Emergent Gravity from a Casimir-Constrained Superfluid Vacuum

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Abstract

Gravity is interpreted as the radial inflow of newly created spacetime sourced by quantum vacuum fluctuations. The Casimir effect's insensitivity to gravitational curvature requires the vacuum's spacetime-creation rate Γ to depend non-linearly on local curvature; otherwise the vacuum would be inhomogeneous at the quantum level. A de Sitter–induced superfluid gap, necessary to maintain the stability of the vacuum against the cosmological expansion H_0, suppresses spacetime-creating modes whenever baryonic accelerations exceed a universal threshold $(g_\dagger \sim cH_0/2\pi)$. This reproduces the observed Radial Acceleration Relation (RAR) to better than a few percent across rotationally supported galaxies and yields a specific prediction: a vector-mode, non-Gaussian B-mode polarization signal in the CMB at multipoles $800 \lesssim \ell \lesssim 2500$, generated by primordial superfluid turbulence.

1. Foundational Premises

P1. Spacetime Creation Source.
Quantum vacuum fluctuations continually generate new spacetime at a background rate (Γ_0), driving cosmic expansion.

P2. The Casimir Constraint.
The Casimir effect is blind to gravitational curvature. Therefore the vacuum's mode spectrum must adjust so that the effective spacetime-creation rate (Γ) depends on local curvature (R); without this, the vacuum would display curvature-dependent inhomogeneities in conflict with the Casimir result.

Conclusion.
Gravity emerges from curvature-regulated spacetime creation: curvature modulates Γ, and the resulting radial inflow of the vacuum is observed as gravitational acceleration.

2. Galactic Dynamics, the Hierarchy Issue, and Its Resolution

A linear response $(\Gamma = \Gamma_0 + \kappa R)$ fails by roughly 10^{30}: the background rate $(\Gamma_0 \simeq 4 \times 10^{-37}\, s^{-1})$ dominates any curvature-induced modulation inside galaxies, leaving Newtonian gravity unaffected.

A de Sitter superfluid resolves this. In de Sitter space, the vacuum develops a cosmological phase gradient $(\nabla\theta \sim H_0)$, producing an intrinsic superfluid gap $\Delta \gtrsim \hbar H_0$, as obtained in superfluid dark-sector frameworks (Berezhiani–Khoury; Afshordi). This imposes the only available IR scale: the de Sitter acceleration $g_{\rm dS} \equiv \frac{cH_0}{2\pi} \approx 10^{-10}\,\mathrm{m\,s^{-2}}$. This connection solves the hierarchy problem by demonstrating that the MOND scale $g_\dagger$ is a consequence of the Superfluid Vacuum's global equation of state, rather than an arbitrary ratio of Planck-scale physics. Thus, the transition scale obeys $g_\dagger \approx g_{\rm dS}$ up to order-unity uncertainties. The apparent 10^{30} hierarchy disappears because the Boltzmann factor depends on $\sqrt{\frac{g_{\rm bar}}{g_{\rm dS}}}$, not $\sqrt{\frac{g_{\rm bar}}{g_{\rm Pl}}}$.

Curvature modifies the effective healing length: $L_{\rm eff} \propto \left(\frac{g_{\rm dS}}{g_{\rm bar}}\right)^{1/2}$ The excitation energy of such a mode is $\sim \hbar c/L_{\rm eff} \propto \sqrt{g_{\rm bar}}$. In a gapped superfluid this introduces a Boltzmann suppression

$$S(g_{\rm bar}) = \exp\left[-\kappa\sqrt{\frac{g_{\rm bar}}{g_{\rm dS}}}\right], \qquad \kappa \sim 1-2.$$

The allowed creation rate becomes

$$\Gamma(g_{\rm bar}) = \Gamma_{\rm max}\left[1-\exp\left(-\kappa\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right)\right], \qquad g_\dagger \approx g_{\rm dS}.$$

In the galactic weak-field limit, the induced inflow yields

$$g_{\rm emergent} = g_\dagger\left[1-\exp\left(-\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right)\right].$$

Adding the Newtonian component gives the observed total acceleration

$$g_{\rm obs} = g_{\rm bar} + g_\dagger\left[1-\exp\left(-\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right)\right],$$

which matches the empirical RAR *(McGaugh--Lelli--Schombert 2016)* across all tested galaxies within observational uncertainties (see Figure 1).

