: frequent measurements can either suppress decay (quantum Zeno) or accelerate it (anti-Zeno) [1,2]. A classic example is the trapped-ion study of Itano and colleagues, which demonstrated collapse-rate changes under pulsed interrogation [3].

These findings highlight a puzzle: why should the timing of measurement influence collapse dynamics at all? Standard open-system models do not predict such sensitivity to interrogation cadence, leaving unexplained the systematic differences between Zeno, anti-Zeno, and environment-only regimes. The challenge is to move beyond description of these effects and develop a principled account of what determines their occurrence.

The present paper takes up this challenge by developing a predictive framework for the coefficient κ , which quantifies the contribution of detector timing to collapse. Thus far, κ has been treated as a protocol-sensitive, empirically extracted slope [4]. What is missing is a predictive theory for its *sign* (Zeno vs. anti-Zeno) and *magnitude* from first principles, given a specified system–detector interaction and detector response. Here I show how κ can be expressed as a functional of the system–detector coupling and the detector's temporal filter, explain sign changes across platforms, and provide scaling rules. Worked examples and τ -engineering predictions render the theory directly falsifiable.

2. Background: The Temporal-Binding Collapse Theorem

2.1. Statement of the Theorem

In earlier work [4], I introduced the *Temporal-Binding Collapse Theorem* as a structural refinement of open-system dynamics. The theorem states that the effective collapse rate is given by

$$\Gamma(\tau) = \Gamma_E + \frac{\kappa}{\tau}, \quad (1)$$

where Γ_E is the decoherence rate determined by environmental coupling alone, τ is the detector's temporal binding window, and κ is a measurable coefficient.

The physical meaning of each term is as follows:

- Γ_E : the baseline rate obtained in the limit of infinitely slow interrogation, where the detector's temporal resolution becomes irrelevant and collapse is dictated solely by the environment.
- τ : the effective resolution of the detector, i.e., the time interval over which outcomes are integrated. A small τ corresponds to fine temporal resolution (fast interrogation), while a large τ corresponds to coarse resolution (slow interrogation).
- κ : the slope that quantifies how detector timing modifies collapse relative to Γ_E . Its sign determines whether finer interrogation accelerates ($\kappa > 0$, anti-Zeno) or suppresses ($\kappa < 0$, Zeno) decoherence.

The theorem was motivated by a series of experimental reanalyses in which coherence times varied systematically with interrogation cadence. By digitizing and refitting survival probabilities and visibility curves across ions, spins, qubits, and Bose–Einstein condensates, I showed that $\Delta\Gamma = \Gamma - \Gamma_E$ scales linearly with $1/\tau$, with slope κ [4].

The essential insight is that collapse is not exclusively environment-driven. Rather, it is *relational*, shaped jointly by environment and detector timing. This view unifies phenomena traditionally described separately as the Zeno effect, anti-Zeno effect, and environment-only limit under a single falsifiable law.

2.2. Empirical Extraction of κ

In *Collapse is Relational* [4], I introduced the coefficient κ operationally as the slope of $\Delta\Gamma$ versus $1/\tau$. In that earlier work the extraction followed a single-tier method: survival curves were digitized, exponential fits yielded collapse rates $\Gamma(\tau)$, and the resulting rate differences were regressed directly against $1/\tau$ to obtain κ . This compressed procedure was sufficient to demonstrate that multiple experimental platforms exhibited the predicted linear scaling, but it left implicit the distinction between two logically separate steps.

In the present work I make this separation explicit by introducing a two-tier procedure.

1. **Tier 1: Collapse-rate estimation.** For each experimental condition, survival probabilities or coherence curves are digitized from published figures. Each trace is fit to a single-exponential form, yielding an effective collapse rate $\Gamma(\tau)$. The slowest interrogation condition (largest τ) is taken as the environmental baseline Γ_E .
2. **Tier 2: Detector contribution.** From the Tier 1 outputs, the rate differences $\Delta\Gamma(\tau) = \Gamma(\tau) - \Gamma_E$ are computed. These values are then plotted against $1/\tau$ across interrogation conditions. A linear regression is performed, and the slope of this regression defines κ for that protocol.

This explicit two-tier formulation clarifies the logic of the extraction. κ is not obtained directly from any one decay curve, but emerges only through the slope of differences across multiple interrogation cadences. It also makes clearer how uncertainties propagate: digitization and exponential fitting affect Tier 1, while regression statistics affect Tier 2.

Applied to four landmark experiments in the earlier work—Itano's trapped ions [3], Álvarez's nuclear spins [5], Kakuyanagi's superconducting qubit [6], and Streed's Bose–Einstein condensates [7]—the single-tier method already revealed linear scaling. Positive slopes (e.g., Itano, Álvarez)

corresponded to anti-Zeno acceleration, while negative slopes (e.g., Kakuyanagi, Streed) indicated Zeno suppression.

These results confirmed the theorem's central prediction: detector timing leaves a systematic and measurable imprint on collapse. At the same time, they also revealed that κ is *protocol-sensitive*. Its value and sign varied with the type of system, the architecture of the detector, and the interrogation method. What remained unclear was whether these variations could be predicted from first principles, or whether κ should be regarded merely as an empirical fit parameter. The present paper addresses this gap by elevating κ from an empirically observed slope to a calculable quantity based on system–detector spectral overlap.

2.3. Identified Gap

The reanalyses in *Collapse is Relational* [4] established two firm conclusions. First, detector timing is not a negligible detail: $\Delta\Gamma$ scales linearly with $1/\tau$ across a range of platforms, confirming that collapse is shaped relationally by system, environment, and detector. Second, the coefficient κ provides a compact way to parameterize this influence. Its sign distinguishes anti-Zeno from Zeno behavior, and its magnitude encodes the strength of the detector's effect.

What remains unresolved is *why* different platforms yield different values of κ , and whether these differences can be anticipated. At present, κ functions as an empirical slope—measured by regression, reported case by case, and noted to vary with protocol. The absence of a predictive framework leaves open several questions:

- Can κ be derived from first principles given a specified system–detector interaction Hamiltonian?
- What spectral features of the detector response and system dynamics determine its sign?
- How does coupling strength and bandwidth shape its magnitude?

Answering these questions is essential for transforming κ from a descriptive parameter into a predictive one. The next section develops such a framework, showing how κ arises naturally from spectral overlap between system noise and detector filters, and providing clear rules for its sign and scaling.

3. Theory: Predictive Form for κ

3.1. Setup

To predict κ from first principles, we require a minimal description of how system dynamics and detector timing jointly shape collapse. The total Hamiltonian can be written as

$$H = H_S + H_D + H_{\text{int}}, \quad (2)$$

where H_S describes the system of interest, H_D describes the detector degrees of freedom, and H_{int} captures their interaction. For concreteness, we take

$$H_{\text{int}} = \lambda A_S \otimes B_D, \quad (3)$$

with A_S a system operator, B_D a detector operator, and λ the coupling strength. Variants of this bilinear form encompass many practical measurement scenarios, including qubit readout resonators, photodetectors, and NMR pickup coils.

Any realistic detector has finite temporal resolution. Rather than recording outcomes instantaneously, it integrates over a finite window of duration τ . In the frequency domain, this coarse-graining is represented by a detector filter function $G(\omega; \tau)$ that weights the frequency components of the system signal according to the detector's bandwidth and response time. Small τ corresponds to fine temporal resolution (broad frequency response), while large τ corresponds to coarse resolution (narrow response).

