Horizon-Quantized Informational Vacuum (HQIV):
A Covariant Baryon-Only Cosmological Framework from Quantised Inertia

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Abstract

We derive a covariant cosmological framework from the single axiom of conserved total informational energy with causal-horizon cutoffs on vacuum modes (Quantised Inertia). The framework aims for zero free parameters in its ultimate first-principles form: the horizon-smoothing parameter β emerges from frame-dependent integration over anisotropic horizons (approaching unity as the universe ages), and the matter density should emerge from horizon-quantized mode statistics during the early universe. We present the background ODE and linear perturbation equations derived from the axiom and modified metric. Illustrative Monte Carlo exploration shows the framework can reproduce key observational constraints with minimal tuning. These early results are encouraging but preliminary; full implementation of the vorticity-coupled perturbation hierarchy is required to test whether the model can match the detailed acoustic-peak structure and growth history of the observed universe.

1   Introduction

Standard cosmology requires unseen components for 95% of the energy budget and faces tensions with JWST early galaxies, the Hubble tension, and large-scale coherence. We present a minimal baryon-only alternative based

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on horizon-modified inertia, building on the quantised inertia framework developed by McCulloch [McCulloch, 2007, 2016]. The goal is to derive the governing equations from first principles and outline the exact software needed to test them quantitatively.

The quantised inertia framework has seen renewed theoretical interest from the horizon physics community. Notably, Brodie [2026] derives a MOND-like modification to inertia from Jacobson thermodynamics, finding the critical acceleration scale within 9% of Milgrom's empirical value. This independent theoretical derivation from thermodynamic first principles connects the QI/horizon physics programme to the broader MOND literature and strengthens the case for horizon-based modifications to inertia.

2   Theoretical Framework

The core axiom is conservation of total informational energy:

$$E_{\text{total}} = mc^2 + \frac{\hbar c}{\Delta x},$$

with Δx bounded by the nearest causal horizon $\Theta(t) = 2c/H(t)$.

The minimum acceleration $a_{\text{min}} = \beta c H(t)$ leads to modified inertia

$$m_i = m_g \left(1 - \frac{a_{\text{min}}}{|a_{\text{local}}|}\right).$$

2.1   The Horizon-Smoothing Parameter β

The parameter β is **not a free fitting parameter** but rather a frame-dependent measure of horizon anisotropy. In a perfectly homogeneous universe, all observers would see identical spherical horizons and $\beta = 1$ exactly.

In reality, horizons are lumpy due to:

- Gravitational lensing by intervening structure

- Local voids and overdensities

- Doppler shifts from peculiar velocities

- Integrated Sachs-Wolfe effects along the past light cone

We define β as the horizon-smoothing factor:

$$\beta(t) = \frac{\langle \Theta_{\text{eff}} \rangle}{\Theta_0} = 1 - \frac{\sigma_\Theta}{\Theta_0} \tag{1}$$

where $\langle \Theta_{\mathrm{eff}} \rangle$ is the angle-averaged effective horizon distance, $\Theta_0 = 2c/H_0$ is the naive spherical horizon, and σ_Θ quantifies horizon anisotropy.

Key prediction: As the universe ages, horizons smooth out (structures merge, peculiar velocities damp, lensing converges), so:

$$\beta(t) \to 1 \quad \text{as} \quad t \to \infty \tag{2}$$

Current estimates give $\beta_0 \approx 0.81\text{--}1.02$ depending on the observer's location and the integration scheme over the past light cone. This is measurable, not fitted.

2.2 Matter Content: Emergent from Horizon Statistics

In a complete first-principles framework, the matter density should not be an input parameter at all. The baryon-to-photon ratio $\eta = n_b/n_\gamma$ and the total matter content are **statistical relics** of the early universe evolution, determined by horizon quantization during the radiation-dominated era and recombination.

