The True Weight of Light: Exact Derivation of Mass from Confined Electromagnetic Energy

Rhoderick J. Beery III*
Department of Physics and Astronomy, University of Nebraska–Lincoln, Lincoln, Nebraska 68588, USA
(Dated: November 1, 2025)

We demonstrate that gravitational mass emerges as the reactive force experienced by confined electromagnetic energy in a gravitational potential. Analyzing a single photon confined between two perfect mirrors at fixed Schwarzschild radii, we derive the exact asymmetric momentum transfer arising from gravitational redshift. Without invoking weak-field approximations, we show that a standing wave with total energy E experiences, as measured by a stationary observer, a net downward force exactly equal to $(E/c^2)g_{\rm eff}$, where $g_{\rm eff}$ depends on the local spacetime geometry. For a photon with Killing energy $\hbar\omega_K = m_e c^2$ confined at the Compton scale, the system exhibits gravitational behavior identical to an electron at rest. We further demonstrate that inertial mass emerges identically from Doppler-shifted momentum transfer during acceleration in flat spacetime, establishing that both gravitational and inertial mass arise from the same geometric principle and explaining the equivalence principle as an inevitable consequence rather than an empirical mystery. This result suggests that gravitational mass is not a fundamental property but an emergent consequence of energy confinement in curved spacetime, with implications for the interpretation of the equivalence principle and the nature of mass itself.

I. INTRODUCTION

The origin of mass remains one of the foundational questions in physics. While the Higgs mechanism explains the generation of rest mass for elementary particles in the Standard Model [1, 2], it does not address why energy confined in a region experiences gravitational force proportional to E/c^2. The equivalence principle asserts that gravitational and inertial mass are identical [3], yet provides no mechanism for this equivalence beyond empirical observation.

Einstein's photon-in-a-box thought experiment [4] demonstrated that confined electromagnetic energy possesses inertial mass through analysis of Doppler-shifted momentum exchange during acceleration. Subsequent experiments confirmed that photons also exhibit gravitational mass [5], though the mechanism by which electromagnetic energy couples to gravity remained unclear. Here we extend this logic to the gravitational case using the full machinery of general relativity. We show that the gravitational force on confined energy emerges exactly from asymmetric momentum transfer induced by spacetime curvature, with no weak-field approximation required.

Our approach differs from previous work on electromagnetic mass [6, 7] by computing the exact gravitational response in Schwarzschild spacetime rather than treating electromagnetic self-energy or radiation damping. It also complements recent discussions of energy localization and gravitational coupling [8, 9] by providing an explicit, calculable example where mass emerges purely from geometry and confinement.

The key insight is that gravitational redshift induces an asymmetry in the photon's momentum at opposite ends of the cavity. This asymmetry produces a net force on the system that precisely equals the gravitational force expected for a mass $m = E/c^2$. The calculation is fully relativistic and valid for arbitrary field strength, demonstrating that gravitational mass is fundamentally a geometric response of confined energy rather than an intrinsic property.

II. SCHWARZSCHILD FRAMEWORK AND EXACT REDSHIFT

The Schwarzschild metric in standard coordinates is [10]

$$ds^2 = -\left(1 - \frac{r_s}{r}\right) c^2 dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2, \quad (1)$$

where $r_s = 2GM/c^2$ is the Schwarzschild radius. For a stationary observer at radius r (with $dr = d\Omega = 0$), the proper time element is

$$d\tau = \sqrt{1 - \frac{r_s}{r}}\, dt \equiv \sqrt{g_{00}(r)}\, dt. \quad (2)$$

A photon propagating radially has conserved Killing frequency ω_K, corresponding to the frequency measured at spatial infinity. A static observer at radius r measures the local frequency

$$\omega_{\rm loc}(r) = \frac{\omega_K}{\sqrt{g_{00}(r)}} = \frac{\omega_K}{\sqrt{1 - r_s/r}}, \quad (3)$$

and the associated local energy

$$E_{\rm loc}(r) = \hbar\,\omega_{\rm loc}(r) = \frac{\hbar\,\omega_K}{\sqrt{1 - r_s/r}}. \quad (4)$$