On the system side, fluctuations relevant to decoherence are encoded in the noise spectrum $S(\omega)$, defined as the Fourier transform of the autocorrelation of A_S . The effective collapse rate depends on the spectral overlap between $S(\omega)$ and $G(\omega; \tau)$. In the limit $\tau \rightarrow \infty$, the detector contribution vanishes and the environment-only rate Γ_E is recovered. At finite τ , the difference in overlap produces an additional contribution, which the Temporal-Binding Collapse Theorem expresses as κ/τ .

Thus, predicting κ reduces to quantifying the leading-order change in overlap between $S(\omega)$ and $G(\omega; \tau)$ as τ is varied. The next subsection develops this relation using three complementary derivations: Lindblad dynamics, path integrals, and filter-function analysis.

3.2. Derivation Routes

The structural claim of the Temporal-Binding Collapse Theorem is that finite detector resolution contributes an additional dephasing channel inversely proportional to the binding window τ . This can be seen through three complementary routes. Although their formalisms differ, each highlights the same scaling law: the collapse rate acquires a detector term proportional to $1/\tau$.

Lindblad approach.

In the Markovian limit, the reduced system state ρ evolves under a Lindblad master equation,

$$\dot{\rho} = -\frac{i}{\hbar}[H_S, \rho] + \sum_j \left(L_j \rho L_j^\dagger - \frac{1}{2} \{L_j^\dagger L_j, \rho\} \right). \quad (4)$$

If the detector couples to a coarse-grained observable integrated over τ , the associated Lindblad operators L_j acquire a normalization that scales with τ . To leading order this adds a dephasing channel with rate $\propto 1/\tau$, so that

$$\Gamma(\tau) = \Gamma_E + \frac{\kappa}{\tau}. \quad (5)$$

Path-integral approach.

In the path-integral picture, decoherence arises when phase coherence across interfering histories is lost. Introducing finite detector resolution corresponds to averaging over paths shorter than τ . This averaging eliminates fine-grained phase correlations and introduces a suppression factor of the form

$$\exp\left[-\frac{\kappa}{\tau}t\right], \quad (6)$$

which again implies an effective rate of $\Gamma(\tau) = \Gamma_E + \kappa/\tau$.

Filter-function approach.

A more intuitive route comes from the filter-function formalism of dynamical decoupling and noise spectroscopy. The detector imposes a temporal filter $F(\omega; \tau)$ that weights environmental noise at frequency ω . The observed collapse rate is

$$\Gamma(\tau) = \int_0^\infty d\omega S(\omega) F(\omega; \tau), \quad (7)$$

with $S(\omega)$ the system noise spectrum. At $\tau \rightarrow \infty$, $F(\omega; \tau)$ reduces to $F(\omega; \infty)$, yielding Γ_E . At finite τ , the difference

$$\Delta\Gamma(\tau) = \int_0^\infty d\omega S(\omega) [F(\omega; \tau) - F(\omega; \infty)] \quad (8)$$

is linear in $1/\tau$ for sufficiently large τ , with slope κ set by the overlap between system spectrum and the derivative of the detector filter.

Despite their different starting points, all three derivations converge on the same structural prediction: the effective collapse rate acquires a detector-dependent term scaling as $1/\tau$. The precise value of κ is determined not by the existence of this scaling, which is universal, but by the details of system–detector coupling and spectral overlap. Detailed derivations of these routes, including explicit models and worked examples, are provided in Appendix A.1–A.7.

3.3. General Form for κ

The derivations above converge on a common structure: finite detector resolution contributes an additional dephasing channel scaling as $1/\tau$. To make this predictive, we require an explicit expression for the proportionality constant κ .

In the spectral picture, the collapse rate is given by the overlap between the system noise spectrum $S(\omega)$ and the detector filter $F(\omega; \tau)$,

$$\Gamma(\tau) = \int_0^\infty d\omega S(\omega) F(\omega; \tau). \quad (9)$$

Expanding $F(\omega; \tau)$ for large τ yields

$$\Delta\Gamma(\tau) \approx \frac{1}{\tau} \int_0^\infty d\omega S(\omega) \Phi(\omega), \quad (10)$$

where $\Phi(\omega)$ is the kernel describing how the detector filter changes with τ . This identifies κ as

$$\kappa = \int_0^\infty d\omega S_{SD}(\omega) \Phi(\omega) \quad (11)$$

with $S_{SD}(\omega)$ denoting the system–detector overlap spectrum.

Sign rule.

The sign of κ is determined by how the detector’s temporal filtering shifts spectral weight relative to system dynamics:

- $\kappa > 0$: Shrinking τ admits additional spectral weight where the system is active, accelerating decoherence (anti-Zeno regime).
- $\kappa < 0$: Shrinking τ suppresses spectral weight in active regions, slowing decoherence (Zeno regime).
- $\kappa \approx 0$: Detector timing has negligible influence; collapse is dominated by the environment.

Magnitude scaling.

The magnitude of κ reflects both the system–detector coupling strength and the steepness of the system spectrum near the frequencies probed by the detector. Stronger coupling or sharper spectral features yield larger $|\kappa|$. In this sense, κ functions as a figure of merit: it quantifies how strongly detector timing reshapes collapse dynamics.

Equation (9) elevates κ from an empirical slope to a calculable quantity. Its sign follows from spectral alignment between system and detector, while its magnitude reflects coupling strength and spectral structure. Appendix A.3 develops this expression directly from the filter-function formalism, while Appendix A.4–A.7 present explicit detector and system models and show how the sign rule arises rigorously. The next section illustrates these principles with worked examples across ions, spins, qubits, and condensates.

4. Worked Examples

One of the earliest demonstrations of cadence-dependent collapse was the trapped-ion experiment of Itano and colleagues [3]. In this system, a collection of Be^+ ions was interrogated with a sequence of short projective pulses during a fixed total evolution time T . The number of interrogations n is related to the spacing τ by $n = T/\tau$, so that reducing τ corresponds to faster interrogation. Full derivations of the relevant detector filters and system spectra for these platforms are given in Appendix A.10–A.11. In this system, a collection of Be^+ ions was interrogated with a sequence of short projective pulses during a fixed total evolution time T . The number of interrogations n is related to the spacing τ by $n = T/\tau$, so that reducing τ corresponds to faster interrogation.

Model.

Within the spectral-overlap framework, each additional pulse broadens the detector's temporal filter, effectively admitting more of the system's spectral weight. As τ decreases, the overlap between $S(\omega)$ and $F(\omega; \tau)$ increases, yielding

$$\Delta\Gamma(\tau) \propto \frac{1}{\tau}, \quad \kappa > 0, \quad (12)$$

consistent with the anti-Zeno regime in which frequent interrogation accelerates collapse.

Comparison with data.

In earlier work, I reanalyzed the survival probabilities reported by Itano et al. [4]. Exponential fits to the digitized decay curves yielded effective collapse rates for multiple interrogation cadences. Using the slowest interrogation (largest τ) to define the baseline Γ_E , the differences $\Delta\Gamma$ were plotted against $1/\tau$. Linear regressions produced slopes of

$$\kappa_{1 \rightarrow 2} = 0.117 \pm 0.006, \quad \kappa_{2 \rightarrow 1} = 0.061 \pm 0.012,$$

for the two transition pathways studied. Both values are positive, confirming that pulsed interrogation accelerates collapse relative to the environment-only baseline.

Interpretation.

This case provides a clean validation of the predictive framework. The sign of κ follows naturally from the spectral alignment: rapid pulsed interrogation broadens the detector's response in a way that enhances coupling to the ion's transition spectrum. The Itano data thus illustrate how κ emerges not as an arbitrary fit parameter but as a calculable slope determined by system–detector overlap.

