

Modular Spectroscopy: A Spectral Fingerprint of Gravitationally-Induced Decoherence

Quantum-Geometric Correspondence

Marc Sperzel*

Independent Researcher

MSci Physics, King's College London

July 2, 2026

Abstract

Quantum-Geometric Correspondence (QGC) identifies the modular Hamiltonian of an observer's algebra with the physical Hamiltonian, $K = 2\pi H_{\text{phys}}$, and from this relation predicts a first-order-in- G gravitational decoherence rate $\Gamma_{\text{dec}} = E_G/\hbar$ with $E_G = GM^2/d$. We take that relation as a principle—the Modular-Physical Correspondence (MPC), the sharp form of the thermal-time hypothesis—and ask what it predicts beyond a rate. Because the principle places every which-path environment in the modular Kubo–Martin–Schwinger state at the universal Bisognano–Wichmann inverse temperature $\beta_{\text{mod}} = 2\pi$, the fluctuation–dissipation theorem fixes the entire decoherence noise spectrum: $S(\omega) = \eta \omega \coth(\pi\omega)$ with $\eta = 2E_G/\hbar$. The spectrum is a white plateau whose zero-frequency value $S(0) = \eta/\pi$ reproduces the static rate $E_G/\hbar$, crossing over to a linear rise at a knee $f_{\text{knee}} \sim E_G/(2\pi\hbar) = GM^2/(2\pi\hbar d)$. The fingerprint has two parts. The floor is *uncoolable*: it carries the modular temperature, not the laboratory temperature, so it survives perfect environmental isolation—a property shared with the whole Diósi–Penrose / collapse class. The knee is the MPC-specific signature: its frequency scales as M^2/d with no free parameter, and—unlike the floor, which carries the open rate coefficient C —it is independent of C , since C enters $S(\omega)$ only as an overall factor. Modular (noise) spectroscopy, sweeping a which-path modulation across ~ 0.1 – 100 Hz for femtogram–nanogram masses at micron–millimetre separations, measures the knee directly and discriminates MPC from Diósi–Penrose collapse: above the knee the modulated decoherence *rises* ($\sim 30\times$ the floor at ten times the knee frequency) for MPC and stays flat for a Markovian collapse model, and the knee must track M^2/d , which a collapse cutoff cannot. The bottleneck is coherence and isolation, not modulation. We present the spectrum, its derivation from the principle, the knee and its C -independence, the experimental protocol, and an honest tiering of what is MPC-unique versus shared with the broader first-order-in- G class. The relation $K = 2\pi H_{\text{phys}}$ is posited, not proven; the spectrum is a derived consequence of it, and a measurement of the knee is its decisive test.

*ORCID: [0009-0000-6252-3155](https://orcid.org/0009-0000-6252-3155). Email: me@marcsperzel.com

1 Introduction

A massive body in spatial superposition decoheres through its own gravitational field, and the rate is the same across the competing proposals. Diósi and Penrose [13, 14] set it by the branch-pair gravitational self-energy $E_G = GM^2/d$, giving $\Gamma_{\text{dec}} \sim E_G/\hbar$; continuous spontaneous localisation reaches a comparable scale [15]; and Quantum-Geometric Correspondence (QGC) derives $\Gamma_{\text{dec}} = E_G/\hbar$ at first order in G from a constraint on the gravitational influence functional [1]. For a microgram mass separated by a millimetre, $E_G/\hbar \approx 6 \times 10^8 \text{ s}^{-1}$. The rate is a single number, and because the proposals agree on it, measuring it—already at the frontier of levitated optomechanics and matter-wave interferometry [22, 21, 16]—tells an experimenter that decoherence is gravitational and intrinsic, but not which mechanism produced it.

A rate is the zero-frequency content of a spectrum. The static experiment that measures Γ_{dec} reads only the floor $S(0)$ of the underlying which-path noise spectrum $S(\omega)$; the frequency dependence is discarded. The question this paper answers is whether the QGC mechanism predicts that frequency dependence, and whether it differs from the structureless white noise of a collapse model in a way an experiment can resolve.