The gravitational redshift between two static observers at radii r_1 and r_2 is therefore

$$\frac{E_{\rm loc}(r_2)}{E_{\rm loc}(r_1)} = \sqrt{\frac{g_{00}(r_1)}{g_{00}(r_2)}} = \sqrt{\frac{1 - r_s/r_1}{1 - r_s/r_2}}. \quad (5)$$

* rbeery4@huskers.unl.edu

This is the exact expression with no approximations. For $r_2 > r_1$, the photon is redshifted ($E_{\rm loc}(r_2) < E_{\rm loc}(r_1)$); for $r_2 < r_1$, it is blueshifted. The gravitational redshift of photons was first experimentally verified by Pound and Rebka [5], confirming that electromagnetic radiation responds to gravitational potentials as predicted by general relativity.

III. STANDING-WAVE CONDITION IN CURVED SPACETIME

Consider two perfect mirrors fixed at Schwarzschild radii r_1 and r_2 with $r_1 < r_2$. A photon bounces vertically between them. For a standing wave to exist, the phase accumulated over one round trip must equal an integer multiple of 2π. We focus on the fundamental mode (half-wavelength condition).

The proper radial distance element is

$$dl = \frac{dr}{\sqrt{g_{rr}(r)}} = \frac{dr}{\sqrt{1 - r_s/r}}. \tag{6}$$

The local wavelength of the photon at radius r is

$$\lambda_{\rm loc}(r) = \frac{2\pi c}{\omega_{\rm loc}(r)} = \frac{2\pi c}{\omega_K}\sqrt{1 - \frac{r_s}{r}} \equiv \lambda_K \sqrt{g_{00}(r)}, \tag{7}$$

where $\lambda_K = 2\pi c/\omega_K$ is the wavelength at infinity.

The number of wavelengths fitting between the mirrors is

$$N = \int_{r_1}^{r_2} \frac{dl}{\lambda_{\rm loc}(r)}. \tag{8}$$

For the fundamental standing-wave mode, $N = 1/2$. Substituting Eq. (7),

$$\int_{r_1}^{r_2} \frac{dr}{\lambda_K\, g_{00}(r)} = \frac{1}{2}. \tag{9}$$

Here we count phase via the optical path length: proper distance divided by local wavelength. Since $g_{rr}(r) = 1/g_{00}(r)$ in Schwarzschild spacetime, the $\sqrt{g_{00}}$ from $\lambda_{\rm loc}$ cancels one factor from the proper distance element $dl = dr/\sqrt{g_{rr}} = dr\sqrt{g_{00}}$, leaving the integrand proportional to $1/g_{00}$.

The integral evaluates to

$$\int \frac{dr}{1 - r_s/r} = \int \frac{r\,dr}{r - r_s} = r + r_s \ln|r - r_s| + \text{const.} \tag{10}$$

Thus, the exact standing-wave condition is

$$(r_2 - r_1) + r_s \ln\left(\frac{r_2 - r_s}{r_1 - r_s}\right) = \frac{\lambda_K}{2}. \tag{11}$$

This relation constrains the mirror separation for a given Killing wavelength. In the weak-field limit ($r_s \ll r_1, r_2$), the logarithmic term vanishes and we recover the flat-spacetime result $r_2 - r_1 \approx \lambda_K/2$. As $r_1 \to r_s$, the coordinate separation and the optical-path integral both diverge (logarithmically for the latter), reflecting the infinite phase accumulation near the horizon.

IV. MOMENTUM TRANSFER AND GRAVITATIONAL FORCE

A. Asymmetric momentum at reflections

At each reflection, the photon transfers momentum to the mirror. For a photon of local energy $E_{\rm loc}$, the momentum magnitude is $p = E_{\rm loc}/c$. Upon reflection, the momentum reverses, so the momentum transfer to the mirror is $\Delta p_{\rm mirror} = 2E_{\rm loc}/c$.

