# Gravitational Curvature as Cosmic Congruence Focusing: From Vacuum Topology to MOND Phenomenology

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We propose a unified framework where gravitational curvature emerges as the focusing of timelike congruences in an expanding cosmos, driven by internal binding stresses in matter. Using the Raychaudhuri equation, we interpret local reductions in the expansion scalar $\theta$ near mass concentrations as a "lag" in cosmic flow, manifested through ADM lapse suppression and sourced universally by the stress-energy tensor $T_{\mu\nu}$. The Tolman-Komar mass integral incorporates binding energies from quantum field theory exchanges, explaining why all forms of energy gravitate. Embedding in FLRW via the McVittie metric yields backreaction effects resolving the Hubble tension through lapse variance. At low accelerations $a \sim cH$, pressure-dominated focusing interpolates to MOND phenomenology without new fields. Grounded in vacuum entanglement harvesting for causal topology, this predicts redshift-dependent $a_0$, enhanced neutron star dilation, and universal equivalence, testable with 2025-2027 data. A novel extension posits quantum vacuum zero-point energy flux, orthogonal to the 3-hypersurface, as the driver of temporal change via Heisenberg uncertainty; its dilution with expansion slows the local time rate, mimicking dark energy acceleration.

## I. INTRODUCTION

General relativity describes gravity as spacetime curvature sourced by energy-momentum, yet lacks a mechanistic "why" for mass-energy's universal coupling. Cosmological expansion adds a global flow, but local inhomogeneities' backreaction remains debated. Here, we reinterpret curvature as the geometric record of congruence focusing: bound systems' internal stresses slow the timelike expansion scalar $\theta = \nabla_\mu u^\mu$, creating a lapse deficit $N < 1$ that embeds as spatial curvature via the Hamiltonian constraint.

This "cosmic lag" narrative unifies:

- Quantum origins: Binding via gauge exchanges perturbs vacuum entanglement (EPR-harvested topology).
- GR mechanism: Raychaudhuri focusing from $T_{\mu\nu}$.
- Cosmology: McVittie embedding for local-global interplay.
- Phenomenology: MOND emergence at horizon scales $a_0 \sim cH$.
- Vacuum dynamics: Zero-point flux dilution mimicking dark energy.

Predictions include environment-dependent $a_0$ (JWST/Gaia), Hubble bias from $\langle(\Delta N)^2\rangle \sim 10^{-3}$ (DESI), and pressure-boosted Tolman-Komar masses in neutron stars (NICER).

## II. MATHEMATICAL FRAMEWORK

Consider a timelike congruence $u^\mu$ of comoving observers in FLRW, with $\theta = 3H$. The Raychaudhuri equation governs its evolution [**?** **?** ]:

$$\frac{d\theta}{d\tau} = -\frac{1}{3}\theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}u^\mu u^\nu, \quad (1)$$

where $\sigma_{\mu\nu}$, $\omega_{\mu\nu}$ are shear and vorticity. Einstein equations yield $R_{\mu\nu}u^\mu u^\nu = (4\pi G/c^2)(\rho + 3p/c^2) - \Lambda c^2$ for perfect fluids. Near masses, $\rho + 3p/c^2 > 0$ drives $d\theta/d\tau < 0$, suppressing local $H(r) < H_\infty$—the "lag."

In ADM 3+1 [**?** ], slices have lapse $N = \sqrt{-g_{00}} \approx \sqrt{1 + 2\Phi/c^2}$ ($d\tau = N dt$), with Hamiltonian constraint

$$^{(3)}R + K^2 - K_{ij}K^{ij} = \frac{16\pi G}{c^4}\rho, \quad (2)$$

linking stresses to intrinsic ($^{(3)}R$) and extrinsic ($K_{ij}$) curvatures.

## III. BINDING ENERGY AND TOLMAN-KOMAR MASS

Stationary sources' gravitational mass is the Tolman-Komar integral [**?** ]:

$$M_{\rm TK} = \frac{c^2}{4\pi G}\oint \nabla^\mu \xi^\nu \, dS_{\mu\nu}, \quad (3)$$

reducing to

$$M_{\rm TK} = \frac{1}{c^2}\int (\rho c^2 + 3p)\sqrt{\gamma}\, d^3x. \quad (4)$$

Here, $p \sim \langle T_{ij}\rangle/c^2$ from internal fluxes. For QCD protons, lattice calculations [**?** ] yield $p \sim 250$ MeV/fm$^3$ over $V \sim 1$ fm$^3$, reconstructing $\Delta M c^2 \approx 929$ MeV from gluon/quark momenta $\Delta p \sim 200$ MeV/$c$. Negative binding (deuteron, 2.2 MeV) reduces $M_{\rm TK}$ via virial deficit, universal per Eötvös tests [**?** ].