It does, and the reason is structural. QGC rests on the identification of the modular Hamiltonian K of an observer’s operator algebra with the physical Hamiltonian,

$$K = 2\pi H_{\text{phys}}, \quad (1)$$

the sharp, quantitative form of the thermal-time hypothesis of Connes and Rovelli [4, 5]. We do not derive Eq. (1) here; proving it for interacting gravitons is the construction of quantum gravity’s modular theory, which remains open. We instead posit it as a principle—the Modular–Physical Correspondence—and follow its consequences, in the way the equivalence of inertial and gravitational mass was posited rather than derived. The relation (1) carries the Bisognano–Wichmann normalisation [6]: the modular flow it generates is a thermal flow at the universal inverse temperature $\beta_{\text{mod}} = 2\pi$, the same temperature that underlies the Unruh effect [7].

The consequence is immediate. If physical time is modular flow at $\beta_{\text{mod}} = 2\pi$, then the environment that carries which-path information sits in a Kubo–Martin–Schwinger (KMS) state at that temperature, and the fluctuation–dissipation theorem fixes the decoherence noise spectrum completely:

$$S(\omega) = \eta \omega \coth(\pi\omega), \quad \eta = 2E_G/\hbar. \quad (2)$$

This is a white plateau of height $S(0) = \eta/\pi$, reproducing the static rate $\Gamma_{\text{dec}} = \frac{\pi}{2}S(0) = E_G/\hbar$, that crosses over to a linear rise $\eta\omega$ at a knee

$$f_{\text{knee}} \sim \frac{E_G}{2\pi\hbar} = \frac{GM^2}{2\pi\hbar d} \propto \frac{M^2}{d}. \quad (3)$$

Two features of this spectrum are testable. The floor carries the modular temperature, not the laboratory temperature, so cooling the apparatus does not remove it: it is an *uncoolable* floor, the irreducible decoherence that survives perfect isolation. The knee sits at a frequency that is modulable— ~ 0.1 – 100 Hz for femtogram–nanogram masses at micron–millimetre separations—and scales as M^2/d , a dependence no environmental noise source shares. We are explicit throughout about which of these is genuinely specific to the principle. The uncoolable floor and the M^2/d scaling of the *rate* are shared with the entire Diósi–Penrose / collapse class; they

separate intrinsic gravitational decoherence from environmental decoherence, not QGC from its competitors. The modular-thermal *shape*—the knee at the universal modular frequency—is the part unique to Eq. (1), and it is the harder measurement.

Section 2 states the Modular–Physical Correspondence as a principle and shows that the no-boundary state fixes the one coefficient left open in the rate. Section 3 derives the spectrum (2) from the KMS structure and recovers the static rate as its floor. Section 4 establishes the uncoolable floor, the knee, and the result that the knee frequency is independent of the open rate coefficient. Section 5 gives the noise-spectroscopy protocol and the discriminator that separates the principle from Diósi–Penrose collapse. Section 6 works out the accessible mass–separation regime and states the bottleneck honestly. Section 7 relates the mechanism to decoherence by warm horizons and asks what a measurement would settle.

2 The Modular–Physical Correspondence principle

2.1 Statement

We adopt the following as a principle.

Modular–Physical Correspondence (MPC). Physical time is the modular flow of the quantum state, and the physical Hamiltonian generates it:

$$K = 2\pi H_{\text{phys}} \quad (\text{exact, as a law of nature}). \quad (4)$$

Here $K = -\log \Delta$ is the modular Hamiltonian of the observer’s local algebra, Δ its Tomita–Takesaki modular operator, and the one-parameter automorphism group $\sigma_t = \Delta^{it}$ the modular flow. Equation (4) is the quantitative form of the thermal-time hypothesis [4, 5]: the modular flow *is* physical time evolution, with the Bisognano–Wichmann normalisation [6] fixing the rate. A localised observer with a causal diamond therefore experiences its vacuum as a thermal KMS state at the universal inverse temperature

$$\beta_{\text{mod}} = 2\pi, \quad (5)$$

the Unruh–Bisognano–Wichmann value [7, 6, 8], in units where the modular flow parameter is the proper time of the diamond.

2.2 Posited, not derived

Equation (4) is the central relation of QGC, where it controls the gravitational influence functional and yields the first-order-in- G decoherence rate [1]. Deriving it from below—for interacting gravitons on a finite causal diamond—is the construction of the modular theory of quantum gravity, and is open for the field; the conformal-field-theory case $K = 2\pi H$ has only recently been made rigorous, and nothing comparable exists for the spin-2 field [9]. We do not close that gap. We instead elevate Eq. (4) to a principle and judge it by its consequences, as the equivalence principle was posited rather than proved. A principle earns its standing by predicting something new and falsifiable; the modular-thermal spectrum of Sec. 3 is that prediction.

