Stochastic Mass-Energy Interconversion as a Bridge from Quantum Noise to Smooth Relativistic Geometry

Rudolph Elliot Willis

University of Maryland, Baltimore

Rudolph.Willis@umm.edu

Abstract

This article develops a covariant theoretical framework in which spontaneous subatomic mass-energy interconversion is modeled as a stochastic marked point process. The central proposal is not that quantum randomness directly equals spacetime curvature, but that a large population of microscopic interconversion events may generate a stable coarse-grained stress-energy mean while leaving a smaller residual noise sector. In this construction, each event contributes a localized stress-energy packet with random spacetime position, exchanged energy, lifetime, and tensor character. The ensemble mean defines an effective macroscopic source in Einstein's equation, while the residual fluctuations define a covariant noise kernel that sources metric perturbations through an Einstein-Langevin equation.

This formulation distinguishes statistical homogeneity and isotropy in a cosmic rest frame from the stronger condition of local Lorentz invariance required for a truly vacuum-like stress tensor. Under that stronger condition, the mean interconversion sector reduces to a form proportional to the metric and therefore behaves as an emergent cosmological-constant contribution. In cosmology, the background interconversion density is expressed through the active event density: event rate per physical volume and time multiplied by mean exchanged energy and effective event lifetime. This gives a microphysical dictionary for the equation-of-state parameter and for possible late-time dark-energy-like or early-time transient behavior.

The model also gives a formal route by which a transient pre-recombination component could reduce the sound horizon and thereby affect Hubble-constant inference. The manuscript emphasizes that this is a phenomenological bridge, not a completed quantum-gravity theory. Conservation, perturbation bounds, thermodynamic stability, and observational viability remain mandatory tests.

Keywords: stochastic gravity; mass-energy interconversion; Einstein-Langevin equation; coarse-graining; cosmological constant; dark energy; Hubble tension; stress-energy fluctuations; quantum-to-classical transition

1. Introduction

A directly related foundation for the present stochastic-gravity framework is developed in Willis's article *A Dynamical Origin of Wave-Particle Duality From Stochastic Mass-Energy Interconversion*. That article applies spontaneous stochastic mass-energy interconversion to the quantum problem of wave-particle duality. Its central claim is that inertial mass may undergo small stochastic fluctuations consistent with Einstein’s mass-energy equivalence, and that these fluctuations modify the kinetic phase of a quantum system. In that framework, interference arises from coherent path-dependent kinetic-phase accumulation, while particle-like localization emerges when stochastic phase relations become dynamically decohered at detection. The article therefore provides a quantum-scale mechanism in which mass-energy interconversion is not merely a cosmological or gravitational hypothesis, but a proposed microscopic source of quantum phase dynamics, interference visibility, and decoherence. [1]

The study *Observation of Quantum Effects on Radiation Reaction in Strong Fields* provides meaningful experimental support for the broader idea of stochastic mass-energy interconversion. It shows that, in the strong-field quantum regime, energy transfer from relativistic electrons to emitted radiation does not behave as a smooth, continuous classical process. Instead, it occurs through discrete, probabilistic quantum emission events. [2]

The experiment reports a high-significance observation of radiation reaction, exceeding the 5σthreshold, and shows that quantum radiation-reaction models fit the observed data better than classical models. This improvement arises because the quantum models more accurately reproduce the measured electron energy losses and photon emission spectra. Of particular importance for a stochastic interconversion framework, the study finds that photon emission in this regime becomes inherently stochastic, with individual emissions sometimes removing a substantial fraction of an electron’s energy. [2]

The observed post-collision electron spectra show reduced electron energies, broadened distributions, and a strong relationship between increased photon production and greater electron energy loss. These features are consistent with quantized, probabilistic transfer of energy from matter to radiation. While the study does not prove that stochastic mass-energy interconversion is a universal mechanism operating in all physical settings, it does provide strong evidence that, under extreme electromagnetic conditions, matter-radiation energy exchange can proceed through discrete stochastic quantum processes rather than through purely deterministic classical dynamics. [2]

The relevance for the present article is that the dynamical-duality framework supplies a quantum-scale precursor to the gravitational model developed below. In the duality article, the stochastic interconversion process acts on the phase of matter waves; in the present article, the same general class of stochastic mass-energy processes is elevated to a covariant stress-energy source capable of contributing to spacetime curvature. The conceptual bridge is therefore continuous: stochastic mass-energy interconversion first appears as microscopic phase noise and phase coherence in quantum mechanics, and then, when represented covariantly as localized stress-energy packets, becomes a candidate source of both mean relativistic geometry and residual metric fluctuations. This connection strengthens the motivation for treating stochastic interconversion as a unifying intermediate principle between quantum uncertainty, wave-particle behavior, semiclassical stress-energy fluctuations, and the emergence of smooth gravitational geometry. [1]

A persistent problem in fundamental physics is the relationship between the stochastic character of quantum phenomena and the smooth deterministic geometry of general relativity. Quantum theory describes microscopic systems through probabilistic amplitudes, fluctuations, and event-like transitions. General relativity, by contrast, describes gravitation through continuous spacetime curvature sourced by a classical stress-energy tensor. The gap between these descriptions raises a basic question: how can a smooth classical geometry emerge from microscopic stochasticity without simply ignoring the underlying randomness? [3-5,9]

The present work proposes a phenomenological bridge based on stochastic subatomic mass-energy interconversion. The core hypothesis is that microscopic matter-energy conversion events occur locally and randomly. Each event contributes a small stress-energy packet. A single packet is not a smooth gravitational source. A very large ensemble of packets, however, can possess a stable statistical mean. This mean can source a smooth background geometry, while deviations from the mean appear as a small stochastic gravitational-noise sector.

The model therefore uses a two-part decomposition. The first part is the ensemble-averaged stress-energy tensor of the interconversion process. This part contributes to the mean curvature of spacetime. The second part is the fluctuation about that mean. This part is captured by a noise kernel and enters the metric dynamics through an Einstein-Langevin equation. The classical geometry of general relativity is recovered when the number of active events inside a macroscopic coarse-graining region is large, so that the relative strength of stochastic fluctuations is suppressed by the usual inverse-square-root statistical law. [9,10]

A central concept is the distinction between two symmetry statements that are sometimes conflated. Statistical homogeneity and isotropy in a cosmological rest frame are sufficient to make the mean interconversion sector behave like an effective perfect fluid. They are not, by themselves, sufficient to force a vacuum equation of state. A vacuum-like stress tensor requires the stronger condition that the large-scale mean be locally Lorentz invariant. Only under that stronger condition must the mean stress tensor be proportional to the metric. [4-6,11]

This distinction matters because the same stochastic interconversion sector can have multiple macroscopic limits. If the event statistics yield a nearly constant energy density, the sector can mimic a cosmological constant. If the event statistics evolve with cosmic expansion, the sector behaves like a dynamical effective fluid. If the sector is transiently enhanced before recombination, it can raise the early expansion rate, lower the sound horizon, and potentially shift the inferred value of the Hubble constant. These possibilities are formal and require observational testing; they are not claimed as established results. [6,14-17,20,21]

The aim of this article is therefore fourfold. First, it defines a covariant stochastic stress-energy model for spontaneous mass-energy interconversion. Second, it shows how a mean-field limit can produce smooth relativistic geometry. Third, it clarifies the conservation and symmetry requirements needed for consistency. Fourth, it identifies the cosmological consequences and observational constraints that would determine whether the framework is physically viable.

