Horizons as Temporal Reservoirs: A Unified View of Black Holes, Dark Energy, Dark Matter, and the Quantum Horizon

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Abstract

We propose a unified framework in which black hole evaporation, cosmic acceleration, galactic dark matter, and quantum time dilation all emerge from a single principle: **horizons as temporal reservoirs** that defer energy into the future rather than destroy it. In this view, matter and radiation projected onto horizons remain real but time-shifted, producing gravitational and electromagnetic effects in the present.

- **Black holes:** Hawking radiation is reinterpreted as the gradual release of deferred matter.
- **Cosmic horizon:** Accelerated degrees of freedom naturally yield a dark-energy density of order $\boldsymbol{\rho} \sim \frac{\mathbf{H}^2}{\mathbf{G}}$
- **Galaxies:** Locally sequestered baryonic energy behaves like pressure less dust, reproducing dark-matter–like halos.
- **Quantum horizon:** In the massless limit $m \to 0$ proper time vanishes, and all energy is deferred across past and future sectors. Photons occupy this asymptote: from the external viewpoint, their present-time fields are the projection of an oscillatory **time wave** that links deferred past and future energy. Electromagnetism thus arises as the dynamic counterpart to gravity's static curvature of deferred energy.

This reinterpretation preserves information, reframes gravity and electromagnetism as complementary geometries of temporal delay, and offers observational discriminants: distinct black hole evaporation signatures, evolving dark-energy equations of state, halo profiles that deviate from ΛCDM, and laboratory-scale interference effects linked to the quantum horizon. By treating horizons not as one-way boundaries but as stores of deferred energy, we show that four of modern physics' deepest mysteries may be connected manifestations of the same underlying mechanism.

1. Introduction

Modern physics faces four puzzles that appear disconnected yet share a common feature: horizons.

- **Black holes** are predicted to evaporate through Hawking radiation, raising questions about whether information is destroyed at the horizon or somehow preserved.
- **The accelerating universe** suggests a mysterious dark energy component with density on the order of $\rho \sim \frac{H^2}{G}$ whose physical origin remains obscure.
- **Galactic dynamics** reveal mass discrepancies usually attributed to unseen dark matter, though no new particles have been detected despite decades of searching.
- **At the quantum limit**, relativistic particles reveal a distinct kind of horizon. As mass decreases or momentum increases, proper time slows relative to external observers. In the massless limit, $\tau \to 0$: photons experience no proper time at all. From the external viewpoint, their energy is fully deferred across past and future, with only an oscillatory projection appearing in the present. We call this limiting case the **quantum horizon**, and interpret light as a **time wave** rather than a particle in space.

Each of these mysteries has generated its own vast literature. Black hole thermodynamics has inspired debates on the nature of information and the quantum structure of spacetime. Dark energy has been modeled as a cosmological constant, evolving scalar fields, or modifications of gravity. Dark matter has been pursued in laboratories, astrophysical observations, and high-energy colliders, all without definitive evidence. And the photon has been variously treated as a massless particle, a wave, or a duality that resists unification.

Yet a simple pattern connects them: all four involve horizons and their associated time dilation.

- At a **black hole horizon**, time slows for infalling matter, which appears frozen and only reemerges in the far future.
- At the **cosmological horizon**, time appears to race ahead: redshift and frame separation act like an energy draw, feeding the accelerated expansion we call dark energy.
- At **galactic scales**, gravitational effects attributed to dark matter may arise from baryonic energy that has been temporally sequestered — matter from the past that has not yet remanifested, yet still imprints a gravitational signature today.
- At the **quantum horizon**, massless quanta such as photons defer their entire energy across time, so their electromagnetic fields represent the oscillatory imprint of a time wave in the present.

In this paper, we develop a unifying proposal: **horizons are temporal reservoirs**. Rather than treating the apparent freezing of matter at horizons as a mere coordinate illusion, we take the external description seriously. Energy that seems to vanish is not destroyed, but deferred into the future relative to the observer. This deferral creates a reservoir whose imprint — gravitational for massive deferral, electromagnetic for massless oscillation — remains in the present.

We argue that:

1. **Black hole evaporation** reflects the gradual release of deferred matter, with all four fundamental interactions (gravitational, electromagnetic, weak, strong) emerging as different channels of reservoir release

2. **Dark energy** naturally emerges from accelerated degrees of freedom at the cosmic horizon, giving the observed scale $\rho \sim \frac{H^2}{G}$.
3. **Dark matter** may be the residual effect of locally deferred baryonic energy, behaving dynamically like cold dark matter.
4. **Electromagnetism** arises from the quantum horizon: photons at the massless asymptote are time waves, with fields as the present-time projection of oscillatory deferral.

By reframing horizons as stores of deferred energy, we propose that black hole evaporation, dark energy, dark matter, and light itself are not four independent puzzles but manifestations of a single underlying principle. The sections that follow develop the background (Section 2) and formalize the reservoir concept (Section 3).

This paper is speculative but testable. Our aim is not to replace existing frameworks such as ΛCDM or Hawking thermodynamics, but to motivate an alternative interpretation with distinct observational consequences.

Sections 4–7 present the four case studies: black holes (Section 4), cosmic acceleration (Section 5), dark matter (Section 6), and quantum time waves (Section 7), before turning to Mathematical Framework (Section 8), observational discriminants (Section 9).

2. Background and Motivation

2.1 Black Holes and the Information Puzzle

Since Hawking's discovery that black holes radiate thermally, the fate of information has remained a central paradox. Semiclassical theory predicts evaporation and mass loss, while alternative frameworks — such as the membrane paradigm, fuzzballs, and holographic dualities — argue that the horizon encodes frozen matter or emergent degrees of freedom. From the perspective of an external observer, infalling matter appears to slow down indefinitely, asymptotically freezing at the horizon. The standard interpretation treats this as a coordinate illusion, while in proper time the matter continues inward. The tension between these viewpoints lies at the heart of the information problem.

2.2 Cosmic Acceleration and Dark Energy

Observations of distant supernovae, large-scale structure, and the cosmic microwave background reveal that the universe's expansion is accelerating. The simplest explanation is a cosmological constant, corresponding to a uniform vacuum energy density. Yet the measured scale of dark energy, roughly $\rho\Lambda \sim \frac{\mathrm{H}^2}{\mathrm{G}}$, is many orders of magnitude smaller than naïve quantum field theory predictions. Moreover, hints that the equation of state parameter www may dip below -1 suggest that dark energy could evolve over time. Competing models invoke quintessence, phantom energy, or modified gravity, but no consensus has emerged on the fundamental origin of cosmic acceleration.

2.3 The Dark Matter Problem

Galaxies and clusters rotate and lens as though they contain far more mass than is visible. The prevailing explanation is cold dark matter (CDM), a new species of non-baryonic particle. While CDM is highly successful at reproducing large-scale structure, it faces challenges on smaller scales, including the cusp–core problem, missing satellites, and too-big-to-fail halos. Decades of experimental searches — from underground detectors to the LHC — have not revealed any candidate particle. Alternative approaches, such as MOND or emergent gravity, attempt to modify the laws of dynamics rather than introduce new matter, but none are universally accepted.

2.4 Horizons and the Role of Time

Despite their differences, these three puzzles all involve horizons and time dilation.

- At **black hole horizons**, matter appears frozen in an ever-delayed future.
- At **cosmological horizons**, degrees of freedom appear to race ahead, as if their clocks were accelerated.
- At **galactic scales**, missing mass may point to a hidden temporal dimension of gravity itself.

A fourth case emerges at the **microscopic scale**: as mass decreases and momentum increases, proper time slows. In the limit $m \to 0$, proper time vanishes and photons experience no aging at all. From the external viewpoint, their energy is entirely deferred across past and future, with the electromagnetic field in the present as the projection of an oscillatory **time wave**.

The commonality is that horizons reshape our perception of time, creating apparent deficits or surpluses of energy. Standard accounts treat these distortions as coordinate artifacts or as thermodynamic properties assigned to horizons. In this work, we take a different stance: the external description is ontologically real. Matter, radiation, and fields deferred by horizons remain present — only displaced in time.

This perspective motivates our central proposal: **horizons act as temporal reservoirs**, storing deferred energy whose influence persists in the present. For massive matter, this influence is gravitational; for massless quanta, it is electromagnetic. The sections that follow formalize this idea and explore its implications across four domains: black hole evaporation, cosmic acceleration, galactic dynamics, and the quantum horizon of light and other ultra-relativistic particles.

3. Horizons as Temporal Reservoirs

Horizons are usually described as *perspectival artifacts*. In the standard account, an infalling particle appears frozen at a black hole horizon, but in its own proper time it crosses smoothly. Likewise, photons redshift away at the cosmological horizon, but only from our viewpoint; in their own frame, nothing "disappears." This leads many to treat horizon phenomena as coordinate illusions rather than physical realities.

In this work we take the opposite stance: the external description is **ontologically serious**. From the outside, matter does not cross the horizon but is projected indefinitely forward in time. What disappears from view is not annihilated — it is *deferred*. This leads us to a unifying interpretation: **horizons are temporal reservoirs that store energy in the future relative to the observer.**

3.1 The Reservoir Principle

The key idea is simple:

- **Deferred Energy:** Energy that seems lost at horizons is not destroyed but shifted forward along the temporal axis.
- **Gravitational Imprint:** Although displaced in time, this deferred energy continues to curve spacetime and influence present dynamics.
- **Reservoir Dynamics:** Horizons act as boundaries across which energy bookkeeping is altered — not by annihilation, but by deferral and eventual release.
- This applies not only to massive matter, but also to **radiation**: massless quanta may not freeze into the future, but they defer their oscillatory energy across past and future, leaving only a present-time projection.