2.3 The no-boundary state fixes the rate coefficient

The QGC rate is $\Gamma_{\text{dec}} = C E_G/\hbar$ with a coefficient C bounded to $[2/\pi, 1]$ and natural value $C = 1$, the residual freedom being the modular KMS temperature that normalises the which-path coupling [1]. The principle removes this freedom by selecting a state. The constraint that defines the physical sector, $\mathcal{C}|\psi\rangle = 0$, is invariance under the full modular flow; its maximally symmetric solution—the canonical choice—is the no-boundary vacuum of Hartle and Hawking [10]. For that state the modular temperature takes the Bisognano–Wichmann value (5) exactly, so

$$K = 2\pi H_{\text{phys}} \implies C = 1 \implies \Gamma_{\text{dec}} = E_G/\hbar. \quad (6)$$

This does not prove $C = 1$ from quantum field theory. It relocates the assumption: from an opaque operator normalisation to a cosmological initial condition, the no-boundary state, which cannot be derived from the dynamics in any case and was itself posited. That is a more physical and more falsifiable place for the assumption to sit. As Sec. 4 shows, the value of C controls only the height of the spectral floor; the knee frequency, the principle’s sharpest signature, is independent of it. The reader who declines to adopt the no-boundary selection loses the value of the floor but keeps the entire shape of the spectrum and the location of the knee.

3 The modular-thermal spectrum

3.1 Fluctuation–dissipation at the modular temperature

The which-path degree of freedom couples linearly to the gravitational environment that distinguishes the branches. For a Gaussian environment the decoherence is fixed by the symmetrised noise spectrum $S(\omega)$ of that coupling, and the fluctuation–dissipation theorem relates it to the coupling’s dissipation kernel $J_{\text{eff}}(\omega)$ and the environment’s temperature [11, 12]:

$$S(\omega) = J_{\text{eff}}(\omega) \coth\left(\frac{\beta\omega}{2}\right). \quad (7)$$

The Modular–Physical Correspondence fixes the temperature in Eq. (7). Under the principle the environment is in the modular KMS state, so $\beta = \beta_{\text{mod}} = 2\pi$ and the thermal factor is $\coth(\pi\omega)$, set by the modular flow rather than the apparatus.

3.2 The two spectral inputs

Two facts about the gravitational coupling complete Eq. (7).

The free graviton environment is *super-Ohmic*. A static superposition radiates no gravitons and its Newtonian field does not propagate, so the dissipation kernel of the free field vanishes as $J_{\text{eff}}^{\text{free}}(\omega) \propto \omega^3$ at low frequency. Its contribution to the noise is $S_{\text{free}}(\omega) = \omega^3 \coth(\pi\omega) \rightarrow 0$ as $\omega \rightarrow 0$: the free field carries no low-frequency weight and produces no rate. This is the saturation property of the free influence functional, read on the spectral side.

The constraint supplies *Ohmic* friction. The Hamiltonian constraint that enforces Eq. (4) dresses the which-path coupling and gives it a non-vanishing zero-frequency dissipation, $J_{\text{eff}}(\omega) = \eta\omega$, with

$$\eta = \frac{2E_G}{\hbar} \quad \text{at} \quad C = 1, \quad (8)$$

where $C = \eta\hbar/(2E_G)$ is the rate coefficient of Sec. 2.3 [1]. The free-field value $\eta = 0$ recovers saturation; the rate is entirely constraint-borne.

3.3 The spectrum

Inserting the constraint-supplied Ohmic kernel into Eq. (7) gives the physical decoherence spectrum:

$$\boxed{S(\omega) = \eta\omega \coth(\pi\omega), \quad \eta = 2E_G/\hbar}. \quad (9)$$

The super-Ohmic free part adds an $\mathcal{O}(\omega^2)$ correction only well above the knee and does not affect the low-frequency physics. Equation (9) has two regimes, separated by the modular frequency ω_{mod} at which $\coth(\pi\omega)$ turns over:

$$S(\omega) \simeq \begin{cases} \eta/\pi & \omega \ll \omega_{\text{mod}} \quad (\text{white plateau}), \\ \eta\omega & \omega \gg \omega_{\text{mod}} \quad (\text{linear rise}). \end{cases} \quad (10)$$

3.4 The floor recovers the rate

The static decoherence rate is the Markovian (Tauberian) slope of the coherence decay, set by the zero-frequency weight of the spectrum.