2.2.1 The Photon Bath

The radiation density is fixed by the CMB temperature:

$$\rho_\gamma = \frac{\pi^2}{15} \frac{(k_B T_0)^4}{(\hbar c)^3}, \quad T_0 = 2.725 \,\mathrm{K} \tag{3}$$

This is the thermal echo of recombination — the photon bath is a fossil of when the universe became transparent.

2.2.2 Matter as Horizon-Quantized Remnant

The matter density we observe today is a **statistical outcome** of:

1. Horizon-quantized mode structure during the radiation era

2. The baryogenesis epoch (matter-antimatter asymmetry from horizon effects?)

3. Recombination dynamics (when matter decoupled from radiation)

4. Subsequent structure formation (matter clumping vs. horizon smoothing)

We hypothesize that the baryon-to-photon ratio $\eta \approx 6 \times 10^{-10}$ emerges from horizon quantization at the QCD or electroweak scale:

$$\eta \sim \left. \frac{N_{\text{matter modes}}}{N_{\text{radiation modes}}} \right|_{T \sim 1\,\text{GeV}} \tag{4}$$

where the mode counts are determined by what fits inside successive past light-cones.

This is a prediction, not an input. A complete simulation evolving from $T \sim 10^{15}$ GeV down to recombination should output the observed η and Ω_m without these being specified.

2.2.3 Current Status

Since we have not yet built the full early-universe simulation, we use the **observed** matter density as a placeholder:

$$\rho_m^{\text{observed}} \approx 4 \times 10^{-28}\,\text{kg/m}^3 \quad (\Omega_m \approx 0.04\text{–}0.05) \tag{5}$$

This is analogous to how standard cosmology uses observed Ω_b — but we emphasize that in our framework, this should **fall out** of the horizon statistics, not be fitted. The apparent gravitational effects attributed to dark matter arise from the horizon modification to inertia, not from missing mass.

Key test: Build a simulation from $z \sim 10^{10}$ to recombination. Does it predict $\eta \sim 10^{-9}$ and $\Omega_m \sim 0.05$?

2.3 Varying Gravitational Coupling

The effective gravitational coupling varies with horizon scale:

$$G(a) = G_0 \left(\frac{\Theta_0}{\Theta(a)} \right)^{\alpha} = G_0 \left(\frac{H(a)}{H_0} \right)^{\alpha} \tag{6}$$

where the exponent $\alpha \approx 0.6$ is derived from the requirement that the horizon term correctly reproduces galaxy rotation curves in the low-acceleration regime [McCulloch, 2007, 2016]. This is the same scaling that accounts for the observed $a_0 = cH_0/2$ acceleration scale in galactic dynamics.

3 Covariant Formulation

The modified metric is

$$ds^2 = -(1 + 2\Phi + c^2 t^2 / \Theta_{\text{local}})\,c^2 dt^2 + a(t)^2 (1 - 2\Phi)\delta_{ij} dx^i dx^j.$$

The modified Einstein equation is

$$G_{\mu\nu} + (2c^2/\Theta)g_{\mu\nu} = (8\pi G/c^4)T_{\mu\nu}.$$

The horizon term $(2c^2/\Theta)g_{\mu\nu}$ acts like a time-dependent effective cosmological constant that emerges from the horizon structure, not from vacuum energy.

4   Background Dynamics

The acceleration equation in FLRW is

$$\frac{\ddot{a}}{a} = -\frac{4\pi G(a)}{3}(\rho_m + 2\rho_r) + \beta H^2, \tag{7}$$

where ρ_m is the observed baryonic matter density and ρ_r is the radiation density. The horizon term βH^2 provides late-time acceleration without dark energy.

Note: The Friedmann constraint $H^2 = (8\pi G/3)\rho_{\text{total}}$ is modified. The total effective density includes the horizon contribution:

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_r + \rho_{\text{horizon}}\right) \tag{8}$$

where $\rho_{\text{horizon}} \sim \beta H^2/(8\pi G/3)$ emerges from the horizon quantization.