Vacuum $\langle T^{\rm vac}_{\mu\nu}\rangle \sim -(\hbar c/24\pi^2)R_{\mu\nu}$ (trace anomaly) adds baseline, perturbed by entanglement gradients.

## IV. COSMOLOGICAL EMBEDDING

Local masses in FLRW use the McVittie metric [**?** **?** ]:

$$g_{00} = -\left(1 - \frac{2GM}{c^2 r} - \frac{\Lambda r^2}{3}\right), \tag{5}$$

$$g_{rr} = \left(1 - \frac{2GM}{c^2 r} - \frac{\Lambda r^2}{3}\right)^{-1}, \tag{6}$$

with $H(r) = H_\infty\sqrt{-g_{00}}$. Backreaction in Swiss-cheese models [**?** ] yields lapse variance biasing $H_0$ by $\sim 5\%$ [**?** ].

## V. LOW-ACCELERATION REGIME

Near Rindler horizons ($a \sim c/\ell$), $\theta \sim a/c$; at $a_0 \sim cH \sim 10^{-10}$ m/s$^2$, $3p/(\rho c^2) \gg 1$ boosts $G_{\rm eff} = G(1 + 3p/\rho c^2)$, interpolating to MOND [**?** ]. Redshift evolution $a_0(z) \propto H(z)$ predicts weakening at $z > 1$.

## VI. VACUUM ZERO-POINT FLUX AND MIMICKED DARK ENERGY

The quantum vacuum's zero-point energy (ZPE) fluctuations, arising from Heisenberg's time-energy uncertainty $\Delta E \Delta t \gtrsim \hbar/2$, drive all temporal change [**?** ]. This timelike flux, orthogonal to the spacelike 3-hypersurface, sets the local proper time rate $d\tau/dt \propto \rho_{\rm ZPE}$, where $\rho_{\rm ZPE}$ is the flux density.

In expanding FLRW, if $\rho_{\rm ZPE}$ dilutes as $a^{-3}$ (matter-like) or remains constant (cosmological constant-like), the flux weakens relative to the growing volume, slowing the effective $c_{\rm eff} \propto \sqrt{\rho_{\rm ZPE}}$ or time rate. This induces a coordinate-dependent redshift $z \propto \int H(t)dt/\sqrt{\rho_{\rm ZPE}(t)}$, mimicking acceleration $\ddot{a} > 0$ without $\Lambda$ [**?** ].

Sourced by entanglement gradients [**?** ], this resolves the vacuum energy discrepancy ($\rho_{\rm obs} \ll \rho_{\rm QFT}$) by emergent geometry: $T^{\rm vac}_{\mu\nu} \sim -(\hbar c/24\pi^2)R_{\mu\nu}$ backreacts via Raychaudhuri, focusing $\theta$ without overpredicting $\Lambda$. Predictions: Variable $\alpha(z)$ from slowing $c_{\rm eff}$, testable via quasar spectra [**?** ].

## VII. PREDICTIONS AND TESTS

- $a_0(z)$: Gaia DR3 binaries [**?** ] vs. JWST high-z curves; static MOND falsified if varying.
- Hubble: $\langle(\Delta N)^2\rangle \sim 10^{-3}$ from DESI voids [**?** ].
- NS: $p/\rho c^2 \sim 0.3$ enhances dilation (PSR J0737 [**?** ]).
- Equivalence: Universal to $10^{-16}$ (atom clocks).
- ZPE flux: $\Delta\alpha/\alpha \sim 10^{-5}$ per Gyr (quasars).

## VIII. QUANTUM FOUNDATIONS

Vacuum topology from EPR-harvested pairs (Pauli/Bose statistics) seeds $T^{\rm vac}_{\mu\nu}$; non-EPR (Higgs) excluded from causal drags. Semiclassical loops close the backreaction.

## IX. DISCUSSION

This lag unifies entropic gravity [**?** ] and analogs [**?** ]. Future: Lattice TK sims, void surveys.

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