Proposition 3.1 (Rate from the floor). *The white floor of Eq. (9) reproduces the first-order-in- G decoherence rate:*

$$S(0) = \frac{\eta}{\pi}, \quad \Gamma_{\text{dec}} = \frac{\pi}{2} S(0) = \frac{\eta}{2} = \frac{E_G}{\hbar}. \quad (11)$$

Derivation. As $\omega \rightarrow 0$, $\coth(\pi\omega) \rightarrow 1/(\pi\omega)$, so $S(\omega) \rightarrow \eta\omega \cdot 1/(\pi\omega) = \eta/\pi$, a constant. The Markovian dephasing rate is $\Gamma_{\text{dec}} = \frac{\pi}{2} S(0)$, the standard relation between a white noise floor and the linear-in-time decay it produces [12]. With $\eta = 2E_G/\hbar$ this is $\Gamma_{\text{dec}} = E_G/\hbar$. $\square$

The spectrum thus contains the known rate as a special case: a microgram mass over a millimetre, with $E_G/\hbar \approx 6 \times 10^8 \text{ s}^{-1}$, sets the height of the plateau. What the static rate does not see is everything in Eq. (9) above $\omega = 0$ —the crossover, the knee, and the universal temperature that places them. That is the content of Sec. 4.

4 The fingerprint

4.1 An uncoolable floor

The thermal factor in Eq. (9) carries the modular temperature $\beta_{\text{mod}} = 2\pi$, not the laboratory temperature. The contrast with an ordinary environmental bath at T_{lab} , to which the same coupling would give $S_{\text{lab}}(\omega) = \eta\omega \coth(\beta_{\text{lab}}\omega/2)$, is sharp at zero frequency:

$$S_{\text{lab}}(0) = \frac{2\eta}{\beta_{\text{lab}}} \propto T_{\text{lab}} \xrightarrow{T_{\text{lab}} \rightarrow 0} 0, \quad \text{but} \quad S(0) = \frac{\eta}{\pi} \text{ fixed.} \quad (12)$$

Cooling the apparatus drives every environmental channel down—collisional decoherence with the residual gas, blackbody scattering, thermal-photon emission all vanish as the temperature falls—but the modular floor does not move. Gravitational modular decoherence is an *uncoolable floor*: the decoherence that remains after perfect environmental isolation. Operationally, one

measures the decoherence rate as a function of T_{lab} and extrapolates to $T_{\text{lab}} \rightarrow 0$; the surviving floor, scaling as $\eta \propto E_G \propto M^2/d$, is the gravitational signal.

This floor is the most measurable part of the fingerprint and the least specific to the principle. That intrinsic gravitational decoherence survives cooling, and that it scales as M^2/d , is shared with the whole Diósi–Penrose / collapse class, which gives the same static rate $\sim E_G/\hbar$ [13, 14, 15]. The uncoolable floor separates gravitational from environmental decoherence; it does not separate the principle from its competitors. That separation is the knee.

4.2 The knee

The crossover in Eq. (10) occurs at the modular frequency, of order the static rate. In physical units the knee sits at

$$f_{\text{knee}} \sim \frac{E_G}{2\pi\hbar} = \frac{GM^2}{2\pi\hbar d} = \frac{\Gamma_{\text{dec}}}{2\pi}. \quad (13)$$

The knee lands in a modulable band for femtogram–nanogram masses at micron–millimetre separations (Table 1). Heavier masses push it to gigahertz, beyond which-path modulation; much lighter masses push it to millihertz, where the required coherence time is impractical.

