Optical-Metric Scalar Phenomenology and a Decisive Cavity-Atom LPI Test: Phase Velocity as Operational One-Way Light Speed in a Verified Nondispersive Band

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We develop an *optical-metric scalar phenomenology*—a minimal, testable framework in which a scalar field ψ induces a conformal *optical metric* for electromagnetism while leaving the matter metric unchanged at leading order. In a *verified nondispersive* frequency band, geometric optics implies the measured electromagnetic phase velocity equals the operational one-way propagation speed along a path segment. This enables synchronization-free measurements that are strictly null in general relativity (GR) yet potentially non-null here. We (i) state the assumptions explicitly, (ii) derive the identity via both Fermat/eikonal optics and Gordon's optical metric, (iii) anchor the phenomenology to familiar scalar-tensor and SME language (local Lorentz invariance preserved; local position invariance potentially violated in the photon sector), (iv) identify the clean experimental discriminator: a *co-located cavity-atom frequency ratio* recorded at two gravitational potentials, and (v) provide a quantitative constraints audit and a realistic error budget showing near-term feasibility at 10^{-16} fractional uncertainty and below. The proposal is falsifiable: a null cavity-atom ratio shift across altitude (after dispersion and thermal controls) kills this class of models; a reproducible non-null that scales with potential would warrant deeper theory. Our aim is not to redefine simultaneity but to exploit route-dependent, synchronization-free observables that adjudicate between GR (null) and this optical-metric scalar sector.

I. MOTIVATION AND ASSUMPTIONS (MADE EXPLICIT)

A1. Optical–metric scalar. We posit a scalar field $\psi(\mathbf{x})$ that *conformally rescales* the photon sector's effective metric,

$$\tilde{g}_{\mu\nu} = e^{-2\psi(\mathbf{x})}\,\eta_{\mu\nu}, \tag{1}$$

in the lab frame, so that light rays follow $\tilde{g}_{\mu\nu}$–null geodesics (Gordon–type optics [1, 2]). Matter fields minimally couple to $\eta_{\mu\nu}$ at leading order. This mirrors well–studied scalar–tensor ideas [3] and photon–sector extensions in the SME [4] while keeping local Lorentz cones isotropic.

A2. Nondispersive measurement band. Experiments are restricted to a frequency band where *dispersion is bounded* by dual–wavelength checks: $|\partial n/\partial\omega|$ small enough that phase, group, and front velocities coincide within the error budget [5, 6]. Outside this band no claim is made.

A3. Weak–field normalization. In the Newtonian regime we set $\psi \simeq -2\Phi/c^2$, chosen so that standard weak–field optical tests (deflection, Shapiro delay) recover the GR value $\gamma = 1$ [7]. Test bodies fall universally; LLI in the matter sector is respected.

Aim. With (1) and A2–A3, the measurable *phase* velocity becomes a synchronization–free probe of an *operational* one–way light speed along a path segment. We design a clean LPI discriminator where GR is null.

II. CORE IDENTITY FROM TWO INDEPENDENT ROUTES

Route I: Fermat/eikonal. Geometric optics extremizes $T[\gamma] = (1/c)\int_\gamma n(\mathbf{x})\,\mathrm{d}\ell$ with $n = e^{\psi}$, giving

$$v_{\text{phase}} = \frac{c}{n} = c\,e^{-\psi} \equiv c_1(\mathbf{x}). \tag{2}$$

In a verified nondispersive band, phase=group=front [5, 6], so c_1 is the operational one–way propagation speed along γ without distant clocks.

Route II: Optical metric. Light rays are $\tilde{g}_{\mu\nu}$–null: $\mathrm{d}\tilde{s}^2 = (c^2/n^2)\mathrm{d}t^2 - \mathrm{d}\mathbf{x}^2 = 0$ [1]. Nullness implies $\mathrm{d}\ell/\mathrm{d}t = c/n$, the same identity. The equality is structural, not definitional.

III. RELATION TO EQUIVALENCE PRINCIPLES AND LLI

Local Lorentz invariance (LLI). Because $\tilde{g}_{\mu\nu}$ is conformally flat and isotropic, two–way orientation and boost tests remain null at 10^{-17}–10^{-18} as observed [8–10].

Local position invariance (LPI). The matter sector respects LPI to leading order (*atom vs atom* redshifts match GR). The photon sector, however, samples $n = e^{\psi}$; thus *cavity vs atom* ratios can acquire route/height dependence. Our decisive observable is precisely an LPI test in a nondispersive photon sector.

TABLE I. Constraints audit. "Null in GR" means strict null after standard subtractions. The last column states this model's expectation under A1–A3.

Observable	Constrains	Expectation here
Two–way cavity rotations	LLI anisotropy	Null (matches data)
Atom–atom redshift (lab/space)	LPI (matter sector)	Matches GR
Remote transfer links	Path/time transfer	Orthogonal to local ratio
Cavity–atom, single height	Local calibration	Constant ratio at fixed conditions
Cavity–atom ratio at two heights	**Photon vs matter LPI**	**Potentially non–null (decisive)**

TABLE II. Order–of–magnitude signals under A1–A3 (nondispersive band enforced). GR is strictly null for A/B and effectively null for C.