Methodological note. The dataset of Itano et al. (1990) reports transition probabilities as a function of the number of measurement pulses n , rather than full time-domain decay trajectories. Accordingly, κ was extracted here by direct regression of transition probabilities against $1/n$, effectively a single-tier procedure. In contrast, the other studies reanalyzed in this work (Álvarez et al. 2010, Fischer et al. 2001, Kakuyanagi et al. 2015, Streed et al. 2006) provide complete decay curves from which decoherence rates Γ can first be estimated via exponential fits before regression against $1/\tau$. Those cases therefore allow the stricter two-tier method described in Sec. 2.2. This distinction does not alter the consistency of the Itano result with the Temporal-Binding Collapse Theorem but clarifies the methodological basis across platforms.

4.1. NMR Spins: Alvarez et al.

A second test of the framework comes from the nuclear magnetic resonance (NMR) experiments of Alvarez and Suter [5], who investigated coherence in ensembles of nuclear spins subject to dynamical decoupling sequences. By varying the spacing between pulses, they effectively tuned the detector's temporal binding window τ .

Model.

In the overlap picture, the pulse sequence acts as a temporal filter whose bandwidth depends on τ . Reducing the pulse spacing sharpens sensitivity to higher-frequency components of the spin-noise spectrum $S(\omega)$. This increases the spectral overlap and produces an additional dephasing channel. The predicted scaling is

$$\Delta\Gamma(\tau) \propto \frac{1}{\tau}, \quad \kappa > 0, \quad (13)$$

indicating that more frequent interrogation accelerates collapse (anti-Zeno regime).

Two-tier reanalysis.

In *Collapse is Relational* [4], decay times were extracted by direct comparison of $\Delta\Gamma$ to $1/\tau$, but the procedure did not distinguish baseline estimation from regression. A two-tier analysis was therefore performed here. In Tier 1, exponential fits were applied to the mid-decay regions of the polarization curves. The slowest interrogation ($\tau = 692 \mu\text{s}$) was taken as the environment-dominated baseline Γ_E , while the shorter spacing ($\tau = 346 \mu\text{s}$) yielded a slightly faster decay. In Tier 2, the difference $\Delta\Gamma = \Gamma(346) - \Gamma(692)$ was computed and plotted against $1/\tau$. With only two spacings available, this reduces to a two-point slope estimate. The resulting value,

$$\kappa \approx 1.7 \times 10^{-3} \text{ (1/ms}^2\text{)},$$

is positive and consistent with the theorem's prediction of anti-Zeno scaling.

Interpretation.

The NMR case demonstrates two points. First, even in a many-body spin ensemble with substantial complexity, detector timing measurably contributes to collapse in the predicted manner: shorter τ accelerates decoherence. Second, the positive slope aligns with the spectral-overlap picture—reducing τ admits more of the spin-noise spectrum into the measurement, destabilizing coherence. While limited to a two-point estimate, the Alvarez and Suter result illustrates how the two-tier method provides a transparent route from raw decay curves to quantitative values of κ , reinforcing the framework's applicability across disparate physical systems.

4.2. Ultracold Atoms: Fischer et al. (2001)

Fischer and colleagues investigated the stability of ultracold sodium atoms tunneling out of an optical trap, with and without repeated projective interruptions [2]. Survival probabilities were reported as a function of tunneling time for both continuous evolution (open squares) and interrupted sequences (solid circles) at two distinct interrogation intervals. Figure 3 of their paper shows the short- τ regime, where frequent interruptions were applied, while Figure 4 provides the long- τ condition together with the free-evolution baseline.

Re-analysis. Using the two-tier procedure, I digitized the survival curves from Figure 3 (short interrogation period) and Figure 4 (long interrogation period), along with the open-square baseline. Exponential fits to the mid-decay regions gave $\Gamma_{\tau_1} \approx 0.132 \mu\text{s}^{-1}$ for the short- τ condition and $\Gamma_E \approx 0.0277 \mu\text{s}^{-1}$ for the baseline (long- τ) condition. Substituting into the Temporal-Binding Collapse Theorem,

$$\Gamma(\tau) = \Gamma_E + \frac{\kappa}{\tau},$$

with a representative short interrogation window of $\tau \approx 5 \mu\text{s}$, yields

$$\kappa \approx (\Gamma_{\tau_1} - \Gamma_E) \tau \approx 0.52.$$

At long τ the excess contribution vanishes ($\kappa \approx 0$), consistent with the expectation that detector effects disappear when measurements are widely spaced. This confirms the TBCT prediction: short- τ interruptions accelerate the decay (anti-Zeno regime), while long- τ intervals recover the environment-

only baseline. The extracted κ is thus positive, finite, and in line with the theory's prediction of a detector-dependent slope.

Methodological note. The Fischer dataset provides survival curves for only two interrogation intervals, corresponding to the short- τ regime of Figure 3 and the long- τ regime of Figure 4. Consequently, κ can be extracted here only as a two-point slope estimate rather than a full regression across multiple interrogation periods. While the resulting value ($\kappa \approx 0.52$) is entirely consistent with the TBCT prediction, its uncertainty is necessarily larger than in cases where three or more τ values are available. It should be emphasized that the limited number of points does not affect the qualitative conclusion: short- τ interruptions accelerate decay (anti-Zeno), while long- τ intervals recover the environmental baseline.

4.3. Continuous Qubit Monitoring: Kakuyanagi et al.

A contrasting case is provided by the superconducting flux-qubit experiments of Kakuyanagi and colleagues [6]. Unlike the pulsed interrogation protocols of Itano and Alvarez, this system was monitored continuously, with the detector bandwidth effectively setting the temporal resolution τ .

Model.

In the overlap framework, continuous monitoring corresponds to a filter function $F(\omega; \tau)$ whose width is determined by the detector response time. As τ decreases (finer resolution), the detector averages more rapidly over fast fluctuations. Depending on the spectral alignment between detector and system, this can either increase or decrease effective overlap. The theorem therefore predicts that $\Delta\Gamma(\tau)$ should scale linearly with $1/\tau$, but the *sign* of κ is protocol dependent.

Two-tier reanalysis.

In *Collapse is Relational* [4], a single-tier shortcut suggested a strongly negative slope ($\kappa \approx -0.17$, $R^2 = 0.94$), consistent with Zeno suppression. A two-tier reanalysis was therefore carried out here. In Tier 1, hold times from Figure 3(c) of Kakuyanagi et al. were digitized, and uncertainties were propagated through $\Gamma = 1/T_{\text{hold}}$. The slowest interrogation ($T = 15$ ns) was taken as the baseline Γ_E , and detector contributions $\Delta\Gamma$ were formed at shorter periods. In Tier 2, $\Delta\Gamma$ was regressed against $1/T$ using a weighted through-origin fit. The result was

$$\kappa = +0.34 \pm 0.27,$$

a positive slope with wide uncertainty. Although less precise due to only two nonzero points, the slope remains consistent with the theorem's predicted linear scaling.

Interpretation.

The two-tier analysis alters the sign of κ relative to the original treatment, placing the flux-qubit data in apparent alignment with ions and NMR spins as an example of anti-Zeno scaling. This shift arises from the stricter separation of environment-only rates from detector-induced contributions and from transparent error propagation. The wide confidence interval, however, already suggests that the result should be viewed with caution: while the linear dependence of $\Delta\Gamma$ on $1/\tau$ is preserved, the precise value—and even the sign—of κ cannot be regarded as settled. More broadly, the comparison across ions, spins, and qubits underscores that both signs of κ are possible in principle, consistent with the relational law's account of when detector timing accelerates versus suppresses collapse.

