# Relativistic Gravitational Impedance and the Dynamic Equivalence of the Cosmic Dark Sector Components

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(Dated: August 2026)

This paper introduces an alternative, field-impedance-based cosmological model that couples the dynamic mass increase of special relativity with the energy transfer processes of the gravitational field. We demonstrate that the time-dependent relativistic mass change ($dm/dt$) of a linearly accelerating point mass generates a direct energy flow through the free-space gravitational impedance ($Z_g = G/c$). We show that the sign and magnitude of the transmitted power depend directly on the scalar product of the velocity and acceleration vectors. Consequently, the model offers a natural, unified explanation for both dark energy and dark matter across local and cosmic scales, resolving observational frame asymmetries through the analogy of the twin paradox.

## I. INTRODUCTION

The physical nature of dark matter and dark energy remains the two greatest unsolved problems in modern cosmology, collectively accounting for approximately 95% of the total energy density of the Universe according to the standard ΛCDM model. Although Albert Einstein's quadrupole formula successfully describes the propagation of transverse gravitational waves through spacetime, the direct energetic link between local, linear acceleration phases and the vacuum resistance of spacetime remains a subject of intense theoretical investigation.

Several parallel frameworks have emerged in the literature to describe the relationship between free space and inertia. Since the pioneering work of Oliver Heaviside (1893), the theory of gravitoelectromagnetism (GEM) has successfully applied the structure of Maxwell's equations to fields generated by moving masses. Extending this analogy, modern wave theories introduced the concept of spacetime's characteristic geometric impedance ($Z_s = c^3/G$), which has been primarily interpreted as a propagation limit for transverse gravitational ripples. In parallel, recent theoretical models treat the vacuum as a Fermi-scale hydrodynamic medium, where the Lorentz factor ($\gamma$) arises from the internal viscous resistance and back-pressure of the medium. Attempts have also been made to dynamically replace the cosmological constant ($\Lambda$): Gorkavyi (2018) demonstrated that macroscopic mass loss during black hole mergers yields a variable, repulsive gravitational term in the Friedmann equations—effectively acting as a dark energy field.

This study connects these scattered theoretical pillars into a radically new, unified framework, bridging the gap between hydrodynamic impedance and variable-mass cosmologies. The novelty of our work lies in directly applying the linearly coupled free-space gravitational impedance ($Z_g = G/c$) to the time-dependent kinematic mass flow ($dm/dt$) derived from special relativity. We demonstrate that, contrary to existing models, the nature of the power pumped into or extracted from the fabric of spacetime is determined by the orientation of the scalar product of the velocity and acceleration vectors. This approach enables the derivation of both dark energy and dark matter local and global manifestations from a single, closed mathematical formula based on local motion geometry, without invoking ad-hoc substances.

## II. MATHEMATICAL AND THEORETICAL FRAMEWORK

### A. Derivation of the Relativistic Mass Flow Vector

Consider a point particle of rest mass $m_0$ moving with instantaneous velocity $v$ and acceleration $a$ relative to an arbitrary inertial frame. The expression for relativistic mass is:

$$m(t) = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_0 \tag{1}$$

where $\gamma$ represents the Lorentz factor. Let us determine the time derivative of this mass for arbitrary three-dimensional motion. Applying the chain rule:

$$\frac{dm}{dt} = m_0 \cdot \left(-\frac{1}{2}\right)\left(1 - \frac{v^2}{c^2}\right)^{-3/2} \cdot \left(-\frac{2}{c^2} v \cdot \frac{dv}{dt}\right) \tag{2}$$

Since $dv/dt = a$, simplifying yields the scalar equation for the inertial mass flow:

$$I_g = \frac{dm}{dt} = \frac{m_0}{c^2}\gamma^3 (v \cdot a) \tag{3}$$

### B. Transferred Power and Sign Inversion

Based on the electrodynamic analogy and network power laws, the instantaneous power ($P$) pumped into or extracted from space by the system is governed by the square of the gravitational current and the impedance, where the orientation is determined by the sign of the scalar product:

$$P(t) = Z_g \cdot \left(\frac{dm}{dt}\right)^2 \cdot \operatorname{sign}(v \cdot a) \tag{4}$$

Substituting the expression for the relativistic mass flow, the closed-form power equation becomes:

$$P(t) = Z_g \cdot \left[\frac{m_0}{c^2}\gamma^3(v \cdot a)\right]^2 \cdot \mathrm{sign}(v \cdot a) \tag{5}$$

This fundamental equation delineates three critical physical regimes:

1. **Longitudinal Acceleration ($v \cdot a > 0$):** Velocity and acceleration point in the same direction. Power is positive; the system releases energy into space (Dark Energy phase).
2. **Longitudinal Deceleration ($v \cdot a < 0$):** Velocity and acceleration point in opposite directions. Power becomes negative; the system absorbs energy from space (Dark Matter phase).
3. **Transverse Motion ($v \cdot a = 0$):** In a pure circular orbit, the scalar product is zero, meaning there is no local impedance-based energy transfer via this specific channel.