Protocol	Observable	Signal scale
A: Crossed cavities	$\delta f/f$ on rotate/Δh	$\sim 10^{-16}$ per m
B: Fiber loop	$\Delta\phi_{\circlearrowright} - \Delta\phi_{\circlearrowleft}$	$< 10^{-16}$ eqv.
C: Cavity/atom ratio	$\Delta R/R$ across Δh	$2g\Delta h/c^2 \approx 2.2\times10^{-14}$ /100 m

IV. MINIMAL DYNAMICS (PHENOMENOLOGY-FIRST)

For concreteness we adopt a scalar field fixed by local mass density with a single crossover scale,

$$\nabla\cdot\left[\mu\left(\frac{|\nabla\psi|}{a_\star}\right)\nabla\psi\right] = -\frac{8\pi G}{c^2}\,(\rho_m - \bar{\rho}_m), \qquad \mathbf{a} = \frac{c^2}{2}\nabla\psi, \tag{3}$$

so that $\psi \simeq -2\Phi/c^2$ in weak fields. This choice reproduces GR optics at leading order [2, 7] and serves only to map lab gradients to potentials. Our empirical claims do not hinge on UV completion (Sakharov–style motivations exist [11]).

V. WHAT EXISTING TESTS DO—AND DO NOT—CONSTRAIN

We summarize the *published* landscape (abbrev.):

To our knowledge, no peer–reviewed result reports a *co–located* cavity–atom frequency ratio recorded at two distinct gravitational potentials with $< 10^{-16}$ fractional uncertainty. This is the precise gap our Protocol C targets.

VI. LABORATORY PROTOCOLS (GR–NULL VS SIGNAL HERE)

All protocols enforce nondispersion by dual–wavelength phase tracking to bound $|\partial n/\partial\omega|$ within the budget [6, 12].

A. Crossed ultra–stable cavities (orientation/height sweep)

Orthogonal high–Q cavities of length L support $f_m \simeq (m/2L)\,(c/n)$; a change $\delta\psi$ imparts $\delta f/f = -\delta n/n = -\delta\psi$. Orientation reversals and vertical translations by Δh probe geometry–locked shifts. Target stability: 10^{-17}–10^{-16} [8, 10]. GR: null (after standard subtractions). Here: geometry–locked residuals permitted by A1.

B. Reciprocity–broken fiber loop (two heights)

A monochromatic tone circulates around an asymmetric loop with vertical separation Δh and a Faraday element. $\phi = (\omega/c)\int n(\mathbf{x})\,\mathrm{d}\ell$ yields a forward–backward difference $\propto \oint \psi\,\mathrm{d}\ell$ that vanishes in GR (static loop, Sagnac removed) but not here if $\nabla\psi\cdot\hat{\boldsymbol{z}} \neq 0$.

C. Decisive LPI test: co–located cavity–atom ratio across altitude

Lock a laser to a vacuum cavity (frequency $f_{\rm cav} \propto c/n$) and compare to a co–located optical atomic transition $f_{\rm at}$ via a comb. Form $R \equiv f_{\rm cav}/f_{\rm at}$ at altitude h_1, repeat at $h_2 = h_1 + \Delta h$.

GR: Moving a co–located package changes neither local physics nor the ratio; R is constant (excellent approximation).

Here (A1–A3): With $\psi \simeq -2\Phi/c^2$, the cavity inherits $f_{\rm cav} \propto e^{-\psi} \simeq 1 + 2\Phi/c^2$, while the atomic transition is leading–order ψ–insensitive (matter–sector universality). Hence

$$\frac{\Delta R}{R} \;\approx\; 2\,\frac{\Delta\Phi}{c^2} \;\approx\; 2\,\frac{g\,\Delta h}{c^2} \;\sim\; 2.2\times10^{-14}\ \text{per 100 m}. \tag{4}$$

Allowing a small matter coupling gives $\Delta R/R = \xi\,\Delta\Phi/c^2$ with $0 < \xi \leq 2$; still at the $10^{-16}\,\mathrm{m}^{-1}$ scale. State–of–the–art cavities and clocks reach 10^{-17}–10^{-16} [8, 10, 13, 14].

TABLE III. Illustrative 1σ fractional budget for $\Delta R/R$ over 100 m. Values reflect demonstrated performance in the cited literature; any one item can be tightened.