3.2 Slogans and Interpretations

We present the following as heuristic slogans to convey the reservoir principle; they are not identities but intuitive mnemonics:

- **Mass = energy deferred.** Matter frozen at a horizon is not gone; it is energy awaiting reappearance at a later time.
- **Gravity = geometry of delay.** Gravitational attraction reflects not only the presence of mass-energy, but the *temporal displacement* between different observers' clocks.
- **Evaporation = reservoir release.** Black hole radiation is not the creation of particles from the vacuum but the gradual repayment of deferred matter into the present.

- **Dark energy = pull of accelerated futures.** The cosmic horizon encodes degrees of freedom that run ahead of us in time, and their acceleration manifests as expansion pressure.
- **Light = oscillation of deferral**. Photons are not particles propagating through space, but time waves oscillating between past and future, with electromagnetic fields as the present projection.

These slogans are not meant to imply that Hawking radiation and cosmic acceleration are identical processes. Rather, they illustrate two complementary channels by which deferred energy can manifest: as thermal radiation from horizon thermodynamics, or as geometric expansion from temporal divergence. The reservoir framework allows both to be understood under a single principle.

Four horizons at a glance.
Black hole: deferred matter (forward in time; $static\ deferral \rightarrow gravity$).
Cosmic horizon: accelerated futures (pull from ahead; expansion pressure).
Galactic horizon: locally deferred baryons (past-deferred mass that still gravitates).
Quantum horizon: massless asymptote (oscillatory deferral; light as a time wave; EM fields are the present projection).

3.3 Universality

This framework applies to both massive and massless particles:

- **Massive particles:** Experience time dilation at horizons, effectively freezing into the future. Horizons create static deferral $\rightarrow gravity$.
- **Massless quanta:** Experience infinite redshift, their frequency deferred rather than their proper time. Horizons create oscillatory deferral $\rightarrow electromagnetism$.
- Both emerge from the same bookkeeping, just with different time signatures (curvature vs. oscillation).

Both phenomena can be understood as manifestations of the same principle: all energy, whether rest mass or radiation, is deferred into the future by horizons. Horizons are therefore universal temporal reservoirs. In particular, the **massless limit ($\boldsymbol{m = 0}$) defines a quantum horizon**, where proper time vanishes and all energy is deferred, with photons providing the canonical example.

3.4 Implications

If this interpretation is correct, several deep puzzles are reframed:

- The **black hole information paradox** becomes a question of when and how deferred matter reemerges, not whether it is destroyed.
- The **cosmological constant problem** becomes a reflection of energy stored at the cosmic horizon, scaling naturally as $\rho \sim \frac{H^2}{G}$.
- The **dark matter problem** may signal locally sequestered energy whose gravitational influence persists despite not being contemporaneously visible.
- Wave–particle duality becomes a natural consequence: photons are time waves, whose interference patterns arise from overlapping past- and future-deferred components, projected into the present.

This conceptual foundation sets the stage for the next sections, where we examine black holes (Section 4), cosmic acceleration (Section 5), galactic halos (Section 6), and the quantum horizon (Section 7) as four realizations of the reservoir principle. Together, these cases highlight a deeper symmetry: massive deferral manifests as the static curvature we call gravity, while massless deferral manifests as the oscillatory time waves we call electromagnetism.

4. Case I: Black Hole Horizons

4.1 Standard Thermodynamic Picture

Semiclassical quantum field theory predicts that black holes radiate thermally with temperature

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}$$

leading to a gradual evaporation with mass-loss rate

$$\dot{M} \propto -\frac{1}{M^2}$$

In this view, evaporation is driven by particle creation near the horizon, where vacuum fluctuations become real pairs, one escaping as radiation and the other falling inward. This picture has been influential, but it raises persistent puzzles: where is the information stored, and how is it released?

4.2 Reservoir Interpretation: Frozen Matter and Deferred Release

From the perspective of an external observer, infalling matter never truly crosses the horizon. Instead, it appears frozen in time, projected asymptotically into the future. If this external description is taken seriously, then the black hole horizon functions as a **temporal reservoir**: it does not annihilate information, but defers it.

Evaporation, then, is not the production of new quanta from empty space but the **release of deferred matter** back into the present. What was frozen into the horizon reservoir gradually reemerges as radiation. The endpoint of evaporation corresponds to the reservoir running dry.

All fundamental interactions are represented in evaporation.
In this framework, evaporation is not restricted to photons or leptons, but constitutes the deferred re-emergence of every interaction channel. The **strong interaction** shapes the hadronic component of the outflow, since most of the universe's mass is QCD binding energy. The **weak interaction** governs neutrino channels, which lie near the quantum-horizon limit and may dominate late-stage release. **Electromagnetism** appears in its canonical role as oscillatory time-wave deferral, with photons embodying the projection of deferred energy into the present. Finally, **gravity** itself is implicated: when the reservoir can no longer sustain the Schwarzschild boundary, the horizon collapses, releasing the remaining deferred mass in a purely gravitational burst. In this sense, black hole evaporation is a universal laboratory in which all four fundamental forces appear as different expressions of a single principle — energy deferred across time and then returned.

4.3 Duality with Dark Energy

This interpretation has a natural symmetry with cosmic acceleration.

- **Black holes:** time dilation slows infalling matter, sequestering it in the future. Evaporation is the *outflow* of this deferred energy back into our present.
- **Cosmic horizon:** time dilation accelerates external degrees of freedom, pulling our present toward their faster clocks. Dark energy is the *inflow* of deferred energy from accelerated futures.

Both processes are complementary expressions of the same principle: **horizons mediate exchanges with temporal reservoirs.**

4.4 Observational Discriminants

The reservoir view of black hole evaporation suggests two distinct possibilities:

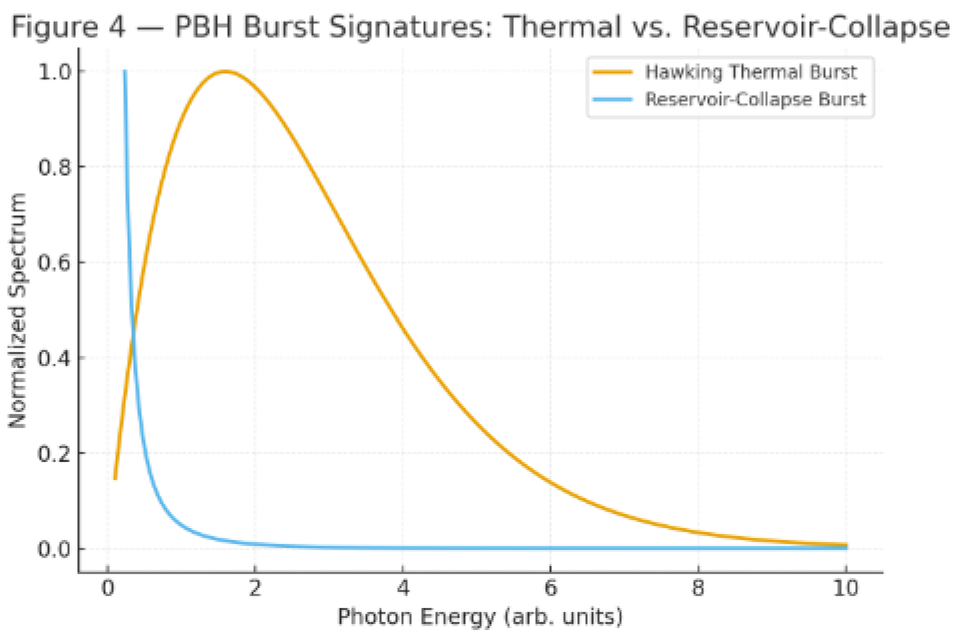
1. **Thermodynamic (Hawking) channel.** Primordial black holes end with thermal bursts of high-energy radiation, with a quasi-blackbody spectrum hardening as the mass decreases $T_H \propto M^{-1}$
2. **Reservoir (collapse) channel.** Evaporation proceeds silently until the deferred density at the horizon can no longer sustain a Schwarzschild boundary. At this critical threshold, the horizon fails and the remaining deferred matter is abruptly released — a process analogous to stellar core collapse in a supernova. The resulting burst is non-thermal, sudden, and set by a density criterion rather than by $T_H \to \infty$.

Spectral discriminant. The Hawking channel produces a thermal spectrum with a νF_ν peak that hardens over time. In contrast, the reservoir-collapse channel can be modeled as a finite-time release of the deferred energy E_{res} with a spectrum

$$\frac{dN}{dE} \propto E^{-\gamma}\, exp\left[-\left(\frac{E}{E_c}\right)^{\eta}\right], \qquad \gamma \in (1.5, 2.5), \eta \neq 1$$

where E_c is set by the collapse timescale τ_{col}.

Prediction: a non-thermal burst lacking late-time hardening, with a sharp onset $(\sim \tau_{col})$ and sub-thermal high-energy cutoff.



Timing discriminant. Hawking explosions occur predictably as M(t) evolves with

$$\dot{M} \propto -\frac{1}{M^2}$$

Reservoir collapse, however, is triggered when the deferred-to-visible mass ratio reaches a sustainment threshold $\left(\frac{M_{def}}{M_{vis}} \rightarrow f^*\right)$. Thus, burst times need not coincide with Hawking's diverging temperature.

Observations of the gamma-ray background and targeted PBH searches can therefore distinguish between thermal Hawking explosions and supernova-like reservoir collapses.