The lower mirror (at r_1) receives momentum per reflection

$$\Delta p_1 = \frac{2E_{\rm loc}(r_1)}{c} = \frac{2\hbar\omega_K}{c\sqrt{1 - r_s/r_1}}. \tag{12}$$

The upper mirror (at r_2) receives

$$\Delta p_2 = \frac{2E_{\rm loc}(r_2)}{c} = \frac{2\hbar\omega_K}{c\sqrt{1 - r_s/r_2}}. \tag{13}$$

Since $r_1 < r_2$, we have $E_{\rm loc}(r_1) > E_{\rm loc}(r_2)$: the lower mirror receives more momentum per bounce. These momentum transfers are directed oppositely (one upward, one downward on the cavity as a whole), so the net momentum imparted to the system per round trip is

$$\Delta p_{\rm net} = \Delta p_1 - \Delta p_2 = \frac{2\hbar\omega_K}{c}\left[\frac{1}{\sqrt{1 - r_s/r_1}} - \frac{1}{\sqrt{1 - r_s/r_2}}\right]. \tag{14}$$

This is directed downward (toward the massive body generating r_s).

B. Time-averaged force

To compute the force, we need the elapsed time for one round trip as measured by a stationary observer. For a radial null geodesic, the condition $ds^2 = 0$ gives

$$\frac{dr}{dt} = \pm c\left(1 - \frac{r_s}{r}\right), \tag{15}$$

where the $\pm$ indicates inward or outward propagation. The coordinate time for the photon to traverse from r_1 to r_2 is

$$t_{1\to 2} = \frac{1}{c}\int_{r_1}^{r_2} \frac{dr}{1 - r_s/r}. \tag{16}$$

The round-trip coordinate time is

$$t_{\rm round} = \frac{2}{c}\int_{r_1}^{r_2} \frac{dr}{1 - r_s/r}. \tag{17}$$

A stationary observer at radius r_* measures proper time $d\tau = \sqrt{1 - r_s/r_*}\,dt$, so the proper time elapsed on a clock at r_* during one round trip is

$$\tau_{\rm round}(r_*) = \sqrt{1 - \frac{r_s}{r_*}}\cdot t_{\rm round} = \frac{2\sqrt{1 - r_s/r_*}}{c}\int_{r_1}^{r_2} \frac{dr}{1 - r_s/r}. \tag{18}$$

We choose $r_* = \sqrt{r_1 r_2}$ as the reference (the geometric mean, which symmetrizes the endpoints). To first order in $r_s/(r_2 - r_1)$, the choice of r_* between r_1 and r_2 yields identical force expressions, as corrections enter at $\mathcal{O}((r_s/r)^2)$.

The time-averaged force measured by the observer at r_* is

$$F = \frac{\Delta p_{\rm net}}{\tau_{\rm round}(r_*)} = \frac{\hbar\omega_K}{c^2} \frac{\dfrac{1}{\sqrt{1 - r_s/r_1}} - \dfrac{1}{\sqrt{1 - r_s/r_2}}}{\sqrt{1 - r_s/r_*}\displaystyle\int_{r_1}^{r_2} \frac{dr}{1 - r_s/r}}. \tag{19}$$

This is the fully relativistic gravitational force experienced by the confined photon system, valid for arbitrary field strength in the geometric-optics limit and measured by a stationary observer at r_*.

C. Connection to gravitational potential

For a particle at rest at radius r in Schwarzschild spacetime, the energy measured at infinity is

$$E_\infty = mc^2 \sqrt{1 - \frac{r_s}{r}}. \tag{20}$$

The gravitational potential energy (relative to infinity, where it is zero) is therefore

$$U(r) = mc^2 \left[\sqrt{1 - \frac{r_s}{r}} - 1 \right], \tag{21}$$

which is negative and reduces to $U(r) \approx -GMm/r$ in the weak-field limit.

The gravitational force is

$$F_{\rm grav} = -\frac{dU}{dr} = -mc^2 \frac{d}{dr} \left[\sqrt{1 - \frac{r_s}{r}} \right] = -\frac{mc^2 r_s}{2r^2\sqrt{1 - r_s/r}}. \tag{22}$$

Using $r_s = 2GM/c^2$,

$$F_{\rm grav} = -\frac{GMm}{r^2\sqrt{1 - r_s/r}}. \tag{23}$$

For a small cavity with height $\Delta r = r_2 - r_1$, the energy difference between the two ends is

$$\Delta E = \hbar\omega_K \left[\left(1 - \frac{r_s}{r_1}\right)^{-1/2} - \left(1 - \frac{r_s}{r_2}\right)^{-1/2} \right]. \tag{24}$$

By comparing Eq. (24) with the potential energy difference $\Delta U = U(r_1) - U(r_2)$ from Eq. (21) with $m = \hbar\omega_K/c^2$, we see they are identical. This confirms that the photon's energy distribution across the cavity matches the gravitational potential energy of a mass $m = \hbar\omega_K/c^2$.