M	d	$f_{\text{knee}} = GM^2/(2\pi\hbar d)$
1 ng (10^{-12} kg)	1 mm	$\approx 1.0 \times 10^2$ Hz
10 fg (10^{-14} kg)	1 μm	$\approx 1.0 \times 10^1$ Hz
1 fg (10^{-15} kg)	1 μm	$\approx 1.0 \times 10^{-1}$ Hz

Table 1. *The decoherence knee for representative masses and separations. The knee scales as M^2/d : doubling the mass multiplies it by four, doubling the separation halves it.*

The absolute frequency carries an order-unity prefactor we do not over-claim. Mapping the dimensionless crossover to a physical frequency uses the modular-time convention $t = 2\pi s$ that Eq. (4) sets, and which power of 2π that map contributes is fixed only by the full influence-functional calculation. The knee is therefore a band,

$$f_{\text{knee}} \in \left[\frac{E_G}{4\pi^2\hbar}, \frac{E_G}{2\pi\hbar} \right] \approx [16, 101] \text{ Hz} \quad (1 \text{ ng}, 1 \text{ mm}), \quad (14)$$

a factor of 2π wide, the central value falling by 2π to the lower edge. The band’s *location scales exactly as M^2/d* regardless of the prefactor, so the scaling discriminant is sharp even though the absolute frequency is not pinned. No environmental noise source—gas pressure, mechanical resonance, T_{lab} —has a knee that moves as M^2/d .

4.3 The knee is independent of the rate coefficient

The open coefficient C of Sec. 2.3 enters the spectrum only through the overall friction $\eta = 2CE_G/\hbar$. It therefore cancels in the normalised shape.

Proposition 4.1 (*C*-independence of the knee). *Write the spectrum normalised to its floor as a function of the dimensionless frequency $\nu = \omega/\omega_{\text{mod}}$:*

$$\frac{S(\nu)}{S(0)} = \pi\nu \coth(\pi\nu). \quad (15)$$

The friction η has cancelled. The crossover, defined by $S(\nu_c)/S(0) = 2$, is at ν_c where $\pi\nu \coth(\pi\nu) = 2$, namely $\nu_c \simeq 0.61$, fixed by $\beta_{\text{mod}} = 2\pi$ alone and independent of C . The coefficient C survives only in the floor height $S(0) = \eta/\pi = 2CE_G/(\pi\hbar)$.

The consequence is that modular spectroscopy delivers two independent observables. The floor measures C —the one quantity the rate leaves open. The knee measures the modular structure: its frequency is set by the fixed temperature $\beta_{\text{mod}} = 2\pi$ and the which-path scale $E_G/\hbar$, with no adjustable parameter. Measuring both over-determines the system, and the knee is the cleaner test of the principle precisely because it does not depend on the coefficient the principle has not yet pinned.

5 Modular spectroscopy and the decisive test

5.1 Sampling the spectrum

The static rate reads only $S(0)$. To resolve the shape one samples $S(\omega)$ at finite frequency, which is what noise spectroscopy does [23]. Applying a dynamical-decoupling or modulation sequence to the which-path coordinate at drive frequency ω makes the decoherence filter function peak at ω , so the measured per-run decoherence tracks the spectrum there:

$$R(\omega) \propto S(\omega) = \eta\omega \coth(\pi\omega). \quad (16)$$

The prediction is the knee of Eq. (10): $R(\omega)$ is flat (modulation-independent) below the knee and rises linearly above it. The protocol is direct.

1. Prepare a spatial superposition of a femtogram–nanogram mass at a separation that places the knee in the moduable band (Table 1), isolated so that environmental decoherence sits below the gravitational floor.
2. Apply a which-path modulation at drive frequency ω scanned across $\sim 1\text{--}10^3$ Hz, bracketing the knee.
3. Measure the interference contrast versus ω over a hold time of order τ_{dec} , extracting $R(\omega) \propto S(\omega)$.
4. Repeat across M and d , and test whether the knee tracks M^2/d .

A knee at the predicted frequency, separating a white floor from a linear rise and moving as M^2/d with no tunable scale, is the signature of the principle. Its absence, or a structureless spectrum, or one that tracks T_{lab} , falsifies it.

5.2 The discriminator: Modular–Physical Correspondence versus Diósi–Penrose

The uncoolable floor and its M^2/d rate scaling are shared with Diósi–Penrose and continuous spontaneous localisation, which produce the same static rate. The spectra are not the same. A Markovian collapse model is white-noise stochastic reduction: $S_{\text{DP}}(\omega)$ is flat up to a cutoff set by a regularisation length σ_0 , a free parameter, and that cutoff does not scale as M^2/d . The modular spectrum rises above its M^2/d knee with no free parameter. The decisive measurement

is therefore the modulation-frequency dependence: drive above the knee and ask whether the decoherence rises or stays flat.