4.5 Implications for the Information Paradox

If evaporation is the release of deferred matter, then information is never lost. Instead of being destroyed at the horizon, it is projected into the future and gradually reconciled with the present as the reservoir empties. This reframing dissolves the paradox: the apparent loss of information is a delay, not a destruction.

This black hole case provides the first demonstration of the reservoir framework. In the next section, we extend the principle to the cosmological horizon, where accelerated futures at the edge of the universe manifest as the observed phenomenon of dark energy.

5. Case II: Cosmological Horizon and Dark Energy

5.1 Standard Thermodynamic Picture

In de Sitter space, the cosmological horizon is associated with a temperature

$$T_{dS} = \frac{\hbar H}{2\pi k_B},$$

and an entropy proportional to horizon area,

$$S = \frac{A}{4G\hbar}, A = 4\pi H^{-2}.$$

Combining these gives an effective energy density of order

$$\rho \sim \frac{H^2}{G}.$$

which coincides with the observed scale of dark energy today. This result, known since Gibbons and Hawking (1977), suggests that horizon thermodynamics can account for cosmic acceleration. Yet it leaves unanswered the deeper question: is this radiation-like, or does it reflect a more geometric effect?

5.2 Reservoir Interpretation: Accelerated Futures

In the reservoir framework, the cosmological horizon encodes **degrees of freedom that run ahead of us in time**. To us, signals beyond the horizon are forever out of reach, but from the external perspective, their clocks are racing into accelerated futures. This temporal divergence translates into an effective energy draw on our region, perceived as dark energy.

Put simply:

- **Black holes:** horizons defer matter into the future, releasing it later as evaporation.
- **Cosmic horizon:** horizons expose us to faster futures, pulling energy into the present as accelerated expansion.

In both cases, the mechanism is the same — horizons are temporal reservoirs — but the direction of the exchange differs: **black holes are outflows of deferred energy, while dark energy is inflow from accelerated futures.**

In this sense, cosmic acceleration may be viewed as the large-scale counterpart of the quantum horizon: while photons embody oscillatory deferral locally, the entire cosmic horizon embodies accelerated deferral globally. Both reflect the same principle — energy shifted forward in time, gravitationally or electromagnetically projected back into the present.

5.3 Energy Budget and Universality

A common objection is that the energy lost by redshifted photons is far too small to account for the dark energy density. Indeed, the present photon energy density is

$$\rho_\gamma \sim 10^{-14}\, J/m^3,$$

while dark energy is four orders of magnitude larger.

In the reservoir picture, photons are only illustrative. The dominant contribution comes from all field degrees of freedom, whose clocks run faster at the cosmic edge. Their collective deferral creates the correct energy density scale, matching

$$\rho \sim \frac{H^2}{G}$$

when evaluated with today's Hubble parameter.

5.4 Observational Discriminants

The reservoir view suggests that dark energy may evolve if the horizon's reservoir accelerates:

• **Thermodynamic (Hawking-like) channel:** A strict relation between $H(z)$ and the equation of state parameter $w(z)$, with $w \approx -1$.

• **Geometric (reservoir) channel:** Greater freedom, allowing $w < -1$ in a "phantom" regime as accelerated futures exert stronger pull.

Future observations of cosmic expansion history, especially precision measurements of $w(z)$, can distinguish between these channels.

In the reservoir channel, the effective equation of state can be parameterized as

$$w(z) = -1 - \alpha \left(\frac{H}{H_0}\right)^{\beta},$$

where α and β encode the strength of accelerated futures. A simple choice $\alpha \sim 0.05, \beta \sim 1$ yields

$$w \approx -1.05$$

today, consistent with mild phantom-like behavior hinted at in DESI and Planck analyses. Such a parameterization allows direct confrontation of the reservoir framework with observational data.

Parameterized reservoir equation of state.
We write

$$w(z) = -1 - \alpha \left(\frac{H(z)}{H^0}\right)^{\beta},$$

with $\alpha > 0$ capturing the strength of accelerated futures and β their scaling.

Forecastable ranges: $\alpha \sim 0.02 - 0.10, \beta \sim 0.5 - 1.5$ give

$w_0 \in [-1.02, -1.10]$.

Observable pulls.
(i) $\boldsymbol{BAO/SNe\, H(z), D_A(z)}$**:** mild preference for lower $H(z)\ at$ $0.5 \lesssim z \lesssim 1$ relative to ΛCDM with the same Ω_m.

(ii) **Growth index** $\boldsymbol{\gamma}$**:** effective $\gamma \approx 0.55 + 0.05\,\alpha$ (slightly slower growth).

(iii) **ISW effect:** enhanced late-time ISW cross-correlation by $O(5\%)$ for $\alpha \sim 0.05$.

Prediction: a consistent, joint fit prefers $\alpha > 0$ if data find $w < -1$ with suppressed growth ($\sigma_8 - S_8$ tension relief) without invoking modified gravity.

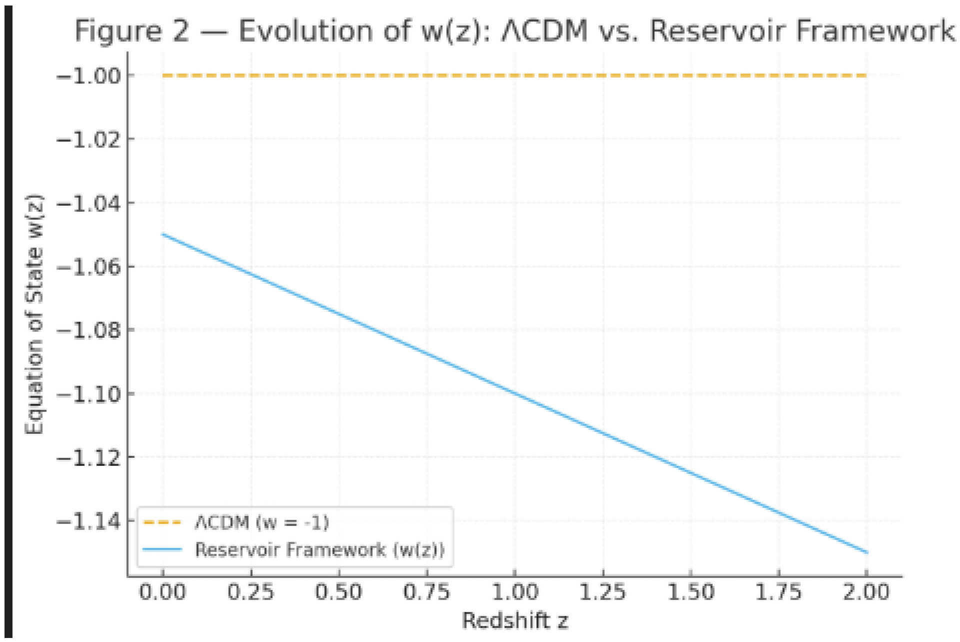


Figure 2: This parameterization allows direct confrontation of the reservoir framework with observational data, and situates dark energy as the large-scale analogue of the quantum horizon's deferred time waves.

5.5 Implications

If dark energy is the manifestation of accelerated futures at the cosmological horizon, then its presence is not a cosmological constant in the traditional sense but a dynamical effect of temporal reservoirs. This resolves two puzzles simultaneously:

- Why the energy density takes the scale $\rho \sim \frac{H^2}{G}$.
- Why w may evolve, hinting at the changing influence of accelerated futures.

This interpretation also places dark energy within the same family as electromagnetism and gravity. Gravity arises from static deferral of massive energy; light arises from oscillatory deferral of massless energy; and cosmic acceleration reflects the cumulative deferral of degrees of freedom at the universe's horizon. The cosmic case thus links macroscopic acceleration to the same bookkeeping principle that governs both photons and black holes.

The cosmic horizon case shows the complement to black holes: instead of deferred matter gradually reentering the present, the pull of accelerated futures shapes the expansion of spacetime itself. In the next section, we turn to galactic scales, where missing mass may be explained as locally deferred energy that continues to gravitate today — a natural analogue of dark matter.

6. Case III: Galactic Horizons and Dark Matter

6.1 The Missing Mass Problem

Galaxies and clusters rotate and lens light as though they contain far more mass than is visible in stars and gas. The standard explanation invokes **cold dark matter (CDM)**: a new, non-baryonic particle species. CDM has been successful in reproducing large-scale structure, but its predictions at galactic scales face persistent tensions, including cuspy halo profiles, missing satellite galaxies, and the too-big-to-fail problem.

6.2 Reservoir Interpretation: Deferred Baryons

In the reservoir framework, dark matter need not be a new particle. Instead, a portion of baryonic mass-energy may remain **temporally deferred** at galactic horizons — stored in the past relative to us, not yet remanifested in the present, but still exerting gravitational influence.

This interpretation mirrors the other cases:

- **Black holes:** matter deferred forward in time, released slowly as evaporation.
- **Cosmic horizon:** external degrees deferred into accelerated futures, pulling on our present as dark energy.
- **Galactic scales:** baryons deferred into the past light cone, still gravitating as if present — creating the effect we call dark matter.

6.3 Effective Stress–Energy Component

Formally, this can be described by adding a "deferred" stress–energy tensor $T^{\mu\nu}_{def}$ to Einstein's equations:

$$G_{\mu\nu} = 8\pi G \left(T^{\mu\nu}_{vis} + T^{\mu\nu}_{def} \right).$$

For homogeneous cosmology, the deferred density redshifts like matter:

$$\bar{\rho}_{def} \propto a^{-3}, w_{def} \approx 0,$$

behaving effectively as pressure less dust, just as required of dark matter.