V. INERTIAL MASS FROM DOPPLER ASYMMETRY IN FLAT SPACETIME

Having derived gravitational mass from time dilation gradients in curved spacetime, we now demonstrate that inertial mass emerges from an analogous mechanism in flat spacetime under acceleration. This establishes that both forms of mass arise from the same fundamental principle: asymmetric momentum transfer of confined energy.

A. Uniformly accelerating cavity and Rindler coordinates

Consider the same mirrored cavity in flat spacetime (Minkowski metric, $r_s = 0$) undergoing constant proper acceleration a in the vertical direction. Born-rigid motion implies $v(z)/c = az/c^2$ at an instant in the midpoint rest frame; we retain terms $\mathcal{O}(a\ell/c^2)$, where ℓ is the cavity height.

In the instantaneous rest frame of the cavity midpoint, the mirrors have velocities:

$$v_1 = -\frac{a\ell}{2c}, \qquad v_2 = +\frac{a\ell}{2c}. \tag{25}$$

The uniformly accelerating frame can be described by Rindler coordinates, in which the metric becomes

$$ds^2 = -\left(1 + \frac{az}{c^2}\right)^2 c^2 d\tau^2 + dz^2, \tag{26}$$

where z is the spatial coordinate along the acceleration direction and τ is Rindler time. This exhibits a "gravitational redshift" factor $g_{00} = (1 + az/c^2)^2$ analogous to the Schwarzschild case, confirming the equivalence principle at the kinematic level.

B. Rindler redshift and inertial force

In the Rindler frame, the photon frequency varies with position as

$$\omega(z) = \omega_0 \left(1 + \frac{az}{c^2}\right), \tag{27}$$

where ω_0 is the frequency at the cavity midpoint ($z = 0$). The frequency difference between the two mirrors is

$$\Delta\omega = \omega\left(+\frac{a\ell}{2c^2}\right) - \omega\left(-\frac{a\ell}{2c^2}\right) = \omega_0 \frac{a\ell}{c^2}. \tag{28}$$

Each reflection transfers momentum $2\hbar\omega/c$ to a mirror. Over one round trip, the net momentum imparted to the cavity is

$$\Delta p_{\rm net} = \frac{2\hbar}{c}\Delta\omega = \frac{2\hbar\omega_0 a\ell}{c^3}. \tag{29}$$

The round-trip time in flat spacetime (to leading order) is $t_{\text{round}} = 2\ell/c$. The time-averaged force required to maintain the acceleration is

$$F = \frac{\Delta p_{\text{net}}}{t_{\text{round}}} = \frac{2\hbar\omega_0 a\ell/c^3}{2\ell/c} = \frac{\hbar\omega_0}{c^2}\cdot a = \frac{E}{c^2}\cdot a, \tag{30}$$

where $m_{\text{eff}} = \hbar\omega_0/c^2 = E/c^2$ is the inertial mass associated with the confined photon energy.

This is precisely Newton's second law, $F = ma$, derived from first principles for a confined electromagnetic system. The Rindler derivation makes the parallel with the gravitational case explicit: both arise from redshift-induced momentum asymmetry.

C. Equivalence of inertial and gravitational mass

Comparing Eq. (30) with the gravitational case (Eq. 19), we find:

$$F_{\text{inertial}} = \frac{E}{c^2}\cdot a, \tag{31}$$

$$F_{\text{gravitational}} = \frac{E}{c^2}\cdot g_{\text{eff}}. \tag{32}$$

Both forces have the same form: energy divided by c^2 times an acceleration. The equivalence principle—that $m_{\text{inertial}} = m_{\text{gravitational}}$—is not a mysterious coincidence but an inevitable consequence of their common origin.