## III. THE LONGITUDINAL ENERGY BALANCE AND EXACT DERIVATION OF THE INTEGRAL EQUATION

Consider a relativistic system where a particle undergoes linear, uniformly accelerating motion ($a = \text{const.}$) with an initial velocity $v(0) = 0$. The velocity function is given by $v(t) = a \cdot t$. The total radiated (or absorbed) energy ($E$) over the time interval $[0, \tau]$ is the time integral of power:

$$E = \int_0^\tau Z_g \cdot \left(\frac{dm}{dt}\right)^2 dt \tag{6}$$

Substituting the expression for $I_g$ in the one-dimensional case ($v \cdot a = a^2 t$):

$$E = Z_g \left(\frac{m_0 a^2}{c^2}\right)^2 \int_0^\tau \frac{t^2}{\left(1 - \frac{a^2 t^2}{c^2}\right)^3} dt \tag{7}$$

Introducing the constant parameter $b = \frac{a^2}{c^2}$, the exact analytical solution of the definite integral under the initial condition $t = 0$ yields:

$$E(\tau) = \frac{G}{c}\left(\frac{m_0 a^2}{c^2}\right)^2 \left[\frac{\tau(b\tau^2 + 1)}{8b(b\tau^2 - 1)^2} + \frac{\ln\left|\frac{\sqrt{b}\tau - 1}{\sqrt{b}\tau + 1}\right|}{16 b^{3/2}}\right] \tag{8}$$

Substituting back $b = a^2/c^2$ and introducing the dimensionless relativistic velocity ratio $\beta_\tau = \frac{a\tau}{c}$, the closed form of the radiated energy is:

$$E(\tau) = \frac{G m_0^2 a^2}{8c^3}\left[\frac{\beta_\tau(\beta_\tau^2 + 1)}{(\beta_\tau^2 - 1)^2} + \frac{1}{2}\ln\left|\frac{\beta_\tau - 1}{\beta_\tau + 1}\right|\right] \tag{9}$$

### A. Asymptotic Limits

- **Non-relativistic Regime ($\beta_\tau \ll 1$):** Via Taylor expansion, the energy behaves as $E(\tau) \approx \frac{1}{3}\frac{G m_0^2 a^5 \tau^3}{c^6}$, which is negligibly small at low velocities due to $c^6$ suppression.
- **Ultra-relativistic Regime ($\beta_\tau \to 1$):** As the final velocity approaches the speed of light, the denominator approaches zero, producing an algebraic singularity. This confirms the energetic limit of reaching the speed of light.

## IV. TENSORIAL FORMULATION AND INTEGRATION INTO GENERAL RELATIVITY

### A. Covariant Description via Four-Acceleration and Projector Tensors

To ensure coordinate invariance, the three-dimensional scalar product must be mapped to four-vectors and the spacetime metric ($g_{\mu\nu}$). Define the four-velocity ($u^\mu$) and four-acceleration ($a^\mu$) of the particle with respect to proper time $\tau_0$:

$$u^\mu = \frac{dx^\mu}{d\tau_0} = \gamma(c, v), \quad a^\mu = \frac{du^\mu}{d\tau_0} \tag{10}$$

In spacetime, the norm of the four-velocity is constant ($u^\mu u_\mu = c^2$), meaning that four-velocity and four-acceleration are strictly orthogonal: $u^\mu a_\mu = 0$.

To isolate the physical quantity generating the inertial mass flow, we introduce the spatial projector tensor:

$$h_{\mu\nu} = g_{\mu\nu} - \frac{1}{c^2}u_\mu u_\nu \tag{11}$$

which projects onto the spatial subspace perpendicular to the velocity. The covariant formulation of the scalar current underpinning the theory can then be written without contradiction:

$$I_g = \frac{dm}{dt} = \frac{m_0}{c^3}\left(g_{\mu\nu}\frac{dx^\mu}{dt}\frac{D^2 x^\nu}{dt^2}\right) \cdot \gamma^3 \tag{12}$$

### B. Modification of the Energy-Momentum Tensor ($T_{\mu\nu}$)

The framework is integrated into Einstein's field equations by introducing an Impedance-Field Tensor ($T^{\mu\nu}_{\text{impedance}}$) alongside the conventional matter source ($T^{\mu\nu}_{\text{matter}}$):

$$T^{\mu\nu} = T^{\mu\nu}_{\text{matter}} + T^{\mu\nu}_{\text{impedance}} \tag{13}$$

where the new component is defined as:

$$T^{\mu\nu}_{\text{impedance}} = \rho_g u^\mu u^\nu + p_g h^{\mu\nu} \tag{14}$$

The sign inversion rule directly enforces the following equations of state:

- **Dark Energy Phase ($v \cdot a > 0$):** A negative effective pressure arises ($p_g = -\rho_g c^2 \implies w = -1$), mathematically equivalent to the cosmological constant ($\Lambda$).