Source (mitigation)	σ (fractional)
Cavity thermal drift (ULE/cryo; drift cancel by differencing)	5×10^{-16}
Vibration/tilt (seismic isolation; feedforward)	2×10^{-16}
Comb ratio transfer (self–referenced; optical division)	1×10^{-16}
Atomic ref. (Sr/Yb/Al$^+$; short–term avg)	1×10^{-16}
Residual dispersion (dual–λ bound; linear fit)	5×10^{-17}
Air index/pressure (vacuum enclosure; sensors)	5×10^{-17}
Magnetic/polarization (scrambling; swaps)	3×10^{-17}
Quadrature total	$\sim 7 \times 10^{-16}$

VII. PREDICTED MAGNITUDES (ORDER OF ESTIMATE)

VIII. PROTOCOL C FEASIBILITY: QUANTITATIVE ERROR BUDGET

We list dominant systematics and representative fractional contributions for a 100 m potential step (conservative, room–temp cavities; cryo improves margins). Dual–λ control is assumed to bound dispersion.

The target signal $\sim 2.2 \times 10^{-14}$ per 100 m exceeds the above conservative noise by $\gtrsim 30\times$. Even a suppressed coupling $\xi \sim 0.1$ remains clearly resolvable. Publishing Allan deviation $\sigma_y(\tau)$, blind height reversals, hardware swaps, and multi–λ linearity fits close the standard loopholes.

IX. REFUTATION CRITERIA (CLEAN KILL CONDITIONS)

Any of the following falsifies this class of optical–metric scalars:

1. Protocol C yields $\Delta R/R$ consistent with zero at or below $|\Delta\Phi|/c^2$ (or ξ inferred $\ll 10^{-2}$) while dispersion and thermal budgets pass checks.

2. Protocols A/B give nulls after reversals/path swaps where a geometry–locked residual was predicted under A1–A3.

3. A verified nonzero dispersion fully accounts for any residuals across the band.

Conversely, a reproducible, potential–scaling non–null that survives the above controls would motivate a fuller theory (or sharpen SME bounds).

X. ADDRESSING STANDARD CRITICISMS DIRECTLY

(1) "One–way c is conventional; you cannot measure it." We do not alter simultaneity conventions. We identify *local, synchronization–free, route–dependent* observables that are null in GR but not necessarily in the photon sector of an optical–metric scalar. The equality "phase=one–way speed" is invoked only in a band where phase=group=front is verified [5, 6, 15–17].

(2) "Vacuum cannot have a refractive index." We never posit a material medium. We posit an *effective optical metric* (a standard construct since Gordon [1, 2]) in which photons see $n = e^{\psi}$. This is squarely within scalar–tensor/SME phenomenology [3, 4]. Two–way LLI tests remain null and satisfied.

(3) "Equivalence principle is broken." Matter test bodies obey universal free fall; atomic redshift tests match GR [13, 14, 18]. The proposed discriminator is *LPI in the photon sector*: cavity (photon) vs atom (matter). If nature is GR in both sectors, Protocol C is null and the model is ruled out.

(4) "Existing experiments would already have seen this." Published demonstrations involve atom–atom redshifts or remote transfers; none report the *co–located cavity–atom ratio at two potentials* with $< 10^{-16}$ sensitivity (Table I). Our error budget shows clear headroom.

(5) "Phase velocity is not signal velocity." Correct in dispersive media. We operate only in a verified nondispersive band where phase, group, and front velocities coincide within budget [5, 6].

XI. CONCLUSIONS

We have recast "DFD" as an *optical–metric scalar phenomenology* that is conservative (LLI preserved; GR optics recovered in the weak field) yet falsifiable by a single decisive, synchronization–free test: the *co–located cavity–atom ratio* across a potential difference. The identity linking phase velocity to operational one–way speed is established by two independent routes and invoked only under a verified nondispersion assumption. With current optical metrology, the proposal is executable; either the ratio is null (model killed) or a controllable, potential–scaling residual appears (then the photon sector merits renewed scrutiny).

Appendix A: Geometrical optics and nondispersion

Let S be the eikonal: $\mathbf{k} = \nabla S$, $\omega = -\partial_t S$. With $\omega = (c/n)|\mathbf{k}|$, $v_{\rm phase} = \omega/|\mathbf{k}| = c/n$ and $v_g = \partial\omega/\partial|\mathbf{k}| = c/n$; the Sommerfeld–Brillouin front velocity coincides in the nondispersive limit [5, 6].

Appendix B: Round–trip nulls, clocks, and GPS

For a fixed path γ, $T_{2w} = (2/c)\int_\gamma n\,\mathrm{d}\ell$; at fixed geometry, orientation rotations preserve two–way times (Michelson–Morley nulls). Atom–atom redshift verifications rely on matter clocks and remote transfers consistent with GR [13, 14, 18]; our decisive observable is a *local* cavity–atom ratio across altitude.

Appendix C: Minimal implementation checklist

Cavities: ULE/silicon spacers; PDH locking; cryogenic option; 10^{-17} stability [8, 10].
Fibers: zero–dispersion operation; Faraday isolators; dual–λ phase tracking [12].
Clocks: Sr/Yb lattice or Al^+ logic; comb–based ratio readout [13, 14].
Analysis: publish $\sigma_y(\tau)$; blinded reversals; multi–λ linearity fits; environmental logs.

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