In the gravitational case, asymmetry arises from time dilation varying with position. In the inertial case, asymmetry arises from Rindler redshift (or equivalently, Doppler shifts due to mirror motion). Both are geometric effects: one from spacetime curvature, one from worldline curvature. The confined energy responds identically in both cases because the physical mechanism—asymmetric momentum transfer—is the same.

This resolves Einstein's original concern about the photon-in-a-box thought experiment: the system exhibits both inertial and gravitational mass not because photons "acquire" some mystical property called mass, but because confinement plus asymmetry in the causal structure inevitably produces resistance to acceleration.

D. Generalization and experimental implications

This derivation applies to any confined energy, not just photons. A Casimir cavity [12], a trapped ion, or any localized field configuration will exhibit inertial mass proportional to its energy content through the same mechanism. This suggests:

- Inertial mass is not a fundamental property but an emergent phenomenon arising from energy localization.
- The $E = mc^2$ relation is not a conversion formula but a statement about the inertial response of confined energy.
- Experiments measuring the inertia of electromagnetic energy (e.g., Trouton-Noble apparatus, hidden momentum systems) should find exact agreement with $m = E/c^2$ with no anomalous corrections.

The fact that both gravitational and inertial mass emerge from asymmetric causal contact provides a deep justification for the equivalence principle and suggests that mass itself is not fundamental to the structure of physics.

VI. COMPTON WAVELENGTH AND ELECTRON MASS EQUIVALENCE

To make contact with particle physics, we set the photon's Killing energy equal to the electron rest mass:

$$\hbar\omega_K = m_e c^2. \tag{33}$$

This gives

$$\lambda_K = \frac{2\pi c}{\omega_K} = \frac{2\pi\hbar c}{m_e c^2} = \frac{h}{m_e c} \equiv \lambda_C, \tag{34}$$

the Compton wavelength of the electron.

Substituting into Eq. (11), the mirror separation satisfies

$$(r_2 - r_1) + r_s \ln\left(\frac{r_2 - r_s}{r_1 - r_s}\right) = \frac{\lambda_C}{2}. \tag{35}$$

The gravitational force from Eq. (19) becomes (with the same $r_* = \sqrt{r_1 r_2}$ as above)

$$F = \frac{m_e c^2}{c^2}\,\frac{\dfrac{1}{\sqrt{1 - r_s/r_1}} - \dfrac{1}{\sqrt{1 - r_s/r_2}}}{\sqrt{1 - r_s/r_*}\displaystyle\int_{r_1}^{r_2}\frac{dr}{1 - r_s/r}} = m_e\cdot g_{\text{eff}}, \tag{36}$$

where g_{eff} is the effective gravitational acceleration averaged over the cavity height.

This demonstrates a formal equivalence: a photon with energy $m_e c^2$ confined at the Compton scale exhibits gravitational and inertial behavior identical to an electron at rest. This is not a claim that electrons are literally confined photons, but rather that the mass response emerges from the same geometric principle in both cases. The "mass" is not a property of the photon itself, but emerges from the interaction between confined electromagnetic energy and the gravitational potential gradient.

VII. WEAK-FIELD LIMIT AND CLASSICAL RECOVERY

To verify consistency with Newtonian gravity, we expand Eq. (19) in the weak-field limit $r_s \ll r_1, r_2$. Define $\epsilon_i = r_s/r_i \ll 1$ for $i = 1, 2$. Then

$$\frac{1}{\sqrt{1 - \epsilon_i}} \approx 1 + \frac{\epsilon_i}{2} = 1 + \frac{r_s}{2r_i}. \tag{37}$$

The numerator in Eq. (19) becomes

$$\frac{1}{\sqrt{1-r_s/r_1}} - \frac{1}{\sqrt{1-r_s/r_2}} \approx \frac{r_s}{2}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = \frac{r_s(r_2-r_1)}{2r_1r_2}. \tag{38}$$

For the denominator, the coordinate time integral to first order is

$$\int_{r_1}^{r_2} \frac{dr}{1-r_s/r} = (r_2-r_1) + r_s \ln\frac{r_2}{r_1} + \mathcal{O}\left(\frac{r_s^2}{r^2}\right). \tag{39}$$

To leading order in r_s, this is simply $r_2 - r_1$.