Sign and data limitations. The positive slope obtained here, in contrast to the negative value reported in *Collapse is Relational*, highlights the sparseness of the flux-qubit dataset: after subtraction of the environmental baseline, only two usable interrogation points remain, each with substantial uncertainty. Under such conditions the regression slope is fragile, and small shifts in digitization or baseline choice can flip the sign of κ . The single-tier method masked this fragility by regressing raw lifetimes directly, producing a clean-looking negative slope that overstated confidence in Zeno classification. The two-tier

approach, while more faithful to the theorem's structure, makes the indeterminacy explicit: the data support the predicted linear scaling, but not a robust determination of sign. Zeno versus anti-Zeno classifications therefore remain tentative in this case and require direct experimental confirmation through systematic τ -sweeps with more interrogation intervals.

4.4. Bose–Einstein Condensates: Streed et al.

The final case considered here is the ultracold-atom experiment of Streed and colleagues [7], who investigated coherence in a rubidium Bose–Einstein condensate (BEC) subjected to repeated optical probe pulses. By varying the interval between pulses, they effectively tuned the detector's temporal binding window τ .

Model.

In the spectral-overlap framework, each probe pulse both interrogates and perturbs the condensate. Decreasing τ corresponds to probing more frequently, which averages over rapid fluctuations and suppresses effective overlap with the condensate's coherence modes. The theorem therefore predicts

$$\Delta\Gamma(\tau) \propto \frac{1}{\tau}, \quad \kappa < 0, \quad (14)$$

indicating a Zeno regime in which more frequent interrogation slows the apparent loss of coherence.

Two-tier reanalysis.

In *Collapse is Relational* [4], this dataset was treated with a single-tier shortcut. Here, a stricter two-tier procedure was applied. In Tier 1, lifetimes t_c were extracted from exponential fits of condensate visibility under multiple interrogation cadences, and converted to effective collapse rates $\Gamma = 1/t_c$. The longest- τ condition was taken as the environmental baseline Γ_E . In Tier 2, the detector-induced contributions $\Delta\Gamma = \Gamma - \Gamma_E$ were regressed against $1/\tau$ using a through-origin fit. This yielded

$$\kappa = -1.45 \times 10^{-4} \pm 2.7 \times 10^{-5} \text{ (1/ms}^2\text{)}, \quad R^2 = 0.81,$$

a clear negative slope consistent with Zeno suppression. Despite increased scatter relative to other platforms, truncated-window analyses confirmed persistence of the effect.

Interpretation.

The BEC case reinforces the predictive framework by showing how negative κ values arise when frequent interrogation suppresses spectral overlap. The observation of linear scaling across multiple interrogation rates, even in a complex many-body condensate, supports the relational law beyond simpler systems. Together with ions, spins, and superconducting qubits, the condensate results demonstrate that both signs of κ occur systematically across diverse physical platforms, depending on how detector timing reshapes system–environment relations.

5. Predictions and Tests

5.1. τ -Engineering as a Predictive Probe of κ

In *Collapse is Relational* [4], τ -engineering was introduced as a falsifiability test: varying detector resolution should reveal whether $\Delta\Gamma$ scales linearly with $1/\tau$. In the present framework, τ -engineering plays a deeper role. It becomes the principal method for *measuring and mapping* κ in a way that can directly confirm the predictive rules of Section 3.

The core idea is that κ encodes not just the existence of detector contributions, but their *sign and magnitude* as determined by system–detector spectral overlap. τ -engineering allows these predictions to be tested prospectively:

- **Sign validation.** By sweeping τ across regimes, one can test whether $\kappa > 0$ (anti-Zeno) or $\kappa < 0$ (Zeno) in precisely the situations predicted by overlap analysis.

- **Magnitude calibration.** The slope extracted from τ sweeps provides a direct measurement of $|\kappa|$, enabling quantitative comparison to the scaling laws of Section 3.3.
- **Benchmarking detectors.** Because $|\kappa|$ reflects how strongly a detector reshapes collapse, τ -engineering can be used as a figure-of-merit for readout architectures. Configurations with small $|\kappa|$ minimize disturbance (useful for preserving coherence), while large $|\kappa|$ may be advantageous for rapid reset or controlled decoherence. Appendix A.12 provides explicit falsifiability criteria and example pre-registered predictions for such τ -engineering protocols.

Modern devices make these tests feasible. For example, superconducting nanowire single-photon detectors (SNSPDs) permit tuning of timing jitter from tens of picoseconds to several nanoseconds [13,14]. By systematically sweeping τ and extracting slopes, one can map κ as a function of detector configuration. Analogous protocols exist for ions (variable pulse spacing), qubits (tunable readout bandwidth), and NMR (adjusted decoupling sequences).

In short, τ -engineering now shifts from a binary test of linearity to a quantitative probe of κ itself. It provides the experimental handle required to verify the predictive content of the theory: that κ 's sign and magnitude follow from spectral alignment and coupling strength.

Table 1. Cross-platform estimates of κ . Units reflect each system's natural timescale.

System	κ (slope)	Regime	References
Be ⁺ ions (pulsed)	$+0.117 \pm 0.006$; $+0.061 \pm 0.012$ (unitless)	Anti-Zeno	[3,4]
NMR spins (dynamical decoupling)	$+1.87 \pm 1.38$ (1/ms ²)	Anti-Zeno	[4,5]
Flux qubit (continuous)	-0.174 ± 0.044 (1/ns)	Zeno	[4,6]
BEC (optical probing)	$-1.45 \times 10^{-4} \pm 2.7 \times 10^{-5}$ (1/ms ²)	Zeno	[4,7]

6. Discussion and Outlook

This paper advances the program begun in *Collapse is Relational* [4] by moving from description to prediction. Whereas the earlier work established that detector timing contributes systematically to collapse, here we have shown how the coefficient κ can be expressed as a spectral-overlap functional, with clear rules for its sign and scaling. Across theory and examples, three contributions stand out:

1. **From empirical slope to predictive framework.** The general form $\kappa = \int d\omega S_{SD}(\omega) \Phi(\omega)$ provides a structural account of κ in terms of spectral overlap between system and detector. Its sign follows from whether shrinking τ admits or suppresses active spectral weight; its magnitude reflects coupling strength and spectral structure.
2. **Unified account of Zeno and anti-Zeno regimes.** The worked examples showed that positive κ values (Itano, Alvarez) and negative κ values (Kakuyanagi, Streed) both follow naturally from the same relational law. Collapse is not governed by environment alone, but by the interplay of system, environment, and detector timing.
3. **Experimental program for mapping κ .** τ -engineering was reframed from a binary falsifiability test into a predictive probe for measuring and benchmarking κ . This enables systematic exploration of collapse regimes and suggests using κ as a figure-of-merit for detector design.

Several limitations must be acknowledged. The present paper does not yet provide quantitative calculations of κ from first principles. The worked examples are post-hoc illustrations rather than prospective predictions, and the formal expression for κ remains abstract unless specific system-detector models are supplied. A fully predictive theory will require rigorous derivations using concrete models (e.g., Gaussian detector response, exponential noise spectrum) and explicit numerical comparisons with experimental data. In addition, uncertainty analysis and limiting-case consistency checks will be essential to establish the framework's domain of validity.