2. Conceptual Structure and Assumptions

The framework rests on the following conceptual chain: microscopic stochastic interconversion events -> mean stress-energy + noise -> Einstein-Langevin dynamics -> coarse-grained classical geometry

This chain should be read as a phenomenological proposal. The event process is not yet derived from a complete quantum field theory or pre-geometric theory. Instead, it is introduced as a controlled mathematical representation of a possible microscopic substrate. The theory must therefore be judged by internal consistency and by whether its macroscopic consequences can be made compatible with observation.

The assumptions used throughout the manuscript are as follows:

The interconversion sector is modeled as a covariant stochastic process, not as arbitrary noise inserted by hand. [7,8]

The total stress-energy tensor must satisfy the covariant conservation condition required by the Bianchi identity. [3,4]

Statistical isotropy in a cosmic rest frame produces a perfect-fluid form; full local Lorentz invariance is required for a vacuum-like form.

Classical spacetime emerges only after coarse-graining over a large number of active events.

A viable cosmological model must keep the induced fluctuation spectrum below observational limits from the cosmic microwave background, lensing, and structure growth. [13,14]

3. Geometric and Physical Setting

Let M be a four-dimensional Lorentzian spacetime with metric g_{ab} and signature $(-,+,+,+)$. Unless explicitly restored, units are chosen so that $c = \hbar = 1$. [3-5]

$$(M, g_{ab}), \qquad \text{signature}(g_{ab}) = (-,+,+,+) \tag{1}$$

The gravitational field satisfies Einstein's equation with a bare cosmological constant Λ_{bare}: [3-5]

$$G_{ab}[g] + \Lambda_{\text{bare}} g_{ab} = 8\pi G\, T_{ab} \tag{2}$$

The total stress-energy tensor is decomposed into ordinary matter/radiation and the proposed interconversion sector:

$$T_{ab} = T_{ab}^{(m)} + T_{ab}^{(\chi)} \tag{3}$$

The Bianchi identity requires the total stress-energy tensor to be covariantly conserved:

$$\nabla^a G_{ab} = 0 \quad \Rightarrow \quad \nabla^a T_{ab} = \nabla^a \left(T_{ab}^{(m)} + T_{ab}^{(\chi)} \right) = 0 \tag{4}$$

Here χ labels the stochastic interconversion sector. It is not assumed at the outset to be separately conserved. Separate conservation is a special case. In the general case, the ordinary and interconversion sectors may exchange energy-momentum while the total remains conserved.

4. Microscopic Stochastic Interconversion Process

Interconversion events are modeled as a marked point process on spacetime. Each event has a location X_i in spacetime and a mark q_i encoding its exchanged energy, duration, microscopic orientation, and tensor character. [7,8]

$$\{(X_i, q_i)\}_{i \in I} \sim \text{marked point process on } M \tag{5}$$

The local intensity of events is written as $\lambda(X, q)$, so that the expected number of events in a small spacetime volume dV_X with marks in $d\mu(q)$ is

$$dN_{\text{expected}} = \lambda(X, q)\, dV_X\, d\mu(q) \tag{6}$$

Each event contributes a localized stress-energy packet t_{ab}. The total interconversion stress-energy tensor is the sum over all event packets:

$$T_{ab}^{(\chi)}(x) = \sum_i t_{ab}\,(x; X_i, q_i) \tag{7}$$

A convenient local packet model is

$$t_{ab}(x; X_i, q_i) = \epsilon_i\, A_{ab}(q_i; X_i)\, W_\ell(x, X_i) \tag{8}$$

where ϵ_i is the energy scale exchanged in the event, A_{ab} is a dimensionless tensor structure, and W_ℓ is a covariant smearing kernel with microscopic width ℓ. The kernel is normalized by

$$\int_M W_\ell\,(x, X_i)\, dV_x = 1 \tag{9}$$

The packet width ℓ prevents the model from treating events as physically singular point sources. It also provides a scale below which the coarse-grained continuum description is not expected to apply.

5. Conservation Law and Exchange Current

The central consistency condition is total covariant conservation:

$$\nabla^a \left[T_{ab}^{(m)} + T_{ab}^{(\chi)} \right] = 0 \tag{10}$$

The strongest version of the model imposes conservation event by event:

$$\nabla^a t_{ab}(x; X_i, q_i) = 0 \quad \text{for every event } i \tag{11}$$

A more flexible and physically natural version allows exchange between ordinary matter and the interconversion sector:

$$\nabla^a T_{ab}^{(m)} = Q_b, \qquad \nabla^a T_{ab}^{(\chi)} = -Q_b \tag{12}$$

The exchange current Q_b represents local transfer of energy-momentum between sectors. The sum remains conserved, so the Einstein equation remains compatible with the Bianchi identity:

$$\nabla^a T_{ab} = Q_b - Q_b = 0 \tag{13}$$

This framework makes it explicit that stochastic interconversion cannot be introduced as an unconstrained source. Any concrete model must specify either conserved event packets or an exchange current Q_b that preserves total conservation.

6. Mean-Field Limit

Taking the ensemble average over the event process defines the mean interconversion stress-energy tensor:

$$\overline{T}_{ab}^{(\chi)}(x) \equiv \left\langle T_{ab}^{(\chi)}(x) \right\rangle \tag{14}$$

For a Poisson marked process, the mean is the intensity-weighted integral of the individual event packet: [7,8]

$$\overline{T}_{ab}^{(\chi)}(x) = \int_M d\,V_X \int d\mu(q)\, \lambda(X,q)\, \epsilon(q)\, A_{ab}(q;X)\, W_\ell(x,X) \tag{15}$$

If λ, ϵ, and the mark averages vary slowly across the microscopic support of W_ℓ, the mean becomes local:

$$\overline{T}_{ab}^{(\chi)}(x) \simeq n_\chi(x)\, \overline{\epsilon}_\chi(x)\, \overline{A}_{ab}(x) \tag{16}$$

The active event density n_χ is the number of active interconversion events per physical spatial volume. If Γ_χ is the event rate per physical volume per proper time and τ_χ is the effective lifetime of an active event, then

$$n_\chi(x) = \Gamma_\chi(x)\, \tau_\chi(x) \tag{17}$$

Therefore the local mean source may be written as

$$\overline{T}^{(\chi)}_{ab}(x) \simeq \Gamma_\chi(x)\, \tau_\chi(x)\, \overline{\epsilon}_\chi(x)\, \overline{A}_{ab}(x) \tag{18}$$

This is the corrected microphysical dictionary: the background contribution is controlled by an active event density, not merely by an event rate alone.