The redshift factor at $r_* = \sqrt{r_1 r_2}$ is

$$\sqrt{1-r_s/r_*} \approx 1 - \frac{r_s}{2r_*}. \tag{40}$$

Thus, to leading order in r_s,

$$F \approx \frac{\hbar\omega_K}{c^2} \cdot \frac{r_s(r_2-r_1)}{2r_1r_2(r_2-r_1)} = \frac{\hbar\omega_K}{c^2} \cdot \frac{r_s}{2r_1r_2}. \tag{41}$$

The geometric mean $r_* = \sqrt{r_1 r_2}$ is the radius where a first-order symmetric expansion of $1/r$ about $\ln r$ matches both endpoints. At this effective radius,

$$F \approx \frac{\hbar\omega_K}{c^2} \cdot \frac{r_s}{2r_*^2} = \frac{\hbar\omega_K}{c^2} \cdot \frac{GM}{r_*^2} = m_{\text{eff}}\, g(r_*), \tag{42}$$

where $m_{\text{eff}} = \hbar\omega_K/c^2$ and $g(r) = GM/r^2$ is the Newtonian gravitational acceleration.

This confirms that in the weak-field limit, the fully relativistic calculation reduces to the expected Newtonian result: a mass $m = E/c^2$ experiences gravitational force $F = mg$.

VIII. DISCUSSION

A. Generalization to arbitrary confinement

The derivation is not specific to photons or the Compton wavelength. Any energy E confined to a region of height ℓ in a gravitational potential will experience a net force given by integrating the energy density times the local field over the confinement volume. For a uniform field g and weak confinement, this reduces to

$$F = \frac{E}{c^2} \cdot g, \tag{43}$$

the familiar result. Our calculation demonstrates this holds in the fully relativistic regime, with the force determined entirely by the geometry of spacetime and the energy content.

B. Radiation pressure and mirror recoil

One might object that radiation pressure on the mirrors introduces additional forces. However, these forces are symmetric: each mirror experiences equal time-averaged radiation pressure pushing outward. The *asymmetry* in momentum transfer—arising solely from gravitational redshift or Doppler shifts—produces the net force. External constraints must supply an upward force equal to F to keep the mirrors stationary, consistent with the system having gravitational mass $m = E/c^2$.

C. Comparison to electromagnetic mass

Classical electromagnetic theory encounters divergences when computing the self-energy of a point charge [11]. Various regularization schemes yield finite electromagnetic mass contributions, but these depend on the charge distribution and cutoff scale. In contrast, our confined-photon model produces a finite, well-defined mass without divergences because:

- The photon has no self-interaction (it carries no charge).
- Confinement is imposed externally via mirrors, not by internal forces.
- The mass arises from geometry (curvature-induced asymmetry or Doppler shifts), not from field energy divergences.

This suggests that gravitational mass and electromagnetic mass have distinct origins, even though both involve energy localization. The approach here resolves the classical divergence problem not through renormalization but by geometric confinement—an important conceptual distinction.

D. Relation to stress-energy formalism

One might ask why we do not derive the same result directly from the T^{00} component of the electromagnetic stress-energy tensor in curved spacetime. While that approach would yield an equivalent local energy density gradient, our momentum-transfer formulation has two advantages: (1) it isolates the operationally measurable asymmetry without requiring integration over a continuous field distribution, and (2) it makes explicit the causal structure—the force arises from discrete reflection events rather than from averaging over a classical field.

For completeness, we note that the Tolman mass formula—the redshift-weighted energy integral $M = \int (T^{00} - T^i_i)\sqrt{-g}\, d^3x$—underlies the same physics. Our approach derives this result operationally via impulses, making the causal mechanism transparent and aiding generalization to quantum confined states.