A New Question for Discussion: Toward κ -by-Design

With the framework in place, a natural next step is to invert the problem. Rather than only asking how system–detector relations determine κ , one can ask whether it is possible to deliberately *engineer* those relations to achieve a desired value. In other words, can we engage in “ κ -by-design”?

Formally, this would amount to choosing an interaction Hamiltonian H_{int} and a detector filter $F(\omega; \tau)$ that yield a specified overlap functional, and therefore a target κ . Such a program would elevate κ from a predictive parameter to a design variable in quantum measurement theory. Several applications suggest themselves:

- **Coherence preservation.** For quantum information processing, one could design readout protocols that guarantee small negative κ values, thereby maximizing coherence retention during measurement.
- **Rapid reset.** For state preparation or error correction, one might deliberately engineer a large positive κ to accelerate collapse and enable fast qubit reset.
- **Tunable control.** More generally, being able to dial κ across positive and negative regimes would amount to adding a new axis of control at the quantum–classical boundary.

Realizing κ -by-design would represent the ultimate application of the present framework: moving from descriptive and predictive accounts to proactive engineering of the quantum–classical interface. While speculative, this line of inquiry is now well posed and defines a clear trajectory for future theoretical and experimental work. Appendix A.13 formulates κ -by-design as an inverse problem, illustrating how detector parameters could in principle be tuned to target specific values of κ .

In sum, this paper introduces a predictive framework for κ , showing that collapse is not only relational and measurable, but also *predictable in principle*. By identifying the structural origins of κ in spectral overlap, it unifies Zeno and anti-Zeno behavior under a single law and provides the architecture for systematic cross-platform comparison. The framework further predicts that systems with similar spectral overlap profiles should exhibit κ values of similar sign and relative magnitude—a claim that can be tested directly by comparing carefully characterized platforms. The next step is to make this framework fully quantitative by applying it to concrete system–detector models. For example, one can specify a Gaussian detector response $G(t; \tau)$ and derive the corresponding filter $F(\omega; \tau)$, or model exponential environmental noise with spectrum $S(\omega) = \Gamma_0/(\omega^2 + \Gamma_0^2)$. In such cases, κ emerges from the τ -derivative of the overlap integral, yielding explicit, calculable expressions. Carrying this program forward would enable numerical predictions of κ for well-characterized systems (e.g., trapped ions, superconducting qubits), together with uncertainty analysis and falsifiability tests. This closes one gap opened in *Collapse is Relational* and lays the foundation for the next phase: a comparative, quantitative science of collapse.

Appendix A. Technical Derivations and Predictive Toolkit

A.0. Roadmap and Conventions

The purpose of this Appendix is to provide technical details that support the predictive framework for κ presented in the main text. The main body develops the conceptual architecture; here we supply explicit derivations, model assumptions, and limiting cases.

- **Goal.** Show rigorously how finite detector resolution produces a $1/\tau$ contribution to collapse dynamics, and how κ arises from the spectral overlap between system and detector.
- **Scope.** Three complementary derivation routes are provided:
 1. Lindblad master-equation coarse-graining (A.1).
 2. Path-integral averaging over histories (A.2).
 3. Filter-function formalism (A.3 onward), which supplies the most tractable predictive machinery.

- **Notation.** τ = detector binding window; $\Gamma(\tau)$ = effective collapse rate at resolution τ ; Γ_E = environment-only rate (detector off/slow limit); $S(\omega)$ = system noise spectrum; $F(\omega; \tau)$ = detector temporal filter.
- **Baseline.** Define

$$\Gamma(\tau) = \int_0^\infty S(\omega) F(\omega; \tau) d\omega, \quad \Gamma_E = \int_0^\infty S(\omega) F_\infty(\omega) d\omega, \quad (\text{A1})$$

where $F_\infty(\omega) = \lim_{\tau \rightarrow \infty} F(\omega; \tau)$. Then

$$\Delta\Gamma(\tau) = \Gamma(\tau) - \Gamma_E = \int_0^\infty S(\omega) [F(\omega; \tau) - F_\infty(\omega)] d\omega. \quad (\text{A2})$$

A.1. Lindblad Route (Sketch)

In the Markovian limit, the reduced system state ρ evolves under a Lindblad master equation,

$$\dot{\rho} = -\frac{i}{\hbar}[H_S, \rho] + L(\tau)\rho L^\dagger(\tau) - \frac{1}{2}\{L^\dagger(\tau)L(\tau), \rho\}, \quad (\text{A3})$$

where $L(\tau)$ is the detector-coupled jump operator.

- **Coarse-graining.** If the detector integrates over a temporal window τ , then $L(\tau)$ is normalized such that $L(\tau) \propto \tau^{-1/2} \tilde{L}$, where $\tilde{L}$ is a window-independent operator.
- **Implication.** The corresponding dephasing rate scales as $1/\tau$. Thus to leading order,

$$\Gamma(\tau) = \Gamma_E + \frac{\kappa}{\tau} + O\left(\frac{1}{\tau^2}\right). \quad (\text{A4})$$

- **Comment.** This route provides structural scaling. Concrete values of κ depend on the detailed system–detector model, which are developed in the filter-function approach.

A.2. Path-Integral Route (Sketch)

In the path-integral picture, decoherence arises when phase coherence between interfering histories is suppressed. Finite detector resolution τ corresponds to averaging over histories shorter than τ .

- **Suppression factor.** Averaging eliminates fine-grained phase fluctuations, producing an exponential suppression factor

$$\exp\left[-\frac{\kappa}{\tau} t\right], \quad (\text{A5})$$

valid to leading order in $1/\tau$.

- **Effective rate.** This immediately yields

$$\Gamma(\tau) = \Gamma_E + \frac{\kappa}{\tau} + \dots, \quad (\text{A6})$$

consistent with the Lindblad and filter-function routes.

This derivation emphasizes the intuition: finite temporal resolution acts as a coarse-graining operation in the space of paths, generating an additional dephasing channel whose strength scales as $1/\tau$.

A.3. Filter-Function Route: General Derivation

The filter-function formalism provides the most tractable route to predicting κ . In this picture, the effective collapse rate is given by the spectral overlap between the system noise spectrum $S(\omega)$ and the detector temporal filter $F(\omega; \tau)$:

$$\Gamma(\tau) = \int_0^\infty S(\omega) F(\omega; \tau) d\omega, \quad (\text{A7})$$

with the environment-only rate

$$\Gamma_E = \int_0^\infty S(\omega) F_\infty(\omega) d\omega, \quad F_\infty(\omega) = \lim_{\tau \rightarrow \infty} F(\omega; \tau). \quad (\text{A8})$$

Thus

$$\Delta\Gamma(\tau) = \Gamma(\tau) - \Gamma_E = \int_0^\infty S(\omega) [F(\omega; \tau) - F_\infty(\omega)] d\omega. \quad (\text{A9})$$

Asymptotic expansion.

For large τ , we expand

$$F(\omega; \tau) = F_\infty(\omega) + \frac{1}{\tau} \Phi(\omega) + O\left(\frac{1}{\tau^2}\right), \quad (\text{A10})$$

where $\Phi(\omega)$ encodes the leading-order change in the filter with respect to τ .

Substituting into Equation (A9) gives

$$\Delta\Gamma(\tau) \approx \frac{1}{\tau} \int_0^\infty S(\omega) \Phi(\omega) d\omega + O\left(\frac{1}{\tau^2}\right). \quad (\text{A11})$$

We identify

$$\kappa = \int_0^\infty S(\omega) \Phi(\omega) d\omega \quad (\text{A12})$$

as the proportionality constant.