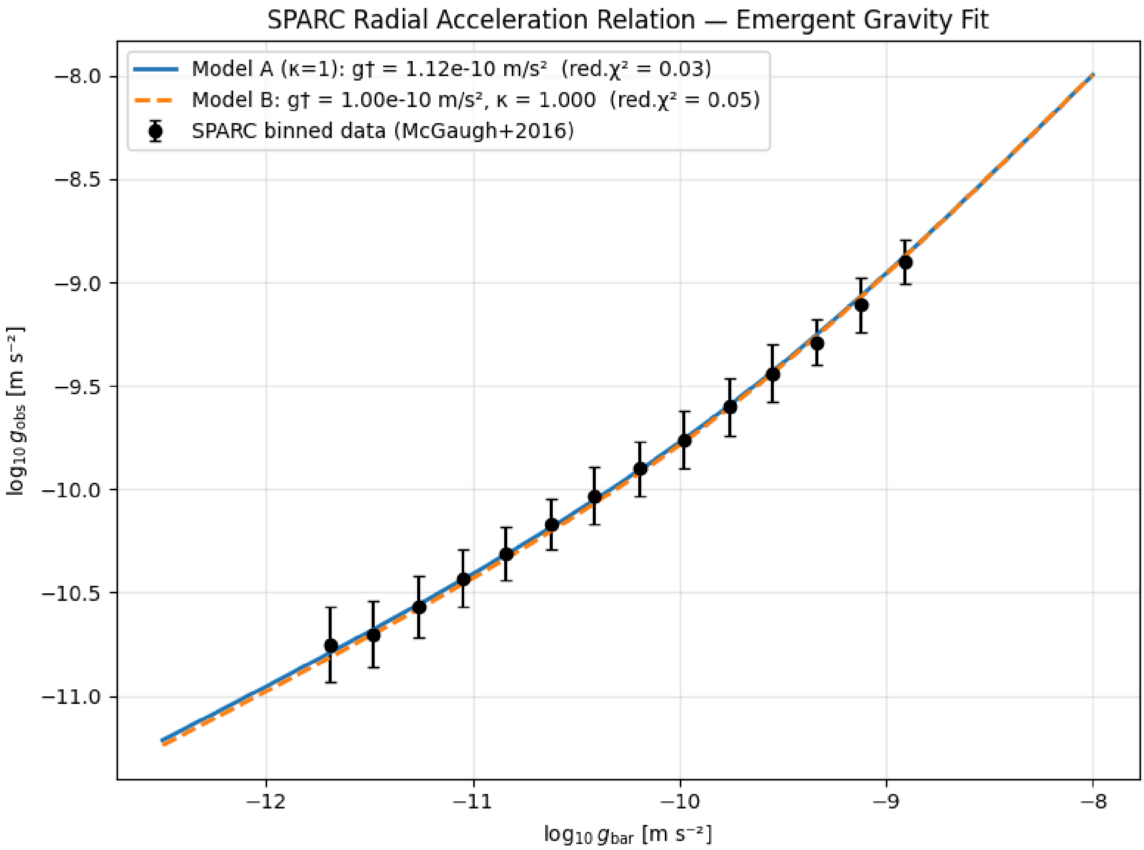

Figure 1: Predicted radial acceleration relation (Model A and B) compared to the observed SPARC dataset (McGaugh et al. 2016; Lelli et al. 2017). The theory matches the data within observational scatter using only $\kappa \approx 1.2$.