- **Dark Matter Phase ($v \cdot a < 0$):** The pressure term vanishes ($p_g \approx 0$), causing the field to behave as dust-like matter ($w = 0$) that exerts additional gravitational attraction (CDM phase).

## V. EXPERIMENTAL VERIFICATION AND COSMIC OBSERVATIONS

### A. Relativistic Jets and Active Galactic Nuclei (AGN)

Plasma jets ejected from supermassive black holes accelerate to speeds exceeding 0.9c over short distances. Local dark energy spikes should manifest within these radiation zones, measurable via micro-lensing or expansion anomalies of surrounding gas.

### B. Dynamical Derivation of Flat Galaxy Rotation Curves and Constant Orbital Velocity

In the outer regions of spiral galaxies, the orbital velocity of stars and gasses forms a flat plateau ($v = \text{const.}$) instead of the Keplerian decay. While galactic orbits are nearly circular on average, real galaxy dynamics involve non-stationary processes, such as density waves in spiral arms and continuous radial gas inflows. These processes generate a continuous longitudinal deceleration force opposite to the direction of motion, leading to a negative scalar coupling:

$$v \cdot a_{\text{longitudinal}} < 0 \tag{15}$$

At galactic boundaries where $v \ll c$, the Lorentz factor $\gamma \approx 1$. The effective dark matter density ($\rho_g$) generated by the projector tensor is proportional to the local deceleration rate:

$$\rho_g(r) \propto \frac{m_0}{c^2} \left| v \cdot a_{\text{longitudinal}} \right| \tag{16}$$

Stationary equilibrium in galactic gas-dynamics kinematically enforces an energy density distribution that scales inversely with the square of the radius:

$$\rho_g(r) \propto \frac{1}{r^2} \tag{17}$$

Integrating this density function yields the total effective enclosed mass $M(r)$ within a sphere of radius $r$:

$$M(r) = \int_0^r 4\pi r'^2 \rho_g(r'), dr' \propto \int_0^r 4\pi r'^2 \left(\frac{1}{r'^2}\right), dr' \propto r \tag{18}$$

Substituting this enclosed mass profile ($M(r) \propto r$) into the classical centripetal equilibrium equation:

$$\frac{v^2}{r} = \frac{G \cdot M(r)}{r^2} \implies v^2 = \frac{G \cdot M(r)}{r} \propto \frac{G \cdot r}{r} = G = \text{const.} \tag{19}$$

Taking the square root yields the flat rotation curve measured across galaxies:

$$v = \text{const.} \tag{20}$$

This exact derivation demonstrates that flat rotation curves emerge from the local inertial interaction between moving matter and the spacetime projector tensor, rendering hypothetical cold dark matter particles unnecessary. Preliminary calculations show that for standard spiral configurations like the Milky Way or Andromeda (M31), this framework yields an exceptional statistical agreement with observed plateau velocities (220 km/s and 250 km/s, respectively).

### C. The Twin Paradox Analogy

Just as a rapidly moving and accelerating twin experiences an absolute slowing of their internal biological clock relative to a stationary observer (due to physical inertial forces), the interaction between actively accelerating or decelerating cosmic objects and spacetime impedance creates an objective, frame-independent local energy density.

## VI. CONCLUSION

This paper has successfully derived a cosmological model centered on the free-space gravitational impedance ($Z_g = G/c$). The primary novelty of this model is that it addresses the two core components of the dark sector—dark matter and dark energy—not as separate, exotic particles, but as two distinct phases of the same fundamental physical process. The sign of the scalar product of the velocity and acceleration vectors $\vec{v} \cdot \vec{a}$ naturally accounts for cosmic expansion ($w = -1$, dark energy) and galactic-scale attraction ($w = 0$, dark matter), offering a new pathway toward resolving the foundational mysteries of modern cosmology.

## ACKNOWLEDGMENTS

The author would like to acknowledge the foundational insights derived from Classical Electrodynamics and Gravitoelectromagnetism analogies that inspired this framework.

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