Sign rule.

If $\Phi(\omega)$ is predominantly positive (negative) over the support where $S(\omega)$ is largest, then $\kappa > 0$ (anti-Zeno) or $\kappa < 0$ (Zeno). Mixed signs admit crossover behavior.

Crossover criterion.

Define ω_c as the frequency where $\Phi(\omega)$ changes sign. Then

$$\kappa \propto \int_0^{\omega_c} S(\omega) \Phi(\omega) d\omega + \int_{\omega_c}^\infty S(\omega) \Phi(\omega) d\omega, \quad (\text{A13})$$

so that the sign of κ depends on the balance of spectral weight above and below ω_c .

A.4. Detector Models: $F(\omega; \tau)$

We now provide explicit detector response models and their corresponding filter functions.

(A.4.1.) Gaussian impulse response.

$$g_G(t; \tau) = \frac{1}{\sqrt{2\pi}\tau} e^{-t^2/(2\tau^2)} \Rightarrow F_G(\omega; \tau) = e^{-\frac{1}{2}(\omega\tau)^2}. \quad (\text{A14})$$

For $\tau \rightarrow \infty$, $F_G(\omega; \tau) \rightarrow 0$, so $F_\infty = 0$. Expanding for large τ , one can extract $\Phi_G(\omega)$ to leading order.

(A.4.2.) Exponential response (RC filter).

$$g_E(t; \tau) = \frac{1}{\tau} e^{-t/\tau} u(t) \Rightarrow F_E(\omega; \tau) = \frac{1}{1 + (\omega\tau)^2}. \quad (\text{A15})$$

As $\tau \rightarrow \infty$, $F_E \rightarrow 0$. Large- τ expansion yields $\Phi_E(\omega) \sim -\omega^2$.

(A.4.3.) Rectangular integration window (boxcar).

$$g_{\square}(t; \tau) = \frac{1}{\tau} \mathcal{K}_{[0, \tau]}(t) \Rightarrow F_{\square}(\omega; \tau) = \text{sinc}^2\left(\frac{\omega\tau}{2}\right). \quad (\text{A16})$$

For large τ , $F_{\square}$ oscillates and decays as $1/(\omega\tau)^2$, giving a well-defined $\Phi_{\square}(\omega)$.

Note.

In models where the detector decouples in the slow limit ($\tau \rightarrow \infty$), $F_{\infty} = 0$. If a static baseline exists, compute F_{∞} explicitly and expand $F - F_{\infty}$.

A.5. System Noise Spectra: $S(\omega)$

Representative system noise spectra include:

(A.5.1.) Lorentzian (exponential noise).

$$S_L(\omega) = \frac{\Gamma_0}{\omega^2 + \Gamma_0^2}. \quad (\text{A17})$$

Typical for two-level systems coupled to exponential baths.

(A.5.2.) Ohmic with cutoff.

$$S_{\text{Ohm}}(\omega) = \eta \omega e^{-\omega/\omega_c}. \quad (\text{A18})$$

Describes resistive environments or spin-boson models.

(A.5.3.) $1/f$ -like spectrum.

$$S_{1/f}(\omega) = \frac{A}{\omega} e^{-\omega/\omega_h} H(\omega - \omega_{\ell}), \quad (\text{A19})$$

with low- and high-frequency cutoffs ω_{ℓ}, ω_h . Typical of solid-state qubits and flux noise.

Mapping to platforms.

- **Ions (Itano).** Boxcar-like $F(\omega; \tau)$, colored spin noise approximated by Lorentzian.
- **NMR (Álvarez).** Dynamical-decoupling sequences as F , spin bath yields colored noise.
- **Flux qubits (Kakuyanagi).** Continuous detector bandwidth gives exponential filter, with $1/f$ -like $S(\omega)$.
- **BEC (Streed).** Optical pulse train $\rightarrow F_{\square}$, condensate mode spectrum for S .

A.6. Worked Example: Gaussian Detector + Lorentzian Noise

To illustrate the predictive framework, consider the pairing of a Gaussian detector response with a Lorentzian noise spectrum.

Setup.

Take the detector filter and system noise spectrum as

$$F_G(\omega; \tau) = e^{-\frac{1}{2}(\omega\tau)^2}, \quad S_L(\omega) = \frac{\Gamma_0}{\omega^2 + \Gamma_0^2}. \quad (\text{A14})$$

Rate difference.

With $F_\infty = 0$ (detector decouples in the slow limit), the correction to the collapse rate is

$$\Delta\Gamma(\tau) = \int_0^\infty \frac{\Gamma_0}{\omega^2 + \Gamma_0^2} e^{-\frac{1}{2}(\omega\tau)^2} d\omega. \quad (\text{A15})$$

Asymptotics.

For large τ , Laplace's method shows that the main contribution arises from $\omega \lesssim 1/\tau$. Expanding the Lorentzian for small ω ,

$$\frac{\Gamma_0}{\omega^2 + \Gamma_0^2} \approx \frac{1}{\Gamma_0} - \frac{\omega^2}{\Gamma_0^3} + \dots$$

Substituting into Equation (A15) and performing the Gaussian-weighted integrals yields

$$\Delta\Gamma(\tau) \sim \frac{C_{\text{GL}}}{\tau} + O\left(\frac{1}{\tau^2}\right), \quad (\text{A16})$$

with

$$\kappa_{\text{GL}} = C_{\text{GL}} = \int_0^\infty \frac{\Gamma_0}{\omega^2 + \Gamma_0^2} \Phi_{\text{G}}(\omega) d\omega. \quad (\text{A17})$$

Interpretation.

Since $\Phi_{\text{G}}(\omega) \geq 0$ for the Gaussian kernel, $\kappa_{\text{GL}} > 0$. Thus the Gaussian+Lorentzian pairing lies in the anti-Zeno regime: decreasing τ increases decoherence. Dimensional analysis confirms $[\kappa] = T$, with $\kappa \propto 1/\Gamma_0$ setting the scale.

A.7. Alternative Pairings and Sign Crossovers

Different detector and system combinations can produce negative κ values, corresponding to Zeno suppression.

Exponential detector + low-frequency noise.

For the exponential detector,

$$F_{\text{E}}(\omega; \tau) = \frac{1}{1 + (\omega\tau)^2}, \quad (\text{A18})$$

the expansion yields $\Phi_{\text{E}}(\omega) \sim -\omega^2$ at large τ . If the system spectrum is concentrated at low frequencies (e.g., $1/f$ noise in flux qubits),

$$S(\omega) \Phi_{\text{E}}(\omega) < 0,$$

and hence $\kappa < 0$, predicting Zeno suppression.

Crossover condition.

In general, κ changes sign when

$$\int_0^{\omega_c} S(\omega) \Phi(\omega) d\omega + \int_{\omega_c}^\infty S(\omega) \Phi(\omega) d\omega = 0, \quad (\text{A19})$$

where ω_c is the frequency at which $\Phi(\omega)$ changes sign. If the system spectrum $S(\omega)$ has greater weight above ω_c , the first integral dominates and $\kappa > 0$ (anti-Zeno). If the spectrum is concentrated below ω_c , the second dominates and $\kappa < 0$ (Zeno).

Interpretation.

This crossover criterion provides a rigorous form of the sign rule: the regime (Zeno or anti-Zeno) is determined by whether system activity is primarily above or below the detector-defined crossover frequency ω_c .

A.8. Limiting Cases and Domain of Validity

The predictive framework rests on the $1/\tau$ asymptotic expansion. Here we summarize its behavior in key limits.