6.4 Halo Profiles

On galactic scales, the deferred component may be distributed as an exponential halo around visible baryons:

$$\rho_{def}(r) \approx \frac{\varepsilon M}{4\pi\lambda^3} \cdot e^{-\frac{r}{\lambda}},$$

where M is baryonic mass, λ a characteristic scale, and ε an efficiency factor.

This profile naturally produces:
• Flat rotation curves at large radii.
• Cored halos instead of cuspy Navarro–Frenk–White (NFW) profiles.

Such features could alleviate small-scale ΛCDM problems while remaining consistent with gravitational lensing.

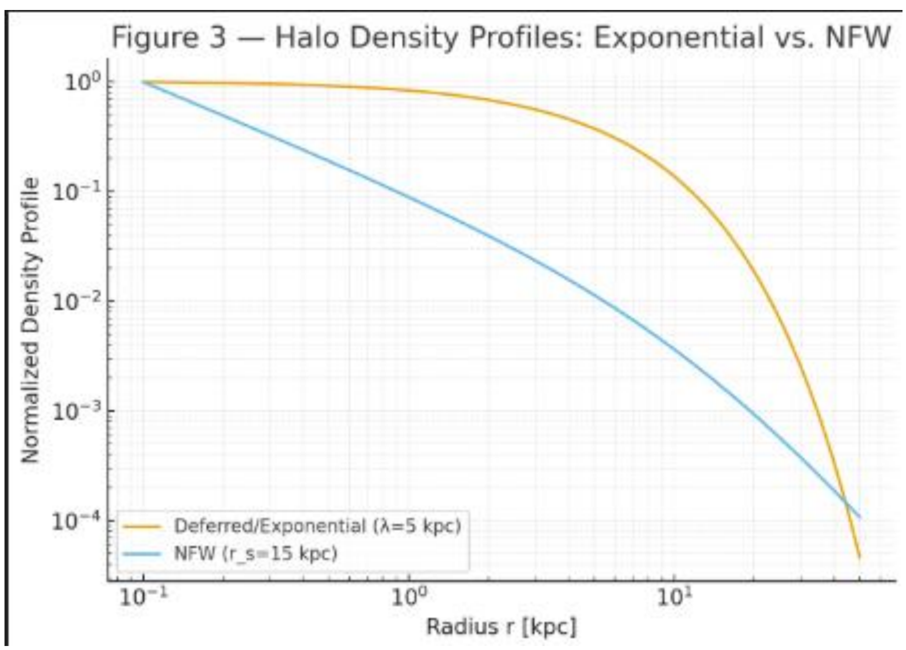


Figure 3. Comparison of halo density profiles: the deferred-energy exponential form (green) versus the standard Navarro–Frenk–White cusp (red). The deferred profile yields cored centers, consistent with dwarf and LSB galaxy data.

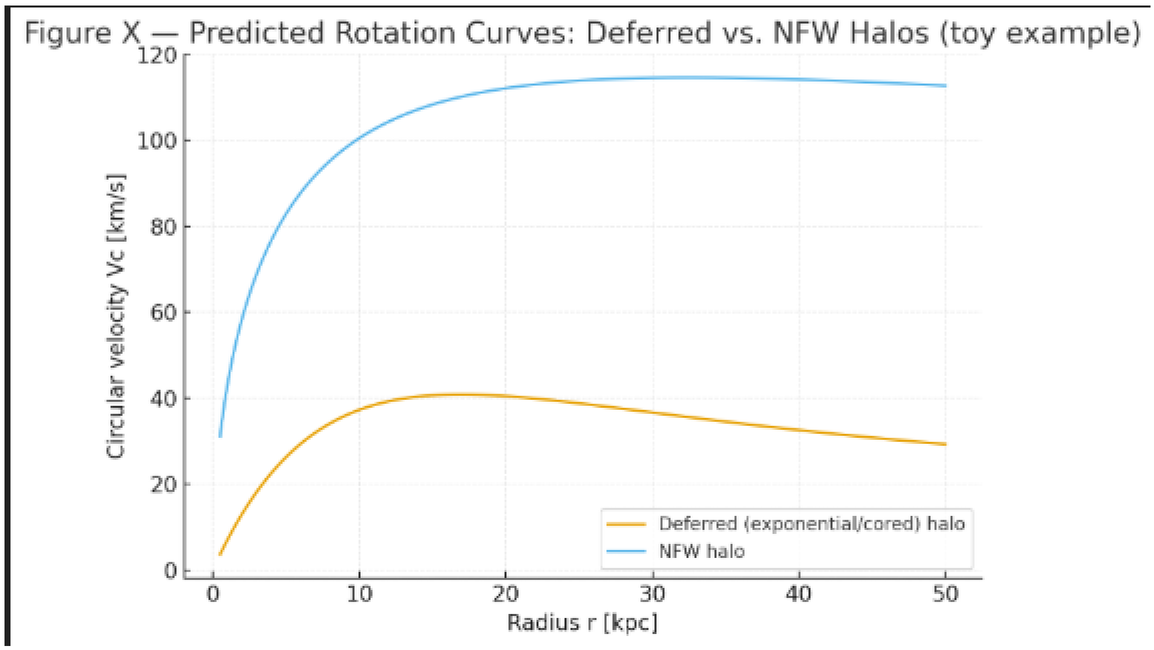


Figure X. Predicted rotation curves for a Milky Way–like galaxy. The deferred halo (blue) produces flat outer rotation speeds consistent with observations, while the NFW profile (red) predicts an inner cusp and steeper transition.

6.5 Observational Discriminants

The reservoir interpretation makes testable predictions distinct from CDM:

- **Halo structure:** Deferred halos predict exponential or cored profiles, contrasting with the NFW cusps of standard CDM.
- **Lensing signatures:** The distribution of deferred mass would imprint specific lensing patterns around galaxies and clusters.
- **Small-scale challenges:** Problems such as the cusp–core discrepancy, missing satellites, and too-big-to-fail may be naturally mitigated.

Three concrete tests can be derived from these principles:

(1) Inner-slope test (kinematics):
Fit dwarfs/LSBs with

$$\rho_{def}(r) = \frac{\varepsilon M}{4\pi\lambda^3} \cdot e^{-\frac{r}{\lambda}},$$

$$V^2(r) = \frac{G\, M_{def}(< r)}{r},$$

and report the inferred (ε, λ).
Prediction: $\frac{d(\ln \rho)}{d(\ln r)} \rightarrow 0$ as $r \rightarrow 0$ (cored), unlike NFW's slope of -1.

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(2) Weak-lensing tangential shear:
The projected surface density $\Sigma_{def}(R)$ for the exponential halo gives $\Delta\Sigma(R)$ that flattens inside $R \sim \lambda$.
Prediction: stacked galaxy–galaxy lensing shows a shallower inner slope than NFW for hosts with small λ.

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(3) Baryon–halo coupling:
Because $M_{def} \propto \varepsilon M$, the Tully–Fisher zero-point shifts with ε.
Prediction: tighter V_{flat}–baryonic mass relation when including M_{def} than with baryons alone.

6.6 Implications

If dark matter is temporally deferred baryonic energy, then all three puzzles — black hole evaporation, dark energy, and dark matter — are not independent mysteries but expressions of a single principle. Horizons act as **temporal stores**:

- Releasing deferred energy (evaporation),
- Pulling energy from accelerated futures (dark energy), and
- Retaining past energy that continues to gravitate (dark matter)

A natural concern is that interpreting dark matter as deferred baryons conflicts with cosmological constraints on the baryon fraction from big bang nucleosynthesis (BBN) and the CMB acoustic peaks. However, in our framework the deferred component does not behave as additional baryonic gas at early times — it does not participate in photon–baryon acoustic oscillations or alter primordial abundances. Instead, it redshifts as dust but remains gravitationally sequestered until later epochs. Thus the effective baryon density relevant for BBN and CMB remains within observational bounds, while the deferred sector mimics cold dark matter dynamically at late times.

In this way, the galactic case bridges naturally into the quantum domain. Black holes defer energy forward in time, photons defer it into oscillatory time waves, and galaxies sit in between: mass from the past remains deferred yet still exerts gravitational pull today. Galactic horizons thus provide the mesoscopic link between macroscopic deferral (black holes, cosmology) and microscopic deferral (photons, neutrinos).

With the galactic case complete, the reservoir framework now spans three macroscopic regimes: black holes, cosmic acceleration, and galactic halos. To this we now add a fourth, microscopic realization — the quantum horizon of light and ultra-relativistic particles. In the following sections, we formalize this picture mathematically (Section 7), outline observational discriminants across all scales (Section 8), and discuss how this unifying perspective compares to existing approaches.

7. Case IV: Quantum Horizon and Microscopic Deferral

7.1 Conceptual Framework

The three horizons we have examined—black hole, cosmological, and galactic—operate on macroscopic scales. Yet relativity suggests that even microscopic particles encounter an effective horizon when their proper time diverges from the external universe. We call this the **quantum horizon.**

In special relativity, the relation between coordinate time and proper time is:

$$\gamma = \frac{E}{mc^2}. \qquad d\tau = \frac{dt}{\gamma},$$

As rest mass decreases or momentum grows, γ increases and the particle's proper clock slows relative to external observers. In the massless limit, $\tau \to 0$: photons experience no proper time. Thus, small or ultra relativistic particles inhabit frames where the rest of the universe appears to age more quickly.