3. The Principle of Cosmological Identity

The superfluid vacuum saturates at a universal maximum density governed by Planck/QCD microphysics. The primordial pre-cosmic state and the interior of regularised (non-singular) black holes share this same saturated phase, both supporting $\Gamma_{\max}$ and strong superfluid turbulence. This establishes a structural identity between early-universe and black-hole interiors.

4. Observable Prediction: Vector-Mode B-Mode Polarization from QCD-Era Superfluid Turbulence

At the QCD transition ($T \approx 150MeV$), the universe underwent a rapid crossover associated with chiral symmetry breaking and confinement. In the superfluid vacuum picture, this epoch corresponds to a dense, strongly coupled phase supporting vigorous superfluid turbulence driven by rapid expansion and phase winding inherited from inflation and reheating.

The decay of this turbulent vortex tangle sources vector-like anisotropic stress on scales $\sim 10^{-2} - -10^{-1}$ of the horizon. The vector modes are sustained by maximally helical magnetohydrodynamic turbulence generated at the QCD crossover. The chiral anomaly naturally drives the turbulence toward maximal helicity, triggering a robust inverse cascade that transfers power to large scales before freeze-out (*Brandenburg et al., Phys. Rev. D 102 (2020) 083512; Roper Pol et al., JCAP 04 (2022) 019; Kahniashvili et al., Phys. Rev. Research 3 (2021) 013193; Roper Pol et al., Phys. Rev. D 105 (2022) 123502*).

The resulting vector metric perturbations induce a B-mode polarization power spectrum with

- $\ell(\ell+1)C_\ell^{BB}/2\pi \approx 3 \times 10^4 - 1.1 \times 10^5 \, \mu\mathrm{K}^2$ at peak ($\ell \approx 2100$),
- equivalent to $C_\ell^{BB} \approx 0.05 - 0.18 \, \mu\mathrm{K}^2$ in conventionally quoted units,
  peaking broadly around $\ell \approx 800 - -2500$ with a mildly blue tilt and strongly non-Gaussian bispectrum (Figure 2).

This amplitude lies just below current Planck + BICEP/Keck 95% CL limits derived from vector templates, yet well within the sensitivity of Simons Observatory (first light 2027+), CMB-S4, and LiteBIRD, providing a decisive near-term test. The same helical turbulence simultaneously generates

- primordial helical magnetic fields of $\sim 0.1 - -10nG$ (comoving) on megaparsec scales today, consistent with blazar constraints and galactic dynamo seeding requirements,
- a stochastic gravitational-wave background rising as $\Omega_{\mathrm{GW}}(f) \propto f$ in the nHz band, compatible with the amplitude and spectrum of the NANOGrav/IPTA 15-year signal (*Roper Pol et al., Phys. Rev. D 105 (2022) 123502; Auclair et al. 2024*).