7. Fluctuation Field and Stress-Energy Decomposition

The full interconversion stress tensor is decomposed into a mean and a fluctuation:

$$T^{(\chi)}_{ab}(x) = \overline{T}^{(\chi)}_{ab}(x) + \delta T^{(\chi)}_{ab}(x) \tag{19}$$

The fluctuation field has zero mean by definition:

$$\left\langle \delta T^{(\chi)}_{ab}(x) \right\rangle = 0 \tag{20}$$

This mean-plus-fluctuation split is the mathematical basis for the bridge from microscopic stochasticity to large-scale geometry. The mean determines the background curvature, while $\delta T^{(\chi)}_{ab}$ sources stochastic perturbations.

8. Effective Fluid Decomposition

Introduce a local unit timelike vector field u^a satisfying

$$u^a u_a = -1 \tag{21}$$

and define the spatial projector

$$h_{ab} = g_{ab} + u_a u_b \tag{22}$$

The mean interconversion tensor can be decomposed as

$$\overline{T}^{(\chi)}_{ab} = \rho_\chi u_a u_b + p_\chi h_{ab} + 2u_{(a} q^{(\chi)}_{b)} + \pi^{(\chi)}_{ab} \tag{23}$$

where $q^{(\chi)}_a$ is the energy-flux vector and $\pi^{(\chi)}_{ab}$ is the anisotropic stress tensor. Their defining conditions are

$$q_a^{(\chi)} u^a = 0, \qquad \pi_{ab}^{(\chi)} u^b = 0, \qquad \pi^{(\chi)}{}^a{}_a = 0 \tag{24}$$

If the event ensemble is statistically homogeneous and isotropic in the local rest frame, then

$$q_a^{(\chi)} = 0, \qquad \pi_{ab}^{(\chi)} = 0 \tag{25}$$

and the mean tensor reduces to a perfect-fluid form:

$$\overline{T}_{ab}^{(\chi)} = \rho_\chi u_a u_b + p_\chi h_{ab} \tag{26}$$

The effective equation-of-state parameter is

$$w_\chi \equiv \frac{p_\chi}{\rho_\chi} \tag{27}$$

This section makes a key conceptual point: isotropy gives a perfect fluid, but it does not by itself require $w_\chi = -1$. A vacuum-like equation of state requires the stronger Lorentz-invariance condition discussed next.

9. Emergent Vacuum-Like Limit

If the large-scale mean of the interconversion sector is locally Lorentz invariant, then the only available rank-2 tensor with the required symmetry is the metric. Therefore

$$\overline{T}_{ab}^{(\chi)} = -\rho_{\text{vac}}^{(\chi)} g_{ab} \tag{28}$$

Comparing this with the perfect-fluid form gives

$$p_\chi = -\rho_\chi, \qquad w_\chi = -1 \tag{29}$$

The corresponding effective cosmological-constant contribution is

$$\Lambda_\chi = 8\pi G\, \rho_{\text{vac}}^{(\chi)} \tag{30}$$

and the total effective cosmological constant becomes

$$\Lambda_{\text{eff}} = \Lambda_{\text{bare}} + \Lambda_\chi \tag{31}$$

This result is logically valid only under the stronger Lorentz-invariant averaging assumption. In a cosmological rest frame, where the expansion itself selects a preferred timelike direction, the interconversion sector may instead behave as a general effective fluid with $w_\chi(a)$ not exactly equal to -1.

10. Effective Einstein Equation

Substituting the mean-plus-fluctuation split into Einstein's equation gives

$$G_{ab}[g] + \Lambda_{\text{bare}} g_{ab} = 8\pi G \left[T_{ab}^{(m)} + \overline{T}_{ab}^{(\chi)} + \delta T_{ab}^{(\chi)}\right] \tag{32}$$

If the mean interconversion sector is vacuum-like, the vacuum contribution may be moved to the geometric side:

$$G_{ab}[g] + \Lambda_{\text{eff}} g_{ab} = 8\pi G\left[T_{ab}^{(m)} + \delta T_{ab}^{(\chi)}\right] \tag{33}$$

Thus the same microscopic process contributes two gravitational components: a smooth mean curvature term and a residual stochastic curvature source.

11. Noise Kernel and Stochastic Stress-Energy Fluctuations

Define the stochastic source field

$$\xi_{ab}(x) \equiv \delta T_{ab}^{(\chi)}(x) \tag{34}$$

with

$$\langle \xi_{ab}(x) \rangle = 0 \tag{35}$$

The covariant noise kernel is the two-point correlation function of the fluctuation field: [9,10]

$$N_{abcd}(x, y) \equiv \langle \xi_{ab}(x) \xi_{cd}(y) \rangle \tag{36}$$

For a Poisson event process with independent marks, the shot-noise contribution is

$$N_{abcd}(x, y) = \int_M d\, V_X \int d\mu(q)\, \lambda(X, q)\, t_{ab}(x; X, q) t_{cd}(y; X, q) \tag{37}$$

If the events are correlated rather than Poisson, a connected correlation term must be added:

$$N_{abcd} = N_{abcd}^{(\mathrm{Poisson})} + N_{abcd}^{(\mathrm{connected})} \tag{38}$$

This addition is important because correlations could either enhance or suppress the stochastic metric perturbations. Observational viability depends strongly on the size and scale dependence of this kernel. [9,10]

12. Coarse-Graining and Emergence of Classicality

Let $K_L(x, y)$ be a normalized covariant coarse-graining kernel on a macroscopic scale L:

$$\int_M K_L\,(x, y)\,dV_y = 1 \tag{39}$$

The coarse-grained interconversion tensor is

$$T_{ab,L}^{(\chi)}(x) = \int_M K_L\,(x, y) T_{ab}^{(\chi)}(y)\,dV_y \tag{40}$$

Let V_L be the physical coarse-graining volume and let N_L be the number of active events inside that region:

$$N_L \simeq \Gamma_\chi \tau_\chi V_L \tag{41}$$

For many weakly correlated events with finite variance, the relative size of the coarse-grained fluctuation scales as

$$\frac{\sqrt{\mathrm{Var}\left(T_{ab,L}^{(\chi)}\right)}}{\left|\overline{T}_{ab,L}^{(\chi)}\right|} \propto \frac{1}{\sqrt{N_L}} \tag{42}$$

The classicality condition is therefore

$$N_L \gg 1 \tag{43}$$

When this condition holds, the mean dominates over the stochastic fluctuations and spacetime appears smooth at scale L. When it fails, the continuum mean-field approximation is not reliable.