Proposition 5.1 (Modulation discriminator). *Let $r = \omega/f_{\text{knee}}$. The modulated decoherence normalised to the floor is*

$$\frac{R_{\text{MPC}}(r)}{R(0)} = \pi r \coth(\pi r), \quad \frac{R_{\text{DP}}(r)}{R(0)} = 1. \quad (17)$$

Below the knee the two agree to within a few percent. At ten times the knee frequency they diverge:

$$\frac{R_{\text{MPC}}(10)}{R(0)} \approx 10\pi \approx 31, \quad \frac{R_{\text{DP}}(10)}{R(0)} = 1, \quad (18)$$

a factor of ~ 30 that is the experimental separation.

The two predictions are flat versus rising, and the crossover sits at a frequency the principle fixes through M^2/d . A dissipative finite-temperature collapse model could in principle imitate a thermal factor, but at a free temperature rather than the parameter-free modular value, so the M^2/d tracking of the knee still separates them. This is the genuinely principle-specific test: not merely that gravitational decoherence is intrinsic and uncoolable, which any member of the class predicts, but that its noise spectrum has the modular-thermal shape, with the knee where the universal temperature $\beta_{\text{mod}} = 2\pi$ and the scale $E_G/\hbar$ place it.

6 Feasibility and limitations

6.1 The accessible regime

The knee is modulable where Eq. (13) lands it between roughly 0.1 and 100 Hz, which Table 1 places at femtogram–nanogram masses and micron–millimetre separations. The two ends of this window bound the experiment. A heavier Bose–Marletto–Vedral-class mass pushes the knee into the kilohertz–gigahertz range, where which-path modulation is no longer available; a much lighter mass pushes it to millihertz, where the required coherence time grows past seconds. The sweet spot is a ~ 10 fg particle at ~ 1 μm , with a knee near 10 Hz and a coherence requirement of order tens of milliseconds—a target for levitated optomechanics and matter-wave interferometry [22, 21].

6.2 The bottleneck is coherence, not modulation

The favourable part is that the knee frequency itself is easy to reach: hertz-to-kilohertz modulation of a which-path coordinate is routine. The difficulty is everything around it. Resolving the knee requires maintaining coherence for $\tau_{\text{dec}} \sim$ milliseconds to seconds *while environmental decoherence is held below the gravitational floor*. That is the same condition needed to detect the gravitational rate at all—the frontier that levitated and matter-wave platforms are approaching—now with the added demand of frequency-resolved control across the knee. The measurement is next-generation, not current, and we do not claim otherwise.

6.3 What is unique, and what is shared

We separate the three claims by how specific each is to the principle and how hard each is to measure.

1. *The uncoolable floor* is the most measurable and the least specific. That intrinsic gravitational decoherence survives $T_{\text{lab}} \rightarrow 0$ is shared with the whole first-order-in- G / Diósi–Penrose class. It distinguishes gravitational from environmental decoherence, not the principle from its competitors.
2. *The M^2/d scaling of the floor* is measurable and also shared with that class. It is the Bose–Marletto–Vedral-style signature, already a framework prediction.
3. *The modular-thermal shape*—the knee at the universal modular frequency, with $R(\omega)$ rising above it—is the part unique to $K = 2\pi H_{\text{phys}}$, and the hardest to measure. It requires probing the decoherence at $\omega \sim \omega_{\text{mod}} \sim \Gamma_{\text{dec}}$, faster than the decoherence itself.

The honest verdict is that the principle makes a genuinely new prediction, the modular-thermal spectral shape, whose cleanest measurable consequences are shared with a broader class and were largely already in the framework. The new physics is real; its principle-specific part is the more demanding measurement. This sharpens how the principle is to be tested without changing the status of the relation it rests on: $K = 2\pi H_{\text{phys}}$ remains posited, and a measurement of the knee is what would test it.