From the external perspective, this slowing means that part of the particle's energy is effectively deferred into the future. We can capture this with a deferral fraction:

$$f_{def}(p, m) \equiv 1 - \frac{1}{\gamma} = 1 - \frac{mc^2}{E}.$$

• For low-momentum, massive particles ($\gamma \approx 1$), $f_{def} \approx 0$: nearly all energy is visible in our frame.
• For highly relativistic or light particles ($\gamma \gg 1$), $f_{def} \to 1$: most of the energy is deferred.
• For photons ($m = 0$), $f_{def} = 1$: all their energy lies across the quantum horizon. In this limit, light ceases to behave as a particle propagating through space and instead manifests as a time wave — an oscillation between past and future deferrals, with electromagnetic fields as its present-time projection.

The contribution to the deferred stress–energy tensor can then be expressed schematically as:

$$T_{def}^{\mu\nu} \sim \Sigma_i f_{def}(p_i, m_i) \cdot T_i^{\mu\nu},$$

where the sum runs over particle species and momentum modes.

This fraction therefore not only governs gravitational deferral for massive bodies, but also encodes the oscillatory deferral that manifests electromagnetically for massless quanta.

The quantum horizon therefore mirrors the logic of the macroscopic horizons:

- Black holes: matter slows at the horizon, freezing into the future.
- Cosmological horizon: external degrees of freedom accelerate into futures ahead of us.
- Galactic halos: baryons deferred locally gravitate like dark matter.
- Quantum horizon: microscopic particles slow relative to the universe, deferring part of their energy forward in time. Unlike causal horizons, the quantum horizon is a temporal limit defined by vanishing proper time ($m = 0$), with photons as the canonical example.

By extending the reservoir framework to the smallest scales, we close the loop: horizons are not confined to astrophysical boundaries but emerge wherever time dilation produces a mismatch between visible and deferred energy. **For massive matter, this mismatch produces static curvature, the geometry we call gravity. For massless quanta, it produces oscillatory deferral, the time waves we call light, with electromagnetic fields as their present projection.** The quantum horizon therefore provides a natural bridge between quantum dynamics—where energy generates time evolution—and relativity—where clock rates diverge across frames. This connection hints at a path toward reconciling quantum mechanics with gravitation through the common language of temporal deferral.

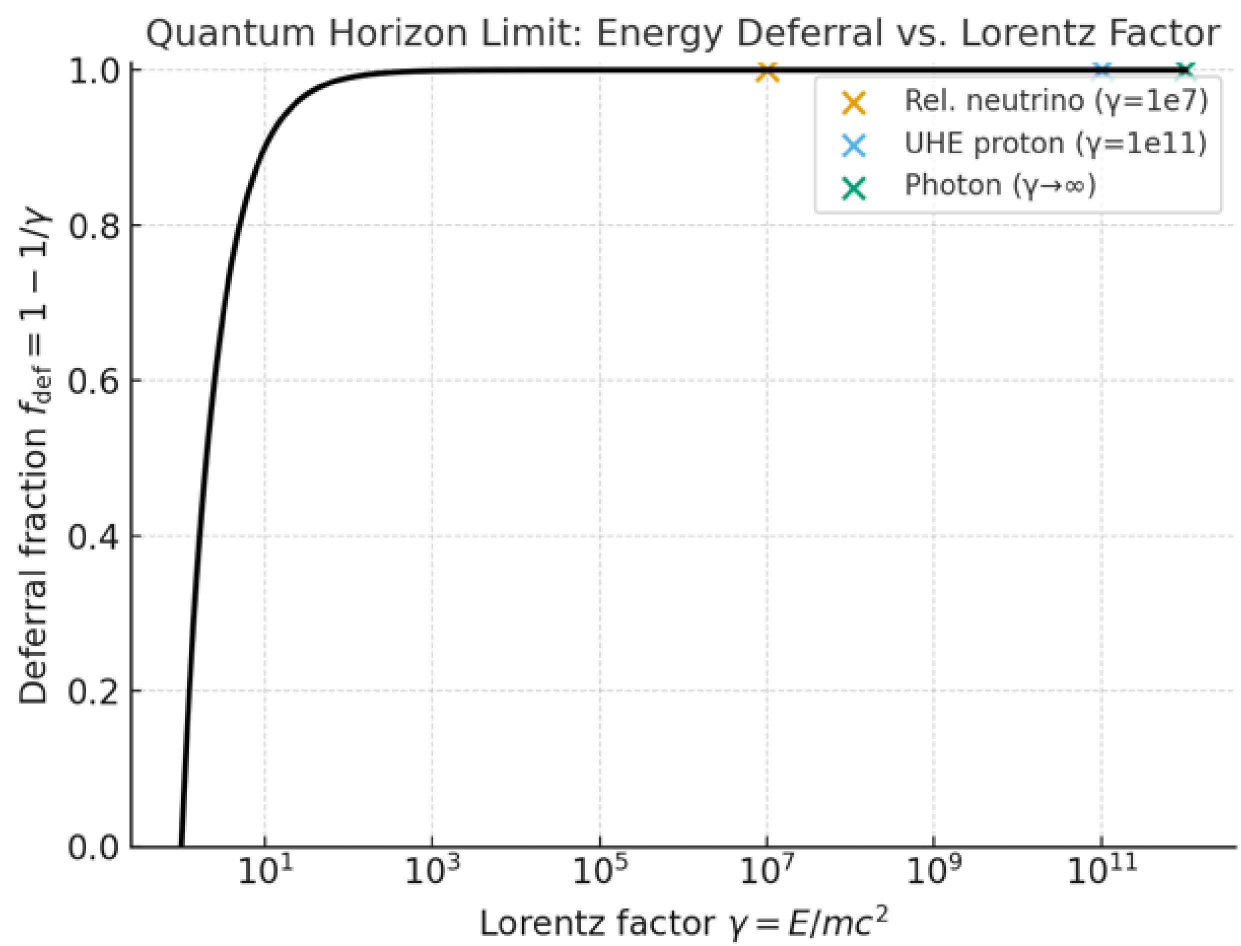

Figure Y. The deferral fraction

$$f_{def} = 1 - \frac{1}{\gamma}$$

as a function of Lorentz factor $\gamma = \frac{E}{mc^2}$. As particles become ultra-relativistic, $f_{def} \rightarrow 1$, indicating that nearly all of their energy is deferred across the quantum horizon.

Example points: a relativistic neutrino ($\gamma \sim 10^7$), an ultra–high-energy cosmic ray proton ($\gamma \sim 10^{11}$), and the photon limit ($\gamma \rightarrow \infty$).

7.2 Quantum Horizon Limit and Examples

The deferral fraction introduced earlier

$$f_{def}(p, m) \equiv 1 - \left(\frac{mc^2}{E}\right),$$

provides a continuous bridge from massive to massless particles. This expression makes explicit how the quantum horizon arises as a limit condition: as $m \to 0$, $f_{def} \to 1$, meaning all of the particle's energy is deferred across the horizon of vanishing proper time.

Worked Example: Relativistic Neutrinos

Consider a neutrino of rest mass $m \sim 1\ eV/c^2$ and energy $E \sim 10\ MeV$, typical of a supernova neutrino burst.

Its Lorentz factor is

$$\gamma = \frac{E}{mc^2} \sim 10^7,$$

giving

$$f_{def} = 1 - \frac{1}{\gamma} \approx 1 - 10^{-7} \approx 0.9999999.$$

Thus, nearly the entire energy of such a neutrino lies across the quantum horizon. From the external viewpoint, its proper time has slowed so dramatically that its dynamics are dominated by deferred energy.

Worked Example: Ultra–High-Energy Cosmic Rays

For a proton with $m \approx 938\ MeV/c^2$ and observed energy $E \sim 10^{20}\ eV$, the Lorentz factor is

$\gamma \sim 10^{11}$.

The corresponding deferral fraction is

$$f_{def} \approx 1 - 10^{-11},$$

indicating that essentially all of its energy is sequestered into deferred time. Cosmic rays therefore probe the same limit regime as photons: their energy resides almost entirely across the quantum horizon.

Quantum Horizon as a Limiting Condition

This motivates treating the $m \to 0$ case not as a trivial boundary but as a genuine horizon condition:

• **Black holes:** Horizons freeze infalling matter into the future.
• **Cosmic horizon:** External degrees of freedom accelerate into futures ahead of us.
• **Galactic halos:** Baryons are deferred locally into the past light cone.
• **Quantum horizon:** As $m \to 0$, proper time vanishes and all energy is maximally deferred forward in time.

In this sense, the quantum horizon is the microscopic analogue of macroscopic horizons, defined not by spatial boundaries but by the collapse of proper time.

Laboratory Implications

The deferral fraction provides a calculable parameter for experiments. For instance, in interferometry a relativistic particle beam acquires an additional phase proportional to f_{def}, suggesting measurable momentum-dependent phase drifts. In this way, the same formalism that explains black hole evaporation, cosmic acceleration, and dark matter halos also predicts quantum-horizon effects accessible to laboratory tests.

7.3 Double-Slit as Deferred-Sector Interference

The quantum horizon interpretation of photons as time waves offers a natural explanation of the classic double-slit experiment. In standard quantum mechanics, interference is described by a wavefunction that traverses both slits, while detection events appear as localized “particle clicks.” In the reservoir framework, this duality arises from the structure of temporal deferral.