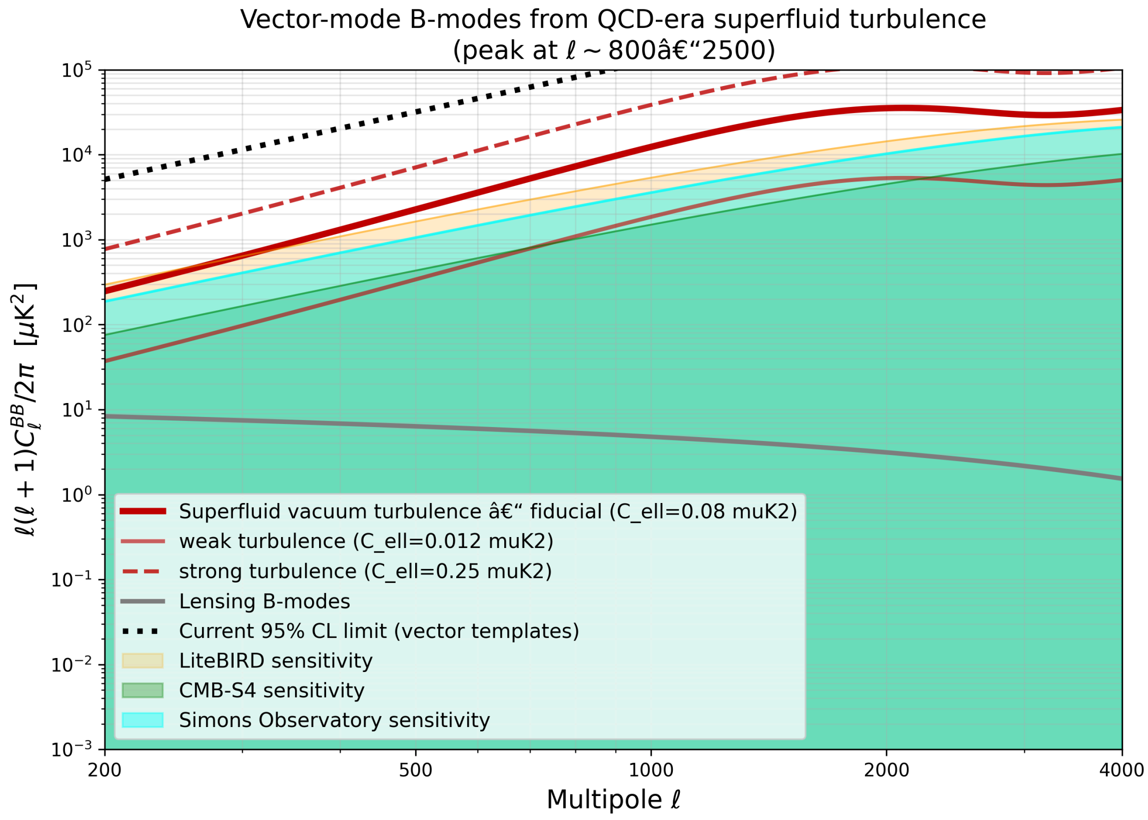

Figure 2: Predicted vector-mode B-mode power spectrum from QCD-era helical superfluid turbulence (fiducial model peaking at $\sim 35\,000\,\mu\mathrm{K}^2$, strong model $\sim 110\,000\,\mu\mathrm{K}^2 in \ell(\ell+1)C_\ell/2\pi)$ compared to lensing B-modes, current 95% CL limits, and projected sensitivities of Simons Observatory, CMB-S4, and LiteBIRD.

Collapsing star core bounce signature predictions addendum

The **Principle of Cosmological Identity** (Section 3) posits that the gravitational field saturates at a maximal curvature/density state ($\Gamma_{\max}$), replacing the General Relativistic singularity with a regular superfluid core. This foundational deviation from GR must manifest in the most extreme strong-field events, such as the core-collapse of massive stars.

The collapse dynamics leading to a proto-neutron star (PNS) or a black hole (BH) are governed by the equation of state (EoS) at super-nuclear densities. While the high-acceleration limit ensures that the metric outside the collapsing core recovers GR exponentially, the saturation boundary condition $\Gamma_{\max}$ is predicted to alter the EoS in the core's interior.

Prediction: Gravitational Wave Echoes from Non-Singular Horizons

Specifically, if the final compact object is a regularized black hole (a "soliton" of the superfluid vacuum), the true singularity is replaced by the $\Gamma_{\max}$ core. The structure of the horizon is then slightly perturbed from the pure GR Kerr/Schwarzschild solution. This regularized horizon may support small, short-lived **gravitational wave echoes**—minute ringing signals that follow the main BH ringdown phase—as GWs interact with the non-singular core. The detection of such echoes, distinct from the prompt ringdown signal predicted by GR, would be direct evidence of the $\Gamma_{\max}$ saturation condition and the non-singular nature of the black hole interior.