7 Discussion

7.1 The same friction at a warm horizon

The mechanism behind the spectrum—Ohmic friction enhanced by a thermal factor at a KMS temperature $\beta = 2\pi$ —appears independently in a very different setting. Danielson, Satishchandran, and Wald showed that a quantum superposition near a Killing horizon decoheres at a constant rate [18, 19], and Wilson-Gerow, Dugad, and Chen gave that rate a local form [20],

$$\Gamma = \frac{2}{\beta} \lim_{\Omega \rightarrow 0} \frac{\text{Im } \chi_F(\Omega)}{\Omega}, \quad (19)$$

with the Ohmic dissipation $\text{Im } \chi_F \propto a^2 \Omega$ supplied by radiation reaction in the accelerated frame and the thermal factor evaluated at the Unruh temperature $\beta = 2\pi/a$. This is structurally the dictionary of Sec. 3: a constant decoherence rate from Ohmic friction at a KMS temperature $\beta = 2\pi$.

The settings differ in what supplies the horizon and how the rate scales. Decoherence by warm horizons needs an *external* Killing horizon—a uniformly accelerated frame, a black hole, or de Sitter space—and gives a rate $\propto a^3$ that is independent of the superposed mass; it does not apply to a superposition in an inertial laboratory. The present mechanism conjectures the same friction structure with the observer’s own diamond modular horizon, intrinsic to the quantum state and present without external acceleration, and gives the mass-dependent rate $E_G/\hbar$. The warm-horizon result is therefore independent confirmation of the friction side of the mechanism—Ohmic dissipation thermally enhanced at $\beta = 2\pi$ —rather than a derivation of

the laboratory rate. That the same structure surfaces from horizon thermodynamics and from modular flow is the kind of convergence a principle should produce.

7.2 What a measurement would settle

The spectrum is a consequence of the principle, not a proof of it, and the two stand or fall together in the data. A knee at $f_{\text{knee}} \propto M^2/d$, separating a white floor from a linear rise, with the floor surviving $T_{\text{lab}} \rightarrow 0$, would establish that gravitational decoherence carries the modular-thermal shape—direct evidence that the environment sits in the modular KMS state at $\beta_{\text{mod}} = 2\pi$, which is what $K = 2\pi H_{\text{phys}}$ asserts. A flat spectrum below a mass-independent cutoff would point instead to Markovian collapse. A spectrum tracking the laboratory temperature would point to an unisolated environment. Each outcome is decisive, and the knee—independent of the one coefficient the rate leaves open—is the cleanest of the three to read. The measurement is hard, at the same frontier as detecting the rate itself, but it is concrete: it asks an experiment to resolve the frequency dependence of a decoherence that is already the target of the field, and to check whether it has the one shape the principle allows.

References

- [1] M. Sperzel, *The Quantum-Geometric Correspondence: Three Axioms and Gravitational Decoherence at Order G* , (2026), Quantum-Geometric Correspondence, canonical core paper.
- [2] M. Sperzel, *Geometric Modular Flow for Gravitons in a Causal Diamond: Dimensional Reduction and the Type II Crossed Product for a Non-Conformal Field*, (2026), Quantum-Geometric Correspondence series.
- [3] M. Sperzel, *A Mass-Independent Visibility Suppression in the Bose–Marletto–Vedral Experiment from Quantum-Geometric Correspondence*, (2026), Quantum-Geometric Correspondence series.
- [4] A. Connes and C. Rovelli, *Von Neumann algebra automorphisms and time–thermodynamics relation in generally covariant quantum theories*, Class. Quantum Grav. **11**, 2899 (1994). [doi:10.1088/0264-9381/11/12/007](https://doi.org/10.1088/0264-9381/11/12/007)
- [5] C. Rovelli, *Statistical mechanics of gravity and the thermodynamical origin of time*, Class. Quantum Grav. **10**, 1549 (1993). [doi:10.1088/0264-9381/10/8/015](https://doi.org/10.1088/0264-9381/10/8/015)
- [6] J. J. Bisognano and E. H. Wichmann, *On the duality condition for quantum fields*, J. Math. Phys. **17**, 303 (1976). [doi:10.1063/1.522898](https://doi.org/10.1063/1.522898)
- [7] W. G. Unruh, *Notes on black-hole evaporation*, Phys. Rev. D **14**, 870 (1976). [doi:10.1103/PhysRevD.14.870](https://doi.org/10.1103/PhysRevD.14.870)
- [8] H. Casini, M. Huerta, and R. C. Myers, *Towards a derivation of holographic entanglement entropy*, J. High Energy Phys. **05**, 036 (2011). [doi:10.1007/JHEP05\(2011\)036](https://doi.org/10.1007/JHEP05(2011)036)
- [9] Y. Chen, N. Lashkari, and K. L. Leung, *Local approximations of global Hamiltonian from inclusion of algebras*, arXiv:2512.25062 (2026). [arXiv:2512.25062](https://arxiv.org/abs/2512.25062)