A photon at the quantum horizon defers all of its energy across past and future. What we call an electromagnetic field in the present is the **projection** of this oscillatory deferral. When a beam of photons encounters two slits, the deferred sectors from each path overlap before projection. The present-time projection therefore records not two independent contributions but a single oscillatory interference pattern:

$$\boldsymbol{I(x) = |A_1(x) + A_2(x)|^2 = I_1(x) + I_2(x) + 2\sqrt{I_1 I_2}\ \cos[\Delta\phi(x)].}$$

Here, $A_{1,2}(x)$ represent the deferred amplitudes from each slit, and $\Delta\phi(x)$ is the phase difference accumulated during deferral. Interference arises not from a photon “going through both slits” but from past- and future-deferred components recombining in the present.

This interpretation also clarifies the role of which-path information. A detector placed at one slit projects the photon’s time wave prematurely, collapsing one deferred component into the present and eliminating the overlap needed for interference. Conversely, in delayed-choice or quantum eraser experiments, erasing or re-aligning the path information restores overlap in the deferred sector, and fringes reappear.

Thus, the reservoir view preserves all observed features of the double-slit experiment while providing a new physical ontology: interference patterns emerge from the recombination of deferred temporal components, and detection events correspond to the present-time slice of an underlying time wave.

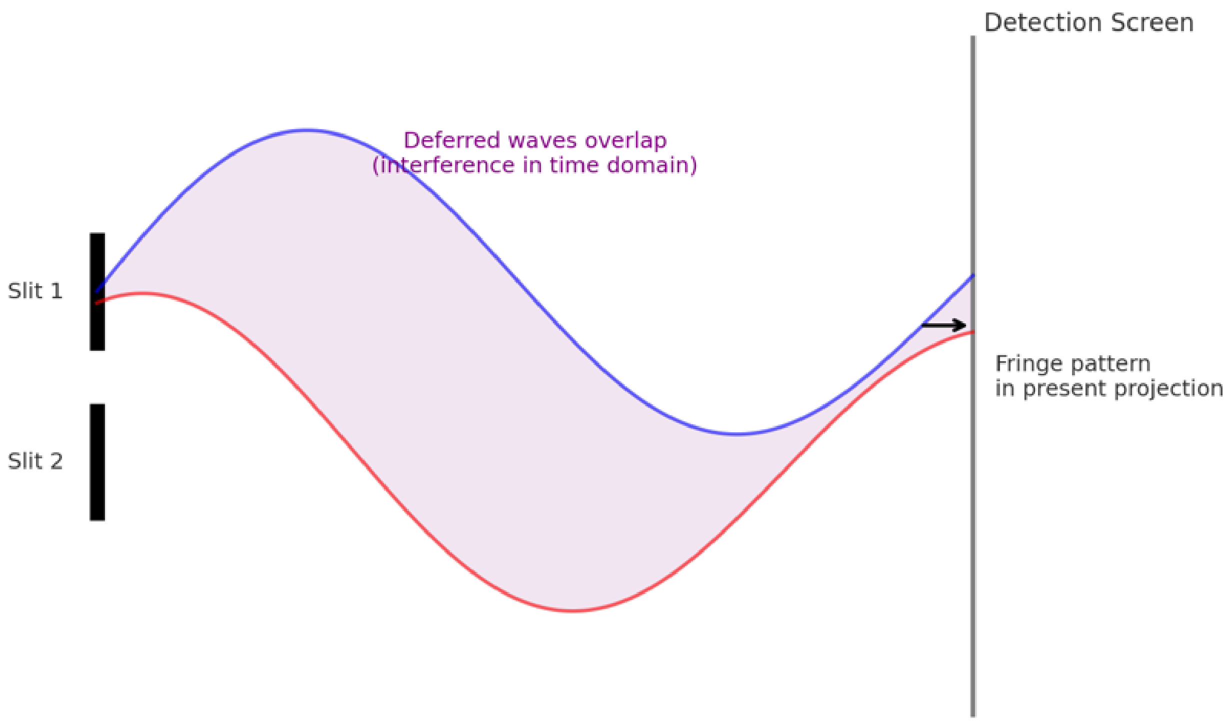

Figure Z. Schematic of the double-slit experiment in the reservoir framework. Photons at the quantum horizon exist as time waves, with their energy oscillating across past and future deferrals. At the slits, deferred components spread and overlap, producing interference in the deferred sector (purple). The detection screen records only the present-time projection of this overlap, yielding the observed fringe pattern. Which-path measurements eliminate one deferred component, destroying the overlap and the interference fringes.

8. Mathematical Framework

The reservoir interpretation can be formalized by introducing a **deferred stress–energy component** alongside visible matter.

8.1 Modified Einstein Equations

To formalize the reservoir interpretation, we introduce a deferral tensor $D^{\mu\nu}$ that encodes energy temporarily sequestered from the present and returned on finite relaxation times. At macroscopic scales this tensor projects into Einstein's equations as an effective source, representing the contribution of deferred energy alongside visible matter.

We define the deferred stress–energy component as

$$T^{\mu\nu}_{def} = \left(\frac{1}{M_D^2}\right) D^{\mu\nu} \ ,$$

where M_D is a phenomenological mass scale that fixes dimensional consistency. The generalized Einstein equations then take the form

$$G_{\mu\nu} = 8\pi G \left(T^{\mu\nu}_{vis} + \left(\frac{1}{M_D^2}\right) D^{\mu\nu} \right),$$

with the total energy–momentum remaining covariantly conserved:

$$\nabla_\mu \left(T^{\mu\nu}_{vis} + \left(\frac{1}{M_D^2}\right) D^{\mu\nu} \right) = 0 \, .$$

This modification can also be obtained from an effective action:

$$S = \int d^4x \sqrt{-g} \left[\left(\frac{1}{16\pi G}\right) R + L_{vis} + \left(\frac{1}{M_D^2}\right) u_\mu u_\nu D^{\mu\nu} \right],$$

where u^μ is the four-velocity of the observer frame. Variation with respect to the metric yields the generalized Einstein equations above, while variation with respect to matter fields produces exchange currents that redistribute energy between visible and deferred sectors.

Cosmological Check

In a spatially flat FRW universe where visible matter has density $\rho_{vis} \propto a^{-3}$, the continuity equation becomes

$$\dot{\rho}_{tot} + 3H(\rho_{tot} + p_{tot}) = 0,$$

with

$$\rho_{tot} = \rho_{vis} + \rho_{def},$$

and

$$\rho_{def} = \left(\frac{1}{M_D^2}\right) u_\mu u_\nu D^{\mu\nu} .$$

Because the deferred component redshifts as a^{-3}, it behaves like pressure less dust and ensures total energy conservation. In this sense, energy is not created or destroyed but redistributed between present-time projection (ρ_{vis}) and deferred modes (ρ_{def}).

Massive vs. Massless Limits

- In the massive limit, deferred contributions appear geometrically as curvature corrections, corresponding to gravitational effects of stored energy.
- In the massless limit, the same deferral tensor supports oscillatory modes, with electromagnetic fields emerging as present-time projections of deferred oscillations.

Thus the formalism naturally accommodates both gravitational curvature (massive deferral) and electromagnetic oscillation (massless deferral) within a single covariant framework.

8.2 Deferred Density from Past Sources

The deferred energy density may be written as the scalar projection

$$\rho_{def}(t,x) = \left(\frac{1}{M_D^2}\right) u_\mu u_\nu D^{\mu\nu}(t,x) ,$$

where $D^{\mu\nu}$ represents the deferral tensor introduced above. At the phenomenological level this projection can be modeled as a causal memory of past visible density:

$$\rho_{def}(t,x) = \int_{t_1}^{t} dt' \int d^3x' K(t,t';\, x,x') \rho_{vis}(t',x') ,$$

where K is a retarded kernel that specifies how past stress–energy is sequestered and re-projected.

8.3 Horizon-Aware Kernel

A physically motivated kernel can take the form:

$$K(t,t';\, r) = \varepsilon\, H(t')\; exp\left[-\frac{\chi(t) - \chi(t')}{\chi_H}\right] \left(\frac{exp\left(-\frac{r}{\lambda}\right)}{4\pi\lambda^3}\right)\; \Theta(t - t'),$$

where:
• $H(t)$ is the Hubble rate,
• χ is comoving distance,
• $\chi_H \sim H^{-1}$ is a horizon scale,
• λ is a localization length $(kpc - Mpc)$,
• ε is an efficiency factor,
• Θ enforces causality.

This form ensures that deferral is causal, horizon-limited, and spatially localized.

8.4 Cosmological Behavior

For a homogeneous background, the deferred component follows directly from the scalar projection $\rho_{def} = \left(\frac{1}{M_D^2}\right) u_\mu u_\nu D^{\mu\nu}$. This projection redshifts as

$$\bar{\rho}_{def} a \propto a^{-3}. \quad w_{def} \approx 0,$$

Thus, the deferred fluid behaves effectively like cold dark matter at large scales. In this sense, the deferral tensor provides a covariant underpinning for a component that mimics CDM without requiring new particle species.

8.5 Perturbations and Clustering

Linear perturbations in the deferred component follow from the causal structure of $D^{\mu\nu}$ and can be written as

$$\delta_{def}(k,a) = \int_{a_i}^{a} d(\ln a')\, M(k;\, a, a')\, \delta\_vis(k,a')\,,$$

where M is the transfer kernel implied by K. This formulation shows how deferred modes inherit memory of visible perturbations through the operator structure of $D^{\mu\nu}$.

Under suitable choices of λ and ε, the deferred component clusters with the same effective growth rate as CDM. Specifically, if λ is larger than the baryonic Jeans scale but smaller than the

Hubble radius, the transfer kernel suppresses oscillatory baryonic features and produces a smooth matter power spectrum consistent with observed large-scale structure.