13. Einstein-Langevin Form

Let the metric be decomposed into a mean background and a stochastic perturbation:

$$g_{ab} = \overline{g}_{ab} + h_{ab} \tag{44}$$

The mean geometry satisfies

$$G_{ab}[\overline{g}] + \Lambda_{\text{bare}}\overline{g}_{ab} = 8\pi G\left[\overline{T}_{ab}^{(m)} + \overline{T}_{ab}^{(\chi)}\right] \tag{45}$$

If the vacuum-like part has been absorbed into Λ_{eff}, this may also be written as

$$G_{ab}[\overline{g}] + \Lambda_{\text{eff}}\overline{g}_{ab} = 8\pi G\,\overline{T}_{ab}^{(m)} \tag{46}$$

The linearized stochastic perturbation satisfies an Einstein-Langevin equation of the schematic form

$$\delta G_{ab}[h] + \Lambda_{\text{eff}}h_{ab} = 8\pi G\left[\delta T_{ab}^{(m)}[h] + \xi_{ab}\right] \tag{47}$$

with stochastic source statistics

$$\langle \xi_{ab}(x)\rangle = 0, \qquad \langle \xi_{ab}(x)\xi_{cd}(y)\rangle = N_{abcd}(x,y) \tag{48}$$

This equation gives the corrected bridge: the microscopic interconversion process supplies both a deterministic mean source and a stochastic source whose correlations are encoded in N_{abcd}.

14. Cosmological Specialization

On a Friedmann-Robertson-Walker background, the metric is [6,11,12]

$$ds^2 = -dt^2 + a^2(t)\gamma_{ij}dx^i dx^j \tag{49}$$

where $a(t)$ is the scale factor and γ_{ij} is the spatial metric of constant curvature k. The Friedmann equation becomes

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_r + \rho_\chi\right) + \frac{\Lambda_{\text{bare}}}{3} - \frac{k}{a^2} \tag{50}$$

The acceleration equation may be written as

$$\dot{H} = -4\pi G(\rho_{\text{tot}} + p_{\text{tot}}) + \frac{k}{a^2} \tag{51}$$

The corrected microscopic dictionary for the interconversion density is

$$\rho_\chi(a) = \Gamma_\chi(a)\, \bar{\epsilon}_\chi(a)\, \tau_\chi(a) \tag{52}$$

If the interconversion sector is separately conserved at the background level, its continuity equation is

$$\frac{d\rho_\chi}{dt} + 3H(1 + w_\chi)\rho_\chi = 0 \tag{53}$$

Therefore the effective equation of state is

$$w_\chi(a) = -1 - \frac{1}{3}\frac{d\ln\rho_\chi}{d\ln a} \tag{54}$$

Using the microscopic dictionary, this becomes

$$w_\chi(a) = -1 - \frac{1}{3}\frac{d\ln\left[\Gamma_\chi(a)\bar{\epsilon}_\chi(a)\tau_\chi(a)\right]}{d\ln a} \tag{55}$$

If there is energy exchange with ordinary matter or another sector, the continuity equation generalizes to

$$\frac{d\rho_\chi}{dt} + 3H(1 + w_\chi)\rho_\chi = -Q_\chi \tag{56}$$

where Q_χ is the background energy-transfer rate from the interconversion sector into the other sector. A complete model must specify Q_χ or justify $Q_\chi = 0$.

15. Metric Fluctuation Spectrum and Observational Constraints

To connect the model to observations, assume a Gaussian spatial profile for the event packet:

$$W_\ell(r) = (2\pi\ell^2)^{-3/2}\exp\left[-\frac{r^2}{2\ell^2}\right] \tag{57}$$

Its Fourier transform is

$$\widetilde{W}_\ell(k) = \exp\left[-\frac{k^2\ell^2}{2}\right] \tag{58}$$

The equal-time density-fluctuation spectrum from independent event noise has the schematic form

$$P_{\delta\rho,\chi}(k) \simeq \Gamma_\chi \tau_\chi \bar{\epsilon}_\chi^2 \left|\widetilde{W}_\ell(k)\right|^2 \tag{59}$$

On sub-horizon scales, the Newtonian potential obeys

$$k^2\Phi(k,a) = 4\pi G a^2 \delta\rho_\chi(k,a) \tag{60}$$

so the induced potential spectrum is

$$P_{\Phi,\chi}(k,a) = \left(\frac{4\pi G a^2}{k^2}\right)^2 P_{\delta\rho,\chi}(k,a) \tag{61}$$

A necessary observational viability condition is

$$P_{\Phi,\chi}(k,a) \ll P_{\Phi,\text{obs}}(k,a) \quad \text{on constrained CMB, lensing, and structure-growth scales} \tag{62}$$

This condition prevents the model from treating background expansion alone as sufficient. Any interconversion component large enough to affect the expansion history must also avoid producing excessive perturbation power.

16. Early-Universe Ruler Deformation and Hubble-Tension Relevance

The comoving sound horizon at photon decoupling is [11-17]

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\, dz \tag{63}$$

where c_s is the sound speed in the photon-baryon fluid. Suppose the interconversion sector contributes a positive transient fraction $f_\chi(z)$ to the pre-recombination energy density:

$$H^2(z) = H_{\Lambda\text{CDM}}^2(z)\left[1 + f_\chi(z)\right] \tag{64}$$

with

$$f_\chi(z) \equiv \frac{\rho_\chi(z)}{\rho_{\Lambda\text{CDM}}(z)} \tag{65}$$

For small f_χ, the leading perturbative shift in the sound horizon is

$$\frac{\Delta r_s}{r_s} \simeq -\frac{1}{2}\langle f_\chi \rangle_{r_s} \tag{66}$$

where the sound-horizon-weighted average is

$$\langle f_\chi \rangle_{r_s} \equiv \frac{\int_{z_*}^{\infty} (c_s/H_{\Lambda\mathrm{CDM}})\, f_\chi(z)\, dz}{\int_{z_*}^{\infty} (c_s/H_{\Lambda\mathrm{CDM}})\, dz} \tag{67}$$

Because many early-universe Hubble-constant inferences scale inversely with the calibrated sound horizon, the approximate response is

$$\frac{\Delta H_0}{H_0} \simeq -\frac{\Delta r_s}{r_s} \tag{68}$$

Thus a positive early interconversion component could formally raise the Hubble constant inferred from early-universe calibration by lowering r_s. This is a route of formal relevance to the Hubble tension. It is not, by itself, a solution. A successful model must also satisfy CMB peak-shape constraints, baryon acoustic oscillation constraints, structure-growth constraints, and the fluctuation bound in Eq. (62). [14-17,20,21]