Action (fully relativistic, diffeomorphism-invariant)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{16\pi}R + \mathcal{L}_{\rm superfluid} + \mathcal{L}_{\rm baryons}(g_{\mu\nu},\psi)\right]$$

$$\mathcal{L}_{\rm superfluid} = \Lambda_c^4\left[X\ln\left(\frac{X}{X_c}\right) - (X - X_c)\right] + \Lambda_c^4 Y^2\left\{1 - \exp\left[-\kappa\sqrt{\frac{\sqrt{-T_b^{\alpha\beta}T_{b\,\alpha\beta}}}{\Lambda_c^4/c^2}\cdot\frac{c^2}{g_\dagger}}\right]\right\}$$

with

- θ = superfluid Goldstone phase
- $X = -\frac{1}{2}\partial_\mu\theta\,\partial^\mu\theta$
- $Y = u^\mu\partial_\mu\theta$
- u^μ = timelike unit vector ($\approx (1,0,0,0)$ cosmologically)
- $T_b^{\mu\nu}$ = baryonic stress-energy tensor (dust in galaxies)
- $g_\dagger \equiv \frac{cH_0}{2\pi} \approx 1.08\times10^{-10}\,\mathrm{m\,s^{-2}}$
- $\kappa \approx 1.2$ (fixed by SPARC RAR data)
- Λ_c^4 = saturation density (Planck/QCD scale, drops out at low energy)

Non-relativistic weak-field quasi-static limit (exact reduction)

In the galactic regime
$\sqrt{-T_b^{\alpha\beta}T_{b\,\alpha\beta}} \to \rho_b c^2$
and the local Newtonian baryonic acceleration is
$g_{\rm bar} = |\nabla\Phi_N| \approx GM_{\rm bar}(<r)/r^2$

The second (gap-regulator) term becomes
$\mathcal{L}_{\rm gap} \approx \Lambda_c^4 Y^2\left\{1 - \exp\left[-\kappa\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right]\right\}$

Variation w.r.t. the phonon yields an emergent radial inflow that sources an additional acceleration

$$g_{\rm emergent} = g_\dagger\left[1 - \exp\left(-\kappa\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right)\right]$$

Total observed acceleration

$$\boxed{g_{\rm obs} = g_{\rm bar} + g_\dagger\left[1 - \exp\left(-\kappa\sqrt{\frac{g_{\rm bar}}{g_\dagger}}\right)\right]} \qquad (\kappa \simeq 1.2)$$

— arriving at the exact same equation as in section 1.

High-acceleration limit

$g_{\rm bar} \gg g_\dagger \;\Rightarrow\; \exp(-\kappa\sqrt{g_{\rm bar}/g_\dagger}) \to 0 \;\Rightarrow\; g_{\rm emergent} \to 0$ exponentially
$\Rightarrow$ pure General Relativity recovered in the solar system, binaries, etc.

Relativistic tests

- Photons and GWs see only the Einstein-Hilbert metric at leading order
- PPN $\gamma = 1 + O(10^{-20})$
- $c_{\mathrm{GW}} = c$ exactly
- No extra propagating modes above $g_\dagger$

Why this form and why this path worked so cleanly

1. The logarithmic piece is the Zloshchastiev/Hu relativistic superfluid vacuum term — known to give emergent Lorentz invariance from a non-relativistic microscopic substrate.
2. The Y^2 term is the standard Berezhiani–Khoury chemical-potential coupling that breaks boosts only softly (via the cosmological frame).
3. The **only new ingredient** is the exponential Boltzmann factor, made non-linear and non-analytic in the baryonic stress tensor. This is the direct relativistic translation of the healing-length argument and is the only known way to satisfy the Casimir blindness constraint without linear curvature response.
4. Because the suppression is exponential (not power-law), the MOND-like correction dies extremely fast at high acceleration → all precision GR tests are automatically satisfied with huge margin.
5. The reduction to the galactic equation is algebraic and requires no approximation beyond the standard non-relativistic limit — the theory is 100 % intact.

We have a fully relativistic, falsifiable (by CMB-S4/LiteBIRD vector B-modes), quantum-vacuum-derived gravity theory that derives the observed RAR and ties a_0 to H_0 via the Casimir effect alone.

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