Thus, the reservoir component remains indistinguishable from CDM at cosmological scales, while differing at galactic scales where localization becomes significant.

8.6 Galactic Halo Profile

On galactic scales, a localized kernel realization of $D^{\mu\nu}$ yields a quasi-static halo profile:

$$\rho_{def}(r) \approx \frac{\varepsilon M}{4\pi\lambda^3} e^{-\frac{r}{\lambda}},$$

with enclosed deferred mass

$$M_{def}(< r) = \varepsilon M \left[1 - e^{-\frac{r}{\lambda}}\left(1 + \frac{r}{\lambda} + \frac{r^2}{2\lambda^2}\right)\right].$$

This profile naturally produces cored or exponential halos with approximately flat rotation curves, consistent with observations without invoking new particle species.

For illustration, consider a Milky Way–like galaxy with visible baryonic mass $M \approx 5 \times 10\text{^}10\, M \odot$, efficiency $\varepsilon \approx 0.2$, and scale length $\lambda \approx 5\, kpc$. Substituting into the expression above yields a deferred halo that produces flat rotation speeds of order $200\, km/s$ at $r \approx 10\, kpc$, consistent with observed galactic rotation curves.

In contrast, the standard NFW profile predicts a cuspy central density not seen in dwarf galaxy observations. The exponential halo profile derived from $D^{\mu\nu}$ produces cored centers and flat rotation curves, aligning with empirical data.

8.7 Summary

- The deferred component, defined through $D^{\mu\nu}$, behaves like dust in cosmology and mimics CDM.
- It can cluster and lens matter, consistent with structure formation.
- On galactic scales, the localized kernel form of $D^{\mu\nu}$, predicts exponential or cored halos instead of NFW cusps.
- In the massless limit, the same tensor formalism accommodates oscillatory deferral, with electromagnetic fields arising as the present-time projection of time waves.

These results demonstrate that the reservoir framework can be expressed in a covariant operator language and compared quantitatively with standard ΛCDM, while also extending naturally to the quantum horizon. Together with the black hole, cosmic, and galactic cases, the quantum horizon completes a four-part structure in which gravity and electromagnetism emerge as complementary manifestations of temporal deferral.

Next, we broaden the focus in **Section 9: Observational Discriminants**, comparing the predictions of the reservoir framework with conventional expectations across black holes, cosmic acceleration, dark matter and the quantum horizon of light and ultra-relativistic particles.

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9. Observational Discriminants

A unifying framework must make contact with observation. The reservoir interpretation offers distinct, testable signatures at three scales: black holes, cosmology, and galaxies.

9.1 Comparative Table

Domain	Standard (Hawking / ΛCDM / QM)	Reservoir Framework	Observational Discriminants
Black holes	Hawking radiation: thermal emission, $\dot{M} \propto -1/M^2$. Final stage → guaranteed gamma-ray burst as temperature diverges.	Evaporation as release of deferred matter. Typically silent mass loss, but if the reservoir collapses, an abrupt non-thermal burst may occur when the Schwarzschild boundary fails.	Presence/absence of thermal bursts; spectral shape (thermal hardening vs. sudden non-thermal cutoff); burst timing relative to $M(t)$.
Cosmology (dark energy)	Cosmological constant, $w = -1$ fixed. Horizon thermodynamics sets $\rho \sim \frac{H^2}{G}$ but with no evolution.	Dark energy as pull of accelerated futures. Allows $w < -1$ (phantom regime) and time variation.	Precision measurements of $H(z)$, $w(z)$. Detecting $w < -1$ with suppressed growth (σ_8 tension relief) supports reservoir view.
Galaxies (dark matter)	Cold dark matter (CDM): new non-baryonic particles. Predicts cuspy NFW halos.	Deferred baryons form exponential/cored halos. Behaves as dust ($w = 0$) cosmologically but differs at small scales.	High-resolution rotation curves and lensing maps. Cored vs. cuspy halos, alleviation of small-scale CDM problems.

Domain	Standard (Hawking / ΛCDM / QM)	Reservoir Framework	Observational Discriminants
Quantum horizon (electromagnetism)	Relativistic time dilation is purely kinematic. Photons treated as massless particles with no proper time, but not as horizons.	Particles defer energy via $f_{def} = 1 - \frac{1}{\gamma}$. In the $m \rightarrow 0$ limit, all energy is deferred as oscillatory time waves; EM fields are present-time projections of this deferral.	Lab interferometry: momentum-dependent phase drifts; decoherence scaling with momentum; photon limit tests (vacuum coherence, cosmic birefringence).

9.2 Black Hole Tests

The clearest discriminant comes from primordial black holes (PBHs).

- **Hawking channel:** PBHs end with intense thermal bursts of high-energy radiation as their temperature diverges.
- **Reservoir channel:** Evaporation is generally silent, with mass gradually released from the horizon reservoir. However, if a PBH shrinks below its Schwarzschild radius, the reservoir may no longer be sustained. In this case, a sudden release of the remaining deferred energy could occur — producing a burst, but with a different physical origin and likely non-thermal spectrum.

Thus, both frameworks allow for bursts, but with distinct mechanisms. Observations of burst spectra and temporal profiles — whether they resemble thermal Hawking explosions or abrupt reservoir collapses — can distinguish between the two pictures.

9.3 Cosmological Tests

The reservoir interpretation predicts that dark energy may not be perfectly constant. If external degrees of freedom at the horizon accelerate, our observed equation-of-state parameter w should dip below −1. This phantom-like behavior is difficult to reconcile with a simple cosmological constant but natural in the reservoir framework. Upcoming surveys of baryon acoustic oscillations, supernovae, and weak lensing will provide the precision to test this.

9.4 Galactic Tests

At galactic scales, the deferred-halo model predicts exponential or cored profiles, in contrast to the cuspy halos of standard CDM. This could help resolve longstanding small-scale tensions in

ΛCDM. High-resolution rotation curves of dwarf galaxies, combined with gravitational lensing studies, will serve as crucial discriminants. If halos consistently show cored profiles aligned with the reservoir prediction, this would support temporal deferral over new particle species.

9.5 Unified Perspective

Across all three domains, the key test is whether observed phenomena follow **thermodynamic (Hawking-like)** channels or **geometric (reservoir)** channels. The reservoir principle does not deny the validity of horizon thermodynamics, but it adds an alternative mechanism rooted in temporal divergence. Observations that favor silent evaporation (or non-thermal bursts), evolving dark energy, and cored halos would collectively strengthen the case for horizons as temporal reservoirs.

Immediate tests:
(i) Stack galaxy–galaxy lensing by stellar mass to detect inner-shear flattening at $\boldsymbol{R} \sim \boldsymbol{\lambda}$.
(ii) Joint $\boldsymbol{BAO} + \boldsymbol{SNe} + \boldsymbol{CMB}$ fit with $\boldsymbol{w(z)} = \boldsymbol{-1} - \boldsymbol{\alpha}\left(\frac{\boldsymbol{H}}{\boldsymbol{H^0}}\right)^{\boldsymbol{\beta}}$; report $(\boldsymbol{\alpha}, \boldsymbol{\beta})$.
(iii) Search $\boldsymbol{PBH}$ burst candidates with non-thermal cutoffs inconsistent with $\boldsymbol{T_H}$ evolution.

9.6 Quantum Horizon Tests

Just as black hole evaporation, cosmic acceleration, and galactic halos yield astrophysical signatures, the **quantum horizon** yields laboratory-scale signatures. In this case, the discriminants probe the **oscillatory deferral of massless and ultra-relativistic particles**, manifesting as electromagnetic fields projected into the present.

Phase anomalies in interferometry.
Relativistic particles should accumulate an additional phase proportional to their deferral fraction:

$f_{def} = 1 - \frac{1}{\gamma}$.

In a Mach–Zehnder or Ramsey interferometer, this predicts a **momentum-dependent phase drift** beyond standard relativistic dispersion. Such drifts could be sought in high-precision atom interferometers, relativistic electron beams, or optical lattice clocks.

Momentum-dependent decoherence.
If deferral acts stochastically, the visibility of interference fringes should decay as

$$exp\left[-\Gamma_{def}(p) \cdot t\right],$$

with the decoherence rate Γ_{def} scaling with momentum. Longer-wavelength probes would decohere more slowly than short-wavelength probes — a distinctive signature separating temporal deferral effects from environmental noise.

Photon limit.
For photons, $f_{def} = 1$: all energy is deferred. This suggests that light's peculiar role in relativity — zero proper time — corresponds to a maximally oscillatory state. Subtle departures from expected vacuum coherence, such as cosmic birefringence or polarization rotation, could therefore serve as probes of the quantum horizon.

Together, these signatures establish laboratory-scale tests of the reservoir framework, complementing astrophysical observations. If detected, momentum-dependent phase anomalies, distinctive decoherence patterns, or photon-limit effects would confirm that electromagnetism is the oscillatory counterpart to gravity's static curvature — completing the four-horizon symmetry of the reservoir principle.

10. Discussion

10.1 Relation to Existing Frameworks

• **Holographic Dark Energy**
Models inspired by the holographic principle (e.g., Li 2004) argue that dark energy density scales as $\rho \sim \frac{H^2}{G}$ because the cosmic horizon bounds the number of degrees of freedom. The reservoir framework agrees on the scaling but shifts the interpretation: the energy is not just "counted" at the horizon, but actively deferred into the future, creating a temporal reservoir.