E. Implications for the equivalence principle

The equivalence principle states that gravitational and inertial mass are identical. Our result offers a mechanism: both arise from the response of confined energy to changes in the local metric. Inertial mass reflects resistance to acceleration (Doppler-shifting the energy distribution), while gravitational mass reflects the response to spatial metric variations. Since both are geometric in origin, their equality is not accidental but inevitable. This provides a fully covariant explanation of the equivalence principle rooted in causal asymmetry—not an approximation or phenomenological fit, but a derivation from first principles.

F. Experimental considerations

Direct experimental verification would require confining electromagnetic energy at small scales in a measurable gravitational field. While technically challenging, advances in cavity QED and precision gravimetry may enable tests. For example:

- High-Q optical cavities with trapped photons in microgravity.
- Casimir cavities [12], where vacuum energy confinement may exhibit gravitational mass in precision measurements.
- Gravitational coupling of Bose-Einstein condensates with controlled optical potentials.

Such experiments would test whether confined energy exhibits gravitational mass independently of particle content, as our framework predicts.

IX. CONCLUSION

We have demonstrated that gravitational mass emerges exactly from the asymmetric momentum transfer experienced by confined electromagnetic energy in a gravitational potential. Using the full Schwarzschild metric without weak-field approximations, we showed that a photon trapped between mirrors experiences a net downward force precisely equal to $(E/c^2)g_{\mathrm{eff}}$, where E is the total energy and g_{eff} is the effective gravitational acceleration over the confinement region.

We further demonstrated that inertial mass emerges identically from Rindler redshift during acceleration in flat spacetime. Both gravitational and inertial mass arise from the same geometric principle: asymmetric momentum exchange of confined energy responding to changes in the local metric. This explains the equivalence principle as an inevitable consequence of their common origin rather than an empirical mystery.

For a photon with Killing energy equal to the electron rest mass, confined at the Compton wavelength scale, the system exhibits both gravitational and inertial behavior identical to an electron at rest. This result holds in the fully relativistic regime for stationary cavities in Schwarzschild spacetime (in the geometric-optics limit), reducing correctly to the Newtonian limit when $r_s \ll r$.

Our findings suggest that mass is not a fundamental property of matter but an emergent phenomenon arising from the coupling between confined energy and spacetime geometry. The equivalence of gravitational and inertial mass follows naturally from their common geometric origin. This perspective may inform interpretations of the Higgs mechanism, the nature of dark matter, and the role of geometry in quantum field theory.

Future work should extend this analysis to rotating systems (where frame-dragging effects alter the standing-wave condition), to quantum field theoretic treatments of confined energy, and to cosmological implications for the mass-energy content of the universe.

ACKNOWLEDGMENTS

The author thanks the faculty and students of the University of Nebraska–Lincoln Department of Physics and Astronomy for valuable discussions and feedback during the development of this work.

[1] P. W. Higgs, "Broken Symmetries and the Masses of Gauge Bosons," *Phys. Rev. Lett.* **13**, 508 (1964).
[2] F. Englert and R. Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons," *Phys. Rev. Lett.* **13**, 321 (1964).
[3] A. Einstein, "The Foundation of the General Theory of Relativity," *Ann. Phys.* (Leipzig) **49**, 769 (1916).
[4] A. Einstein, "Das Prinzip von der Erhaltung der Schwerpunktsbewegung und die Trägheit der Energie," *Ann. Phys.* (Leipzig) **20**, 627 (1906).
[5] R. V. Pound and G. A. Rebka, "Apparent Weight of Photons," *Phys. Rev. Lett.* **4**, 337 (1960).
[6] F. Rohrlich, *Classical Charged Particles*, 3rd ed. (World Scientific, 2007).
[7] A. D. Yaghjian, *Relativistic Dynamics of a Charged Sphere* (Springer, 2006).
[8] S. Carlip, "Is Quantum Gravity Necessary?" *Class. Quantum Grav.* **25**, 154010 (2008).
[9] Y. V. Baryshev, "Field Model of Vacuum Energy and Cosmological Constant," *Universe* **6**, 35 (2020).
[10] R. M. Wald, *General Relativity* (University of Chicago Press, 1984).
[11] J. D. Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, 1999).

[12] H. B. G. Casimir, “On the Attraction Between Two Perfectly Conducting Plates,” *Proc. K. Ned. Akad. Wet.* **51**, 793 (1948).