A Dynamical Two-Component Quantum Vacuum:

Causal Topology, Entanglement Harvesting, and the Origin of Dark Matter

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Abstract

We develop a unified dynamical theory in which dark matter arises not from new particles but from a distinguished sector of the quantum vacuum. A causal-topology filter Π_{causal}, defined using algebraic quantum field theory and Schwinger–Keldysh response theory, projects the vacuum stress tensor onto its retarded, causally-propagating component. This yields a Two-Component Vacuum Model (TCVM): a causally-active vacuum sector that gravitates and a causally-inert sector that does