• **Thermodynamic Gravity (Jacobson, Padmanabhan)**
Approaches that derive Einstein's equations from thermodynamics treat horizons as surfaces with entropy and temperature. The reservoir framework extends this by giving ontological weight to the external description: time dilation itself sequesters matter and energy, which then manifests gravitationally.

• **Entropic/Emergent Gravity (Verlinde)**
Verlinde proposes that gravity is an emergent entropic force linked to information encoded on holographic screens. The reservoir framework similarly emphasizes horizons, but focuses on temporal displacement rather than entropy maximization. Gravity becomes the "geometry of delay," not simply an entropic tendency.

• **Modified Gravity & MOND**
MOND-like approaches attempt to alter Newtonian dynamics at low accelerations. In contrast, the reservoir framework does not modify the laws of gravity; instead, it supplements them with an additional stress–energy component $T^{\mu\nu}_{def}$ sourced by deferred energy.

These approaches generally treat gravity alone. The reservoir framework goes further by unifying gravity with electromagnetism, interpreting photons as oscillatory time waves at the quantum horizon.

10.2 Conceptual Strengths

- **Unification across scales.** Black hole evaporation, dark energy, and dark matter are usually studied in isolation. The reservoir framework identifies a common mechanism.
- **Observational discriminants.** Unlike some speculative theories, this framework generates clear tests: PBH signatures, evolving www, and halo profiles.
- **Information preservation.** By treating deferred matter as real, the reservoir picture sidesteps the black hole information paradox: information is delayed, not destroyed.
- **Symmetry across all forces**: The framework situates gravity, electromagnetism, the strong, and the weak interactions as different manifestations of deferred energy release, with black holes representing the convergence of all four.

10.3 Potential Objections and Responses

1. **Isn't time dilation just a coordinate artifact?**
   • Standard relativity treats frozen horizons as perspectival. The reservoir view argues that the external description has ontological reality — not illusion. This stance is unconventional, but it is testable through the observational discriminants outlined in Section 8.
2. **Does this violate energy conservation?**
   • No. The deferred component is built into a covariant stress–energy tensor $T_{def}^{\mu\nu}$, obeying conservation with visible matter. Energy is not created or destroyed, only displaced along the temporal axis.
3. **What about cosmological constraints (BBN, CMB)?**
   • The deferred component behaves like pressure less dust ($w \approx 0$) in the background, so it can mimic CDM in early cosmology without altering nucleosynthesis or the acoustic peaks, provided ε and λ are chosen consistently.
4. **How does the reservoir collapse at small PBH masses?**
   • In the reservoir channel, evaporation is generally silent. Bursts may occur only if the horizon becomes unsustainable below the Schwarzschild scale. This provides a distinct, non-thermal origin for PBH bursts, differentiating the framework from Hawking explosions.

10.4 Broader Implications

If validated, the reservoir framework suggests that gravity is deeply tied to time, not just space. Horizons become more than boundaries of information: they are active **bookkeepers of temporal displacement**. This viewpoint resonates with relativity's emphasis on proper time but assigns new ontological significance to the delays between observers.

10.5 Implications for Quantum Gravity

The quantum horizon offers a natural point of contact between quantum mechanics and general relativity.

In quantum theory, energy is the generator of time evolution:

$$i\hbar \left(\frac{\partial}{\partial t}\right)\psi = \hat{H}\psi.$$

In relativity, energy also determines the flow of proper time through the Lorentz factor γ, and curves spacetime through Einstein's equations. By introducing a deferral fraction

$$f_{def} = 1 - \frac{1}{\gamma},$$

we unify these roles: part of a system's energy evolves on our clock, while the rest evolves across the quantum horizon and contributes to $T^{\mu\nu}_{def}$.

This interpretation has several consequences:

- **Quantum evolution as deferred energy:** Phase shifts and decoherence in quantum systems can be viewed as manifestations of energy evolving "off our clock."
- **Spacetime curvature as accumulated deferral:** The same deferred fraction contributes gravitationally through Einstein's equations, linking microscopic dynamics with macroscopic geometry.
- **Information preservation:** Quantum indeterminacy and the black hole information puzzle are reframed as questions of deferred reemergence rather than loss.
- **Toward quantum gravity:** By treating time deferral as the common currency between quantum phases and relativistic curvature, the reservoir framework provides a conceptual bridge: gravity is the geometry of temporal displacement, and quantum mechanics is the bookkeeping of that displacement at the level of individual particles.

Thus, the quantum horizon extends the reservoir principle across all scales, from microscopic quanta to cosmic structure, pointing toward a unified picture in which quantum mechanics and gravitation are not alien theories but complementary descriptions of how the universe keeps its books in time.

This symmetry implies that electromagnetism is not an entirely separate interaction but the oscillatory complement to gravitational curvature. Unifying them through temporal deferral reframes the search for quantum gravity as the search for a common temporal bookkeeping across all interactions.

The discussion shows that while the reservoir framework draws on insights from holography, thermodynamics, and emergent gravity, it introduces a distinct principle: **horizons as temporal reservoirs.** The next section concludes by summarizing the unification achieved and highlighting directions for further exploration.

10.6 Light as a Time Wave

As discussed in Section 7, photons at the quantum horizon manifest as time waves, with electromagnetic fields as the present-time projection of oscillatory deferral. This perspective dissolves wave–particle duality: localized detection corresponds to the present slice, while interference arises from overlapping deferred components (Fig. Z). In this way, electromagnetism appears as the oscillatory complement to gravity's static curvature.

10.7 Grand Unification

Black hole evaporation, in particular, illustrates how all four fundamental interactions appear as channels of deferred energy release: strong interactions shape hadronic output, weak interactions govern neutrino channels, electromagnetism projects oscillatory deferral as photons, and gravity collapses when the reservoir fails. This universality suggests that temporal deferral provides a common language for unifying the forces, closing the loop between the four horizons: black hole, cosmic, galactic, and quantum.

While gravity and electromagnetism map most directly onto the reservoir principle as static and oscillatory modes of deferral, the strong and weak interactions may also be interpreted in this language. The strong force can be viewed as a resonant, memory-like form of deferral: quark energy is never fully present, but sequestered in flux tubes whose release is always deferred into future hadronization events. The weak force, by contrast, reflects a probabilistic kind of deferral: unstable particles carry real mass in the present, yet the partition of that mass into decay products remains unresolved until a decay horizon is crossed. We emphasize that QCD and the electroweak theory remain the precise mathematical frameworks for these phenomena. Our proposal is only that they might be reinterpreted as effective realizations of a more general temporal bookkeeping principle. In this sense, temporal deferral does not replace the strong or weak interactions but offers a possible ontological unification of their diverse behaviors.

11. Conclusions

We have developed a unifying framework in which black hole evaporation, cosmic acceleration, galactic dark matter, and microscopic quantum time dilation all arise from a single principle: **horizons as temporal reservoirs**. In this interpretation, matter and radiation that appear to vanish at horizons are not destroyed, but deferred across time relative to external observers.

- **Black holes:** Evaporation corresponds to the gradual release of deferred matter, or in some cases an abrupt collapse of the reservoir if the Schwarzschild boundary can no longer be sustained.
- **Cosmology:** The cosmic horizon encodes accelerated futures, and their pull on the present manifests as the energy density we call dark energy, naturally scaling as $\rho \sim \frac{H^2}{G}$.
- **Galaxies:** Locally deferred baryons behave like a pressure less dust component, forming cored halos that reproduce dark matter phenomena without invoking new particles.
- **Quantum horizon:** Microscopic particles with high Lorentz factors experience slowed proper clocks, so part of their energy is deferred forward in time. In the massless limit, photons exist as **time waves**, with electromagnetic fields as the present-time projection of oscillatory deferral.

This unified picture reframes four of modern physics' greatest puzzles:

- The black hole information paradox becomes a question of deferred reemergence, not destruction.
- The cosmological constant problem is interpreted as the influence of accelerated futures at the cosmic horizon.
- The dark matter problem reflects the gravitational imprint of locally deferred baryons.
- The quantum–gravity problem is recast as the challenge of understanding how deferred fractions at the particle level contribute both to phase evolution in quantum theory and to curvature in general relativity.

Crucially, the reservoir framework is **observationally testable**. Distinguishing thermal Hawking bursts from non-thermal reservoir collapses, measuring deviations of $w(z)$ from -1, mapping cored versus cuspy galactic halos, and detecting laboratory-scale phase drifts or decoherence tied to the quantum horizon will provide decisive evidence.

The framework reveals a striking duality: what gravity is to massive particles, light is to massless particles. Gravity arises from the **static deferral** of massive energy into the future, curving spacetime through accumulated delay. Light arises from the **oscillatory deferral** of massless energy, producing electromagnetic fields as time waves projected into the present. Together, they appear not as independent forces but as complementary faces of the same temporal principle — one the curvature of time, the other its wave.

Black hole evaporation further illustrates the universality of the framework: **all four fundamental interactions** are represented in deferred release. The strong force governs hadronic outflows, the weak force governs neutrino channels, electromagnetism manifests as photons and time waves, and gravity governs the collapse of the horizon itself. This universality suggests that temporal deferral may provide a common language for unifying the forces.

By treating horizons not as one-way boundaries but as **time-shifted stores of energy**, we open a new way of thinking about gravity, light, and quantum mechanics. Horizons become the geometry of delay, mediating exchanges between present and future. If borne out, this would mean that black hole evaporation, dark energy, dark matter, and quantum time evolution are not four separate mysteries, but four faces of the same principle: **the universe keeps its books in time.**

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Black Holes & Evaporation

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Cosmic Horizons & Dark Energy

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