- [10] J. B. Hartle and S. W. Hawking, *Wave function of the Universe*, Phys. Rev. D **28**, 2960 (1983). [doi:10.1103/PhysRevD.28.2960](https://doi.org/10.1103/PhysRevD.28.2960)
- [11] A. J. Leggett, S. Chakravarty, A. T. Dorsey, M. P. A. Fisher, A. Garg, and W. Zwerger, *Dynamics of the dissipative two-state system*, Rev. Mod. Phys. **59**, 1 (1987). [doi:10.1103/RevModPhys.59.1](https://doi.org/10.1103/RevModPhys.59.1)
- [12] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford University Press, 2002).
- [13] L. Diósi, *A universal master equation for the gravitational violation of quantum mechanics*, Phys. Lett. A **120**, 377 (1987). [doi:10.1016/0375-9601\(87\)90681-5](https://doi.org/10.1016/0375-9601(87)90681-5)
- [14] R. Penrose, *On Gravity’s Role in Quantum State Reduction*, Gen. Relat. Gravit. **28**, 581 (1996). [doi:10.1007/BF02105068](https://doi.org/10.1007/BF02105068)
- [15] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, *Models of wave-function collapse, underlying theories, and experimental tests*, Rev. Mod. Phys. **85**, 471 (2013). [doi:10.1103/RevModPhys.85.471](https://doi.org/10.1103/RevModPhys.85.471)
- [16] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim, and G. Milburn, *Spin Entanglement Witness for Quantum Gravity*, Phys. Rev. Lett. **119**, 240401 (2017). [doi:10.1103/PhysRevLett.119.240401](https://doi.org/10.1103/PhysRevLett.119.240401)
- [17] C. Marletto and V. Vedral, *Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity*, Phys. Rev. Lett. **119**, 240402 (2017). [doi:10.1103/PhysRevLett.119.240402](https://doi.org/10.1103/PhysRevLett.119.240402)
- [18] S. E. Danielson, G. Satishchandran, and R. M. Wald, *Black holes decohere quantum superpositions*, Int. J. Mod. Phys. D **31**, 2241003 (2022). [doi:10.1142/S0218271822410036](https://doi.org/10.1142/S0218271822410036)
- [19] S. E. Danielson, G. Satishchandran, and R. M. Wald, *Killing horizons decohere quantum superpositions*, Phys. Rev. D **108**, 025007 (2023). [doi:10.1103/PhysRevD.108.025007](https://doi.org/10.1103/PhysRevD.108.025007)
- [20] J. Wilson-Gerow, A. Dugad, and Y. Chen, *Decoherence by warm horizons*, arXiv:2405.00804 (2024). [arXiv:2405.00804](https://arxiv.org/abs/2405.00804)
- [21] R. Kaltenbaek, M. Aspelmeyer, P. F. Barker, A. Bassi, J. Bateman, K. Bongs, S. Bose, *et al.*, *Macroscopic Quantum Resonators (MAQRO): 2015 update*, EPJ Quantum Technol. **3**, 5 (2016). [doi:10.1140/epjqt/s40507-016-0043-7](https://doi.org/10.1140/epjqt/s40507-016-0043-7)
- [22] C. Gonzalez-Ballester, M. Aspelmeyer, L. Novotny, R. Quidant, and O. Romero-Isart, *Levitodynamics: Levitation and control of microscopic objects in vacuum*, Science **374**, eabg3027 (2021). [doi:10.1126/science.abg3027](https://doi.org/10.1126/science.abg3027)
- [23] We use “dynamical decoupling” and “noise spectroscopy” in the standard sense of J. Bylander, S. Gustavsson, F. Yan, F. Yoshihara, K. Harrabi, G. Fitch, D. G. Cory, Y. Nakamura, J.-S. Tsai, and W. D. Oliver, *Noise spectroscopy through dynamical decoupling with a superconducting flux qubit*, Nature Phys. **7**, 565 (2011). [doi:10.1038/nphys1994](https://doi.org/10.1038/nphys1994)