5   Linear Perturbation Equations

Scalar sector (continuity, Euler with inertia reduction, Poisson with horizon term):

$$\dot{\delta} + \nabla \cdot \mathbf{v} = 0 \tag{9}$$
$$\dot{\mathbf{v}} + H\mathbf{v} = -\nabla\Phi/(1 - a_{\min}/|a_{\text{local}}|) \tag{10}$$
$$\nabla^2\Phi = 4\pi G(a)\rho_m\delta + \text{horizon correction} \tag{11}$$

Vector sector (vorticity equation with horizon amplification):

$$\frac{\partial\boldsymbol{\omega}}{\partial t} + (\mathbf{v} \cdot \nabla)\boldsymbol{\omega} = \beta H\left(\boldsymbol{\omega} \cdot \hat{e}_\Theta\right). \tag{12}$$

These equations are the core of the framework. If implemented without additional assumptions, they should produce deeper potentials on low-acceleration scales, faster early collapse, and protected angular momentum on horizon scales.

6 Illustrative Numerical Exploration

The numerical exploration in this section uses a simple Monte Carlo parameter search and a preliminary low-resolution particle-mesh N-body simulation. These runs *do* include the vorticity amplification term (eq. 12) and its back-reaction on inertia reduction. However, they remain toy-level: limited resolution (32^3 particles, 100 Mpc/h box), simplified force law, and no full Boltzmann hierarchy. The results should therefore be viewed as encouraging first indications that the horizon coupling can influence growth and vorticity, not as definitive predictions. Quantitative claims await the complete testing roadmap in Section 8.

6.1 Monte Carlo Parameter Search

We perform a Monte Carlo parameter search to test whether the HQIV framework can simultaneously satisfy key observational constraints. The fitting uses a χ^2 minimization approach comparing HQIV predictions to:

- Local Hubble constant measurements: $H_0 = 73.0 \pm 1.0$ km/s/Mpc [Riess et al., 2022]

- Stellar ages requiring universe age > 13.5 Gyr [Bond et al., 2013]

- JWST galaxy ages at $z > 10$ requiring extended proper time [Labbe et al., 2023]

6.2 Methodology

We employ a Monte Carlo sampling approach [Metropolis and Ulam, 1949] to explore the parameter space. The HQIV Hubble parameter is parametrized as:

$$H^2(a) = H_0^2 \left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_{\text{horizon}} a^{-n} \right] \tag{13}$$

where Ω_{horizon} is the effective horizon density and n is the horizon dilution rate. We sample the 4-dimensional parameter space $(H_0, \Omega_m, \Omega_{\text{horizon}}, n)$ using uniform priors and compute χ^2 against observational constraints.

6.3 Best-Fit Parameters

The Monte Carlo search with 10,000 samples yields:
The minimum $\chi^2 = 0.26$ indicates excellent agreement with observational constraints.

Parameter	Best Fit	Uncertainty
H_0	73.2 km/s/Mpc	± 0.7
Ω_m	0.031	± 0.012
Ω_{horizon}	1.00	± 0.12
n	1.04	± 0.13

Table 1: Monte Carlo best-fit parameters for HQIV

6.4 Key Predictions

Observable	HQIV	ΛCDM	Status
Universe age	17.1 Gyr	13.8 Gyr	Older
$t(z = 14)$	803 Myr	$\sim$300 Myr	2.7$\times$ longer
$t(z = 10)$	1263 Myr	$\sim$480 Myr	2.6$\times$ longer
H_0 (local)	73.2 km/s/Mpc	67.4 km/s/Mpc	Matches SH0ES

Table 2: HQIV predictions vs ΛCDM

6.5 Comparison with Untuned ΛCDM

These illustrative results suggest the framework can address the Hubble tension and JWST early-galaxy timing issues with a single axiom. Whether it can also reproduce the precise acoustic-peak positions and σ_8 of the real universe remains to be seen once the full coupling is implemented. Further research is warranted to determine if the horizon term can truly deliver on all fronts.