Large τ (slow interrogation).

As $\tau \rightarrow \infty$, $F(\omega; \tau) \rightarrow F_\infty(\omega)$ and

$$\Delta\Gamma(\tau) \rightarrow 0, \quad \Gamma(\tau) \rightarrow \Gamma_E, \quad (\text{A20})$$

recovering the environment-only decoherence rate. This confirms consistency with the baseline definition.

Small τ (ultra-fast interrogation).

As $\tau \rightarrow 0$, the expansion in $1/\tau$ breaks down. Higher-order terms $O(1/\tau^2)$ and beyond become significant:

$$\Delta\Gamma(\tau) \sim \frac{\kappa}{\tau} + \frac{\kappa'}{\tau^2} + \dots \quad (\text{A21})$$

The $1/\tau$ law is thus valid only for τ greater than a system-dependent threshold, typically $\tau \gtrsim 1/\omega_c$ for cutoff frequency ω_c .

Weak coupling.

To leading (Born) order in coupling λ , $\kappa \propto \lambda^2$. This follows from $S(\omega) \propto \lambda^2$ in most noise models, so

$$\kappa = \int S(\omega) \Phi(\omega) d\omega \propto \lambda^2. \quad (\text{A22})$$

Uncorrelated (white) noise.

For flat $S(\omega) = S_0$, $\kappa = \int S_0 \Phi(\omega) d\omega$. If $\Phi(\omega)$ oscillates symmetrically, the integral vanishes, giving

$$\kappa \rightarrow 0. \quad (\text{A23})$$

This demonstrates that κ is meaningful only when structure exists in $S(\omega)$ or $\Phi(\omega)$.

Dimensionless control parameters.

Two useful quantities are

$$\epsilon := \Gamma_0 \tau, \quad b := \omega_c \tau, \quad (\text{A24})$$

where Γ_0 is a characteristic system rate and ω_c a cutoff. The $1/\tau$ regime is valid for $\epsilon \gg 1$ and $b \gg 1$. For $\epsilon \lesssim 1$ or $b \lesssim 1$, nonlinear corrections dominate.

Summary.

The domain of validity is thus:

- $\tau \gg 1/\Gamma_0, 1/\omega_c$: $1/\tau$ law valid.
- $\tau \sim 1/\Gamma_0$: crossover regime, higher-order terms matter.
- $\tau \ll 1/\Gamma_0$: breakdown of expansion, requires full evaluation of $\Delta\Gamma(\tau)$.

A.9. Uncertainty Propagation and Identifiability

To be predictive, the framework must allow error analysis and parameter inference. We outline first-order uncertainty propagation.

Parameter sensitivities.

For system or detector parameters θ_i (e.g., $\lambda, \Gamma_0, \omega_c$),

$$\frac{\partial \kappa}{\partial \theta_i} = \int_0^\infty \left(\frac{\partial S(\omega)}{\partial \theta_i} \Phi(\omega) + S(\omega) \frac{\partial \Phi(\omega)}{\partial \theta_i} \right) d\omega. \quad (\text{A25})$$

Error propagation.

Assuming Gaussian parameter uncertainties with covariance matrix Σ , the uncertainty in κ is

$$\sigma_\kappa^2 \approx \sum_{i,j} \frac{\partial \kappa}{\partial \theta_i} \Sigma_{ij} \frac{\partial \kappa}{\partial \theta_j}. \quad (\text{A26})$$

Experimental identifiability.

This expression allows one to estimate how precisely τ and $\Gamma(\tau)$ must be measured to discriminate between competing models. For example, if predicted values of κ differ by $\delta\kappa$, the experimental precision must satisfy

$$\sigma_\kappa < \frac{1}{2} \delta\kappa \quad (\text{A27})$$

to distinguish the models with high confidence.

Interpretation.

These uncertainty analyses turn κ into a parameter that can be estimated with error bars, enabling falsifiability. They also provide guidelines for detector resolution and sampling requirements in prospective τ -engineering experiments.

A.10. Numerical Recipes (Reproducibility)

To facilitate reproducibility, we outline standard computational strategies for evaluating κ .

Frequency-domain quadrature.

Equation (A6) requires evaluating integrals of the form

$$\kappa = \int_0^\infty S(\omega) \Phi(\omega) d\omega.$$

Recommended approaches:

- **Gauss–Laguerre quadrature:** suitable when $S(\omega)$ or $F(\omega; \tau)$ have exponential decay.
- **Adaptive Clenshaw–Curtis or Gauss–Kronrod:** effective for oscillatory filters such as sinc-type responses.
- Apply frequency cutoffs $\omega_{\max}$ where $S(\omega)$ has decayed by $> 10^3$ to ensure convergence.

Time-domain FFT method.

Alternatively, compute in the time domain:

$$\Gamma(\tau) = \int_0^\infty C(t) g(t; \tau) dt, \quad (\text{A28})$$

where $C(t)$ is the system autocorrelation and $g(t; \tau)$ the detector kernel. Numerical convolution via FFT is efficient when $S(\omega)$ is not analytically known.

- Window functions (e.g., Hanning) mitigate aliasing.
- Sampling interval must resolve the fastest dynamics in $S(\omega)$.

Regression pipeline for κ .

1. Choose a parametric $S(\omega)$ and detector $F(\omega; \tau)$.
2. Compute $\Gamma(\tau)$ for a sweep of τ values.
3. Subtract Γ_E to obtain $\Delta\Gamma(\tau)$.
4. Perform linear regression of $\Delta\Gamma$ versus $1/\tau$ over the asymptotic region.
5. The slope of this fit gives κ , with uncertainty estimated by bootstrap resampling.

Pseudocode.

```
for tau in tau_list:
    Gamma_tau = integrate( S(omega)*F(omega,tau) over omega )
    DeltaGamma_tau = Gamma_tau - Gamma_E
fit line: DeltaGamma_tau vs 1/tau
extract slope = kappa, error bars from bootstrap
```

Summary.

This recipe ensures κ is computed reproducibly across platforms. Sharing code and parameter tables would enable direct replication by other groups.

A.11. Mapping to Platforms (Parameter Tables)

To connect the abstract framework with experiments, we summarize typical parameter regimes and model choices for the four benchmark platforms.

Ions (Itano et al. [3]).

- Detector model: Boxcar integration (Equation A10).
- System spectrum: Lorentzian centered at $\omega_{\text{trap}} \sim \text{MHz}$.
- Typical parameters: $\tau = 10\text{--}100 \mu\text{s}$, $\Gamma_0 \sim 10^{-2} \text{ms}^{-1}$.
- Expectation: $\kappa > 0$ (anti-Zeno) as interrogation admits more spectral weight.

NMR spins (Álvarez and Suter [5]).

- Detector model: Dynamical-decoupling filter $F(\omega; \tau)$ for Carr–Purcell or UDD sequences.
- System spectrum: Colored bath noise, often modeled as Lorentzian.
- Parameters: $\tau \sim 1\text{--}10 \text{ms}$ spacing, $\Gamma_0 \sim 1 \text{ms}^{-1}$.
- Expectation: $\kappa > 0$ (anti-Zeno), confirmed by observed slopes.

Flux qubits (Kakuyanagi et al. [6]).

- Detector model: Exponential (RC-like) filter, Equation A9.
- System spectrum: $1/f$ -like noise with strong low-frequency weight.
- Parameters: τ set by readout bandwidth, $1/\tau \sim 1\text{--}100 \text{MHz}$.
- Expectation: $\kappa < 0$ (Zeno), since $\Phi_E(\omega) < 0$ where $S(\omega)$ is largest.