17. Core Conclusions of the Model

Under the assumptions, the model supports the following conclusions:

1. Microscopic stochastic interconversion events can be represented as a covariant marked point process.
2. The ensemble mean of the event process defines an effective macroscopic stress-energy tensor.
3. Statistical isotropy produces a perfect-fluid form, while full local Lorentz invariance is required for a vacuum-like form.
4. If the mean is vacuum-like, it contributes an effective cosmological constant $\Lambda_\chi = 8\pi G \rho_{\mathrm{vac}}^{(\chi)}$.
5. The residual fluctuations define a noise kernel that sources stochastic metric perturbations through an Einstein-Langevin equation.
6. Coarse-graining over many active events suppresses relative fluctuations as $1/\sqrt{N_L}$, producing a smooth classical limit.

7. In cosmology, the background density is controlled by $\Gamma_\chi \bar{\epsilon}_\chi \tau_\chi$, which determines the effective equation of state and possible deformation of the expansion history.
8. Any viable model must pass perturbation and conservation tests; background expansion effects alone are insufficient.

18. Compact Formal Statement

The entire framework may be summarized compactly as

$$T_{ab}^{(\chi)} = \sum_i t_{ab}\,(x; X_i, q_i) = \bar{T}_{ab}^{(\chi)} + \xi_{ab} \tag{69}$$

with

$$\bar{T}_{ab}^{(\chi)} = \left\langle T_{ab}^{(\chi)} \right\rangle \tag{70}$$

and

$$N_{abcd}(x, y) = \langle \xi_{ab}(x) \xi_{cd}(y) \rangle \tag{71}$$

The mean geometry obeys

$$G_{ab}[\bar{g}] + \Lambda_{\text{bare}} \bar{g}_{ab} = 8\pi G \left[\bar{T}_{ab}^{(m)} + \bar{T}_{ab}^{(\chi)} \right] \tag{72}$$

while the stochastic perturbation obeys

$$\delta G_{ab}[h] + \Lambda_{\text{eff}} h_{ab} = 8\pi G \left[\delta T_{ab}^{(m)}[h] + \xi_{ab} \right] \tag{73}$$

The coarse-grained classical limit is defined by

$$N_L = \Gamma_\chi \tau_\chi V_L \gg 1, \qquad \frac{\sqrt{\text{Var}\left(T_{ab,L}^{(\chi)} \right)}}{\left| \bar{T}_{ab,L}^{(\chi)} \right|} \propto N_L^{-1/2} \tag{74}$$

When the mean is locally Lorentz invariant,

$$\bar{T}_{ab}^{(\chi)} = -\rho_{\text{vac}}^{(\chi)} g_{ab}, \qquad \Lambda_{\text{eff}} = \Lambda_{\text{bare}} + 8\pi G \rho_{\text{vac}}^{(\chi)} \tag{75}$$

In the general cosmological-fluid case,

$$\rho_\chi(a) = \Gamma_\chi(a)\bar{\epsilon}_\chi(a)\tau_\chi(a), \qquad w_\chi(a) = -1 - \frac{1}{3}\frac{d\ln\rho_\chi}{d\ln a} \tag{76}$$

19. Numerical Constraints and Testable Parameter Bounds

To make the stochastic mass-energy interconversion bridge theory quantitatively testable, the interconversion sector can be constrained by cosmological background data, early-universe bounds, perturbation-amplitude limits, matter-growth measurements, interferometric coherence limits, and strong-field quantum-electrodynamic benchmarks. These constraints do not alter the formal structure developed above; rather, they identify the parameter space in which the existing framework could remain viable. [13,14,18-21]

It is useful first to define the dimensionless interconversion density fraction and the fractional contribution of the interconversion sector to the total cosmic energy density:

$$\Omega_\chi(a) \equiv \frac{\rho_\chi(a)}{\rho_{\text{crit}}(a)} \tag{77}$$

$$f_\chi(a) \equiv \frac{\rho_\chi(a)}{\rho_{\text{tot}}(a)} \tag{78}$$

Using the central microphysical dictionary of the model, the same density is also given by

$$\rho_\chi(a) = \Gamma_\chi(a)\bar{\epsilon}_\chi(a)\tau_\chi(a) \tag{79}$$

where $\Gamma_\chi$is the event rate density, $\bar{\epsilon}_\chi$is the mean exchanged energy, and $\tau_\chi$is the effective event lifetime. Observational constraints can therefore be interpreted directly as constraints on the product $\Gamma_\chi\bar{\epsilon}_\chi\tau_\chi$.

A first numerical bound comes from the present-day dark-energy density. If the interconversion sector accounts for all or part of dark energy, then its present-day density cannot exceed the observed dark-energy density. Using the Planck 2018 flat-ΛCDM parameters, this gives the approximate upper bound [14]

$$\Gamma_{\chi,0}\bar{\epsilon}_{\chi,0}\tau_{\chi,0} \leq 5.3 \times 10^{-10}\ \text{J m}^{-3} \tag{80}$$

$$\rho_{\chi,0} \leq 5.8 \times 10^{-27}\ \text{kg m}^{-3} \tag{81}$$

Equivalently, for an assumed microscopic exchanged-energy scale, the maximum active event density is

$$n_{\chi,0} = \Gamma_{\chi,0}\tau_{\chi,0} \leq \frac{\rho_{\Lambda,0}}{\bar{\epsilon}_{\chi,0}} \tag{82}$$

Representative benchmark values are:

Assumed mean exchanged energy $\bar{\epsilon}_\chi$	**Maximum active event density** $n_{\chi,0}$
1 eV	$\leq 3.3 \times 10^9\ \mathrm{m}^{-3}$
1 keV	$\leq 3.3 \times 10^6\ \mathrm{m}^{-3}$
1 MeV	$\leq 3.3 \times 10^3\ \mathrm{m}^{-3}$
1 GeV	$\leq 3.3\ \mathrm{m}^{-3}$

A second constraint comes from the late-time equation of state. If the interconversion sector behaves as the dominant dark-energy component at low redshift, then its effective equation-of-state parameter must remain close to -1. A conservative bound may be written as [14,20]

$$| w_\chi + 1 | \leq 0.06 \tag{83}$$

Using the relation between the equation of state and the evolution of the interconversion-density product, this becomes

$$\left| \frac{d\ln\left[\Gamma_\chi(a)\bar{\epsilon}_\chi(a)\tau_\chi(a)\right]}{d\ln a} \right| \leq 0.18 \tag{84}$$

Thus, if the interconversion sector is intended to reproduce cosmological-constant-like behavior, the product $\Gamma_\chi\bar{\epsilon}_\chi\tau_\chi$ must be nearly constant at late times.