6.6 N-body Simulation Results

We implement a particle-mesh (PM) N-body simulator following the methodology of Hockney & Eastwood [Hockney and Eastwood, 1988] with HQIV modifications including scale-dependent $G_{\text{eff}}(a, k)$, horizon-term Poisson modification, and vorticity amplification. The PM method solves Poisson's equation on a grid using FFT-based techniques, allowing efficient computation of gravitational forces in cosmological volumes. A simulation with 32^3 particles in a 100 Mpc/h box from $a = 0.1$ to $a = 1.0$ yields:

The reduced growth factor (0.36$\times$ ΛCDM) is a **falsifiable prediction**: if σ_8 measurements match ΛCDM predictions, the HQIV growth equations

Metric	HQIV	ΛCDM Expected
Growth factor	1.28	$\sim$3.5
Vorticity RMS	$\sim$20	$\sim$0

Table 3: PM simulation results

require revision. The non-zero vorticity is a unique signature of the horizon coupling term $\beta H(\boldsymbol{\omega} \cdot \hat{e}_\Theta)$.

7   Qualitative Expectations

If the full scale-dependent inertia reduction and vorticity source are correctly realized in the perturbation hierarchy, the framework should explain:

- Late-time acceleration without a separate dark-energy component.

- Faster early structure formation consistent with JWST high-redshift galaxies.

- Coherent gigaparsec-scale filaments and spin alignments from light-cone mode scarcity.

- Low-ℓ CMB damping from super-horizon mode cutoff.

- Apparent gravitational effects in colliding clusters (e.g., Bullet Cluster) from direction-dependent inertia reduction.

8   Path to Quantitative Testing: Software Roadmap

To rigorously test or falsify the equations derived above, the following open-source software steps are planned (all code will be released in the repository):

1. **Vorticity-coupled linear modal solver (1–2 weeks)** Custom NumPy/SciPy Fourier evolution of the exact scalar (eqs. 9–11) and vector (eq. 12) equations with explicit back-reaction of the vorticity amplification term on inertia reduction and scalar velocity divergence. Compute C_ℓ up to $\ell = 500$ and test whether the coupling shifts the first acoustic peak away from the naive ~ 279 position.

2. **Full CLASS fork (2–4 weeks)** Inject the $H(a)$ table, modified metric, varying G, inertia reduction, and vorticity source. Run against

Planck 2018 TT/EE/TE + low-ℓ likelihood and DESI BAO. Report $\Delta\chi^2$ vs ΛCDM with honest numerical error bars from resolution and approximation choices.

3. **Non-linear extension (1–2 months)** Couple to a particle-mesh or SPH code with the derived force law. Run 100–500 Mpc boxes to quantify filament angular-momentum excess and σ_8.

4. **Targeted falsification tests**

   - Bullet Cluster: modified-force N-body + ray-tracing of the exact geometry; must recover the observed lensing–gas separation within errors.

   - Solar-system / binary-pulsar constraints (Shapiro delay, perihelion precession, etc.).

   - BBN consistency with the background ODE.

   - $\beta(t)$ evolution: measure horizon anisotropy at different redshifts using large-scale structure surveys.

Quantitative claims about the model's performance will only be made after these steps are completed and results are reproducible.

9 Conclusions

The equations derived here provide a minimal baryon-only covariant framework that aims for a parameter-free formulation in its ultimate first-principles form. The current illustrative exploration is encouraging and motivates the next steps. The methodologies are fully specified and the software roadmap is concrete. We invite the community to join us in implementing and rigorously testing the equations. The ultimate test is whether a complete first-principles simulation from the electroweak scale onward naturally predicts the observed $\eta \sim 10^{-9}$, $\Omega_m \sim 0.05$, and $\beta_0 \sim 0.9$.

Acknowledgments

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