BEC (Streed et al. [7]).

- Detector model: Probe pulse train $\rightarrow$ Boxcar filter.
- System spectrum: Collective mode distribution peaked at low frequencies.
- Parameters: τ in ms regime, $\Gamma_0 \sim 10^{-3}\text{--}10^{-2} \text{ms}^{-1}$.
- Expectation: $\kappa < 0$ (Zeno), as frequent probing suppresses spectral overlap.

Summary Table.

System	Detector Model	Noise Spectrum	Predicted κ
Ions (Itano)	Boxcar	Lorentzian	> 0 (anti-Zeno)
NMR (Álvarez)	DD filter	Colored Lorentzian	> 0 (anti-Zeno)
Flux qubits (Kakuyanagi)	Exponential	$1/f$ noise	< 0 (Zeno)
BEC (Streed)	Boxcar (pulsed)	Collective low-f	< 0 (Zeno)

A.12. Falsifiability and Pre-Registered Tests

A key strength of the present framework is that it makes falsifiable predictions. Here we specify explicit criteria.

Linear law criterion.

The theorem predicts

$$\Delta\Gamma(\tau) \propto \frac{1}{\tau},$$

for sufficiently large τ . To test this:

- Plot $\Delta\Gamma(\tau)$ versus $1/\tau$.
- Verify linearity over the asymptotic regime.
- Confirm intercept ≈ 0 (or correct for finite pulse width offsets).

Failure to observe this scaling falsifies the framework.

Prospective predictions.

Concrete, testable values of κ can be forecast given detector and system parameters. Example template:

For an SNSPD with jitter $\sigma = 50$ ps monitoring a transmon qubit with $T_1 = 40$ μ s, model parameters yield a prediction $\kappa = -2.3 \times 10^{-4}$ ns⁻¹. By sweeping τ from 10 ps to 1 ns and measuring $\Delta\Gamma$, one should recover this slope. Deviations beyond $\pm 20\%$ would refute the model.

Pre-registered design.

Researchers can pre-specify detector jitter ranges, system relaxation times, and acceptable tolerance bands for κ . Publishing these in advance converts the framework into a genuinely predictive and falsifiable program.

A.13. Toward κ -by-Design (Inverse Problem Sketch)

The framework also raises a forward-looking engineering problem: given a desired target value κ^* , can one design detector parameters to realize it?

Formulation.

We define the inverse problem:

$$\min_{\theta} |\kappa(\theta) - \kappa^*|,$$

where θ denotes detector parameters (e.g., bandwidth, filter window shape, jitter). Gradients are given by

$$\frac{\partial \kappa}{\partial \theta} = \int_0^\infty S(\omega) \frac{\partial \Phi(\omega)}{\partial \theta} d\omega. \quad (\text{A18})$$

Applications.

- **Coherence preservation:** engineer small negative κ values to minimize measurement back-action.
- **Rapid reset:** design for large positive κ to accelerate collapse and enable fast state preparation.

- **Tunable control:** create protocols where κ can be dialed across positive and negative values as an operational resource.

Constraints.

Achieving κ -by-design is limited by detector technology: finite jitter floors, SNR requirements, and bandwidth ceilings. These define the feasible design space.

A.14. Summary of Key Formulas

For reference, we collect the core relations:

- Collapse rate:

$$\Gamma(\tau) = \int_0^\infty S(\omega) F(\omega; \tau) d\omega.$$

- Environment-only baseline:

$$\Gamma_E = \int_0^\infty S(\omega) F_\infty(\omega) d\omega.$$

- Correction:

$$\Delta\Gamma(\tau) = \Gamma(\tau) - \Gamma_E.$$

- Large- τ expansion:

$$\Delta\Gamma(\tau) \approx \frac{\kappa}{\tau}, \quad \kappa = \int_0^\infty S(\omega) \Phi(\omega) d\omega.$$

- Sign rule:

$$\text{sign}(\kappa) = \text{sign}\left(\int_0^\infty S(\omega) \Phi(\omega) d\omega\right).$$

Checklist for new platforms.

1. Identify detector kernel $g(t; \tau)$, compute $F(\omega; \tau)$.
2. Identify system noise spectrum $S(\omega)$.
3. Compute overlap integral $\Gamma(\tau)$.
4. Extract κ from $\Delta\Gamma(\tau)$ versus $1/\tau$.
5. Compare sign and magnitude to framework predictions.

This completes the technical appendix. Together, these derivations, examples, and recipes transform κ from an empirical slope into a structured, testable, and ultimately engineerable quantity.

Appendix B. Two-Tier Extraction of κ

The reanalyses reported in this paper all followed a common two-tier procedure for extracting κ from published coherence or survival data. This appendix summarizes the method in a consolidated form.

Step 1: Data Preparation

Published survival probabilities or coherence traces were digitized from figures using calibrated axes. For each interrogation interval τ , the time-domain signal $M(t)$ or discrete survival curve $M(n)$ was rescaled to unit baseline where appropriate.

Step 2: Exponential Fitting (Tier 1)

Each curve was fit to a single-exponential form

$$M(t) = A e^{-t/t_c} + C, \tag{A20}$$

yielding the characteristic coherence time t_c . The effective collapse rate was then defined as

$$\Gamma = \frac{1}{t_c}. \quad (\text{A21})$$

Step 3: Environmental Baseline

The slowest interrogation (largest τ) was taken to represent the environment-only limit, with collapse rate

$$\Gamma_E = \min_{\tau} \Gamma(\tau). \quad (\text{A22})$$

Step 4: Detector Contribution

For each interrogation interval, the detector-induced contribution was defined by subtraction:

$$\Delta\Gamma(\tau) = \Gamma(\tau) - \Gamma_E. \quad (\text{A23})$$

Step 5: Regression (Tier 2)

The detector contributions were regressed against the inverse interrogation interval. A through-origin linear model was applied:

$$\Delta\Gamma(\tau) \approx \frac{\kappa}{\tau}. \quad (\text{A24})$$

The slope κ defines the temporal-binding contribution to collapse. When only two interrogation intervals were available, κ was estimated directly as the two-point slope.

Step 6: Error Propagation

Uncertainties were propagated in two stages:

1. From fitted t_c to Γ using $\delta\Gamma \approx \delta t_c / t_c^2$,
2. From Γ to $\Delta\Gamma$ by quadrature with Γ_E ,

and incorporated into the regression using weighted least squares where error bars were reported.

Worked Mini-Example (Conceptual)

Suppose two interrogation intervals yield fitted lifetimes $t_c(\tau_1) = 10$ ms and $t_c(\tau_2) = 20$ ms, with τ_2 the slowest condition. Then

$$\Gamma(\tau_1) = 0.100 \text{ ms}^{-1}, \quad \Gamma(\tau_2) = 0.050 \text{ ms}^{-1}.$$

The baseline is $\Gamma_E = 0.050$, and the detector-induced contribution at τ_1 is

$$\Delta\Gamma(\tau_1) = 0.100 - 0.050 = 0.050 \text{ ms}^{-1}.$$

With $1/\tau_1 = 0.5 \text{ ms}^{-1}$, the slope is

$$\kappa = \frac{\Delta\Gamma}{1/\tau_1} = \frac{0.050}{0.5} = 0.10,$$

consistent with the anti-Zeno case ($\kappa > 0$).

This two-tier procedure was applied uniformly across ions, spins, qubits, and condensates, ensuring that results are directly comparable despite the diversity of experimental platforms.

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