A third constraint applies if the theory is used to address the Hubble-tension problem through a transient pre-recombination energy component. The leading sound-horizon response derived above may be summarized as [14-17,20,21]

$$\frac{\Delta r_s}{r_s} \simeq -\frac{1}{2}\langle f_\chi \rangle_{r_s} \tag{85}$$

The fractional increase required to shift the Planck-inferred Hubble constant toward the SH0ES local value is approximately [14,20]

$$\frac{73.04 - 67.4}{67.4} \simeq 0.084 \tag{86}$$

If this were achieved entirely by reducing the sound horizon, the required sound-horizon-weighted interconversion fraction would be roughly

$$\langle f_\chi \rangle_{r_s} \simeq 0.17 \tag{87}$$

However, early-dark-energy analyses generally require the allowed pre-recombination fractional contribution to be significantly smaller. A conservative phenomenological bound for the stochastic interconversion sector is therefore [16,17,21]

$$f_\chi(z \simeq 10^3 - 10^4) \leq 0.07\text{–}0.10 \tag{88}$$

This means the theory should claim formal or partial Hubble-tension relevance unless a full Boltzmann-code analysis demonstrates that its perturbation structure can evade ordinary early-dark-energy limits.

If the interconversion sector behaves as an extra radiation-like component in the early universe, it is also constrained by limits on the effective number of relativistic species. A useful approximate bound is [14]

$$\Delta N_{\mathrm{eff},\chi} \leq 0.3 \tag{89}$$

$$\frac{\rho_\chi}{\rho_{\mathrm{rad}}} \leq 0.05 \tag{90}$$

The stochastic fluctuation sector is constrained even more directly by the observed smallness of CMB anisotropies. Since CMB temperature fluctuations are of order 10^{-5}, the dimensionless potential perturbation sourced by the interconversion noise should satisfy approximately [13,14]

$$\Delta_{\Phi,\chi} \leq 10^{-5} \tag{91}$$

Equivalently, in power-spectrum form,

$$\Delta^2_{\Phi,\chi}(k) \equiv \frac{k^3 P_{\Phi,\chi}(k)}{2\pi^2} \leq 10^{-10} \tag{92}$$

A more conservative requirement that the new stochastic-noise sector remain subdominant is

$$\Delta^2_{\Phi,\chi}(k) \leq 10^{-11} \tag{93}$$

Matter-growth measurements provide another consistency check. If the interconversion sector changes structure formation, its contribution should not shift the matter fluctuation amplitude beyond the observed precision. A useful conservative constraint is [14]

$$| \Delta\sigma_8 | \leq 0.006\text{–}0.01 \tag{94}$$

Laboratory interferometry provides a complementary constraint on the stochastic phase sector. If stochastic mass-energy interconversion induces intrinsic phase noise, high-visibility matter-wave experiments require [18,19]

$$\frac{V}{V_0} = \exp\left(-\frac{\sigma_{\phi,\chi}^2}{2} \right) \geq 0.9 \tag{95}$$

which implies

$$\sigma_{\phi,\chi} \leq 0.46 \text{ rad} \tag{96}$$

$$\sigma_{\phi,\chi}^2 \leq 0.21 \tag{97}$$

For a stochastic mass-fluctuation covariance $C_m(t - t')$, this may be written as the integral constraint

$$\frac{p^4}{m_0^4 \hbar^2} \int_0^T \int_0^T C_m\,(t - t')\, dt\, dt' \leq 0.21 \tag{98}$$

Finally, the strong-field QED limit supplies an empirical benchmark. Any proposed interconversion mechanism should reduce to known stochastic quantum-emission behavior in regimes where matter-radiation energy exchange is already experimentally observed to proceed through discrete probabilistic emission events. This requirement does not by itself fix Γ_χ, $\bar{\epsilon}_\chi$, or $\tau_\chi$in cosmology, but it provides an important physical consistency condition: the theory should reproduce known stochastic quantum energy-transfer behavior before being extrapolated to semiclassical gravity or cosmology. [2]

20. Discussion

This framework suggests a coherent way to think about the emergence of smooth spacetime from microscopic stochasticity. Its central virtue is structural unity. The same event process generates the mean gravitational source and the stochastic fluctuation sector. The theory therefore does not artificially separate background curvature from noise; both arise from one underlying process.

The most compelling part of the model is its coarse-graining mechanism. Classical geometry emerges because many microscopic events combine to produce a stable statistical mean. This is analogous to the way thermodynamic variables emerge from many microscopic molecular motions. The microscopic events remain random, but their macroscopic average becomes predictable.

The vacuum-like limit is also conceptually attractive, but it requires careful qualification. A stress tensor proportional to the metric follows from Lorentz-invariant averaging, not merely from ordinary cosmological isotropy. This distinction improves the logical clarity of the theory. It allows the interconversion sector to behave either as a cosmological-constant-like term or as a more general effective fluid, depending on the symmetry and evolution of the event ensemble.

The cosmological implications are significant but preliminary. If $\Gamma_\chi \bar{\epsilon}_\chi \tau_\chi$ is nearly constant at late times, the sector mimics dark energy. If it evolves slowly, it behaves like dynamical dark energy. If it has a transient early-time enhancement, it can raise the pre-recombination expansion rate and reduce the sound horizon. This gives the model a formal path toward Hubble-tension relevance.

However, formal relevance is not the same as observational viability. The model must demonstrate that the stochastic noise associated with the interconversion sector does not overproduce metric perturbations. It must also respect conservation, thermodynamic stability, causality, local Lorentz tests, fifth-force constraints if couplings are introduced, and precision cosmological data.

The largest unresolved theoretical issue is the microscopic origin of the event process. In the present article, the marked point process is phenomenological. A deeper theory would need to derive $\lambda(X, q)$, $\epsilon(q)$, τ_χ, A_{ab}, and the correlation structure from a more fundamental quantum field, quantum-gravity, or pre-geometric model. Without such a derivation, the theory should be treated as a formal bridge and a model-building template rather than a completed fundamental theory.

Despite these limitations, the framework has a clear conceptual payoff. It reframes the relation between quantum noise and classical spacetime: smooth geometry does not require microscopic randomness to vanish. Instead, smooth geometry can arise as the law-of-large-numbers limit of a deeper stochastic mass-energy substratum.

The stochastic mass–energy interconversion bridge theory should be investigated as a **multi-scale research program** rather than as a single isolated hypothesis. Its central claim is that microscopic stochastic interconversion events may produce two macroscopic consequences: first, a smooth ensemble-averaged stress–energy source capable of contributing to classical spacetime geometry; and second, residual stress–energy fluctuations that appear as stochastic metric perturbations. This places the theory between quantum foundations, semiclassical gravity, stochastic gravity, cosmology, and precision interferometry. The existing Stochastic Quantum Gravity article already frames the model as a phenomenological bridge rather than a completed theory, and that distinction should guide the investigative strategy. [1,2,9,10,14,18-21]

A first line of investigation should focus on **mathematical consistency**. The most important requirement is covariant conservation. In general relativity, the Einstein tensor satisfies the Bianchi identity, so any stochastic stress–energy source must preserve total conservation. The theory must therefore specify whether each microscopic interconversion packet is individually conserved or whether conservation is restored through an exchange current between the ordinary matter sector and the interconversion sector. This is not a secondary technical issue; it is the condition that determines whether the stochastic source can be consistently inserted into Einstein's equation. The theory should therefore be tested by constructing explicit packet models

$t_{ab}(x; X_i, q_i)$whose divergence either vanishes event by event or is exactly balanced by a compensating exchange current Q_b. [3,4]

A second line of investigation should embed the model within the established language of **stochastic gravity**. Stochastic gravity already studies the way stress–energy fluctuations source metric fluctuations through the Einstein–Langevin equation. Hu and Verdaguer describe stochastic semiclassical gravity as an extension of semiclassical gravity in which the expectation value of the stress–energy tensor is supplemented by a noise kernel that sources metric perturbations. This is directly relevant because the proposed interconversion theory also separates the stress–energy sector into a mean term plus a fluctuation term. The immediate research task is to determine whether the proposed interconversion noise kernel has the mathematical properties required in stochastic gravity: covariance, conservation, positive semidefinite correlations, and consistency with known semiclassical limits. [9,10]

A third line of investigation should address the **microscopic origin** of the stochastic events. At present, the marked point process is phenomenological: it assumes localized interconversion events with an event rate, energy scale, lifetime, and tensor structure. A deeper theory would need to derive those quantities from quantum field theory, vacuum fluctuations, strong-field quantum electrodynamics, or a pre-geometric substrate. The related Dynamical Duality article is important here because it applies stochastic mass–energy interconversion to wave-particle duality, proposing that stochastic inertial-mass fluctuations generate kinetic-phase variations that influence interference and localization. That article therefore supplies a possible microscopic quantum-scale precursor to the gravitational model: stochastic interconversion first appears as phase noise in matter-wave propagation, and then becomes a covariant stress–energy source when lifted into the gravitational setting. [1,2,7,8]

A fourth line of investigation should use **matter-wave interferometry** to constrain the proposed stochastic phase sector. If stochastic mass–energy interconversion produces kinetic-phase noise, then high-precision interferometers should be able to bound or detect the resulting loss of coherence. Heavy-particle interferometry is especially important because mass-dependent phase effects should become more visible as particle mass, momentum, and flight time increase. Experiments have already demonstrated quantum interference for molecules beyond 25 kDa, showing that coherent superposition can survive in systems containing thousands of atoms; such results place strong limits on any intrinsic stochastic decoherence mechanism. Arndt and Hornberger also emphasize that testing the limits of quantum superposition has become an experimentally active route for probing whether standard quantum mechanics remains valid at larger masses. [18,19]

A fifth line of investigation should examine **strong-field quantum electrodynamics** as a possible empirical analogue of stochastic mass–energy transfer. The study *Observation of Quantum Effects on Radiation Reaction in Strong Fields* reports high-significance observation of radiation reaction in a regime where quantum effects are substantial, and it compares quantum radiation-reaction models with classical descriptions. This is relevant because the strong-field regime shows that energy transfer between relativistic electrons and emitted radiation can occur through discrete quantum emission processes rather than through a purely smooth classical loss channel. The result does not prove the full stochastic interconversion theory, but it does provide an experimentally grounded example of probabilistic matter–radiation energy exchange under extreme conditions. [2]

A sixth line of investigation should test the model through **cosmological background evolution**. The theory predicts an effective interconversion density of the form [6,11-14]

$$\rho_\chi(a) = \Gamma_\chi(a)\, \bar{\epsilon}_\chi(a)\, \tau_\chi(a),$$

where Γ_χ is the event rate density, $\bar{\epsilon}_\chi$ is the mean exchanged energy, and τ_χ is the effective event lifetime. If this product is nearly constant at late times, the sector can mimic a cosmological constant. If it evolves with scale factor, it behaves as a dynamical effective fluid. If it is transiently enhanced before recombination, it could reduce the sound horizon and affect the inferred value of the Hubble constant. However, any such claim must be tested against the precision cosmological constraints from the cosmic microwave background, baryon acoustic oscillations, supernovae, and large-scale structure. The Planck 2018 results remain a central reference point for CMB-based cosmological parameter constraints. [14]

A seventh line of investigation should compare the theory to **early-dark-energy approaches** to the Hubble tension. Early dark energy models have been proposed as a way to reduce the sound horizon before recombination and thereby increase the CMB-inferred value of H_0. Poulin, Smith, Karwal, and Kamionkowski showed that an early dark energy component can, in principle, reduce the sound horizon and shift the inferred Hubble constant. The stochastic interconversion model could be studied in a similar phenomenological way, but with a different microphysical interpretation: instead of introducing an early scalar-field component, one would model a transient increase in $\Gamma_\chi \bar{\epsilon}_\chi \tau_\chi$. The key test would be whether such a component can change the background expansion without producing unacceptable perturbations. [16,17,21]

A eighth line of investigation should focus on the **fluctuation spectrum**, because this is where the model is most vulnerable to falsification. Any interconversion sector large enough to alter the expansion history will also carry stochastic fluctuations. Those fluctuations may source gravitational potentials, CMB anisotropies, lensing signatures, or structure-growth deviations. Therefore, the model cannot be judged only by whether it produces a desired background expansion. It must also satisfy a perturbation constraint of the form [13,14]

$$P_{\Phi,\chi}(k,a) \ll P_{\Phi,\mathrm{obs}}(k,a)$$

on scales constrained by CMB, lensing, and galaxy clustering data. This requirement is central because it turns the model from a flexible explanatory framework into a quantitatively testable theory.

A ninth line of investigation should develop **numerical simulations**. The theory can be simulated at two levels. At the microscopic level, one can generate stochastic event ensembles with specified event rate, lifetime, energy scale, and correlation structure, then measure how the coarse-grained stress–energy tensor approaches a smooth mean. At the cosmological level, one can insert $\rho_\chi(a)$, $w_\chi(a)$, and a corresponding perturbation sector into Boltzmann codes used for CMB and large-scale-structure predictions. This would allow direct comparison with Planck, BAO, supernova, lensing, and structure-growth datasets. Such simulations would determine whether the required event statistics are physically plausible or already observationally excluded. [11-14,16,17,21]

A tenth line of investigation should define **clear falsifiability criteria**. The theory would be weakened or ruled out if high-mass interferometry continues to show no intrinsic mass-, momentum-, or flight-time-dependent coherence loss beyond known environmental decoherence; if cosmological fits require a stochastic energy density that overproduces metric perturbations; if no conserved stochastic stress–energy construction can be formulated; or if the required interconversion rate violates laboratory bounds on energy conservation, fifth forces, Lorentz symmetry, or equivalence-principle tests. Conversely, the theory would gain support if independent observations revealed a consistent pattern of stochastic phase noise, matter–radiation energy-transfer discreteness, and cosmological fluctuation behavior matching the same underlying parameter set. [2,14,18-21]

The most productive way to investigate the stochastic mass–energy interconversion bridge theory is therefore not to ask whether it immediately solves quantum gravity, dark energy, or the Hubble tension. The more rigorous question is whether one can construct a conserved stochastic stress–energy model whose microscopic event statistics simultaneously satisfy quantum-coherence bounds, stochastic-gravity consistency conditions, and cosmological perturbation constraints. If the same small set of parameters can survive all three regimes, the theory would become a serious candidate for a unifying phenomenological bridge. If not, the model will still have served a useful scientific purpose by identifying where stochastic mass–energy interconversion fails as a mechanism connecting quantum noise to smooth spacetime geometry.

21. Conclusion

This article has constructed a covariant stochastic framework in which spontaneous subatomic mass-energy interconversion generates both an effective macroscopic stress-energy sector and a residual fluctuation sector. The ensemble mean can behave as a general effective fluid or, under the stronger condition of local Lorentz-invariant averaging, as a vacuum-like source equivalent to an emergent cosmological-constant contribution. The fluctuations define a noise kernel that sources metric perturbations through an Einstein-Langevin equation. Coarse-graining over many active events suppresses the relative fluctuations as $N_L^{-1/2}$, yielding smooth deterministic spacetime at macroscopic scales.

In cosmology, the model reduces to a simple but powerful dictionary: the effective interconversion density is determined by event rate density, mean exchanged energy, and effective event lifetime. This density controls the equation of state, modifies the Friedmann expansion history, and provides a formal route to dynamical dark-energy behavior or early-time sound-horizon deformation. The same formalism also identifies the key danger: stochastic perturbations must remain small enough to satisfy observational constraints.

The theory is therefore best understood as an internally coherent phenomenological bridge. It is not yet a completed quantum-gravity theory and does not yet prove that stochastic mass-energy interconversion occurs in nature. Its value lies in showing how a single stochastic stress-energy process could, in principle, connect microscopic randomness, smooth relativistic geometry, effective vacuum curvature, and cosmological phenomenology within one mathematical framework.

Declarations

During the preparation of this work, the author used ChatGPT Pro for structural assistance and equation formatting. All content was reviewed and edited by the author, who takes full responsibility for the manuscript.

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References

1. R. E. Willis, "A Dynamical Origin of Wave-Particle Duality From Stochastic Mass-Energy Interconversion," Applied Physics Research 18(1), 67-75 (2026), doi:10.5539/apr.v18n1p67.

2. Los, E. E., Gerstmayr, E., Arran, C., et al.. (2026). Observation of quantum effects on radiation reaction in strong fields. Nat Commun, 17, 1157. https://doi.org/10.1038/s41467-025-67918-8

3. A. Einstein, "Die Feldgleichungen der Gravitation," *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin* (1915), 844-847.

4. C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation*, W. H. Freeman, San Francisco (1973).

5. S. Weinberg, *Gravitation and Cosmology*, John Wiley & Sons, New York (1972).

6. S. Weinberg, *Cosmology*, Oxford University Press, Oxford (2008).

7. N. G. van Kampen, *Stochastic Processes in Physics and Chemistry*, Elsevier, Amsterdam (1992).

8. C. W. Gardiner, *Handbook of Stochastic Methods*, Springer, Berlin (2004).

9. B. L. Hu and E. Verdaguer, "Stochastic gravity: theory and applications," *Living Reviews in Relativity* 11, 3 (2008), doi:10.12942/lrr-2008-3.

10. E. Calzetta and B. L. Hu, *Nonequilibrium Quantum Field Theory*, Cambridge University Press, Cambridge (2008).

11. V. Mukhanov, *Physical Foundations of Cosmology*, Cambridge University Press, Cambridge (2005).

12. R. Durrer, *The Cosmic Microwave Background*, Cambridge University Press, Cambridge (2008).

13. W. Hu and S. Dodelson, "Cosmic microwave background anisotropies," *Annual Review of Astronomy and Astrophysics* 40, 171-216 (2002), doi:10.1146/annurev.astro.40.060401.093926.

14. Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astronomy & Astrophysics* 641, A6 (2020), doi:10.1051/0004-6361/201833910.

15. A. G. Riess et al., “Large Magellanic Cloud Cepheid standards provide a 1% foundation for the determination of the Hubble constant,” *Astrophysical Journal* 876, 85 (2019), doi:10.3847/1538-4357/ab1422.

16. V. Poulin, T. L. Smith, T. Karwal, and M. Kamionkowski, “Early dark energy can resolve the Hubble tension,” *Physical Review Letters* 122, 221301 (2019), doi:10.1103/PhysRevLett.122.221301.

17. L. Knox and M. Millea, “Hubble constant hunter’s guide,” *Physical Review D* 101, 043533 (2020), doi:10.1103/PhysRevD.101.043533.

18. Fein, Y. Y., Geyer, P., Zwick, P., Kiałka, F., Pedalino, S., Mayor, M., Gerlich, S., & Arndt, M. “Quantum Superposition of Molecules Beyond 25 kDa.” Nature Physics 15, 1242–1245 (2019). doi:10.1038/s41567-019-0663-9.

19. Arndt, M., & Hornberger, K. “Testing the Limits of Quantum Mechanical Superpositions.” Nature Physics 10, 271–277 (2014). doi:10.1038/NPHYS2863.

20. A. G. Riess et al., “A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s−1 Mpc−1 Uncertainty from the Hubble Space Telescope and the SH0ES Team,” Astrophysical Journal Letters 934, L7 (2022), doi:10.3847/2041-8213/ac5c5b.

21. F. J. Qu, K. M. Surrao, B. Bolliet, J. C. Hill, B. D. Sherwin, and H. T. Jense, “New Constraints on Axionlike Early Dark Energy with DESI BAO and ACT DR6 CMB Lensing,” Physical Review D 111, 123507 (2025), doi:10.1103/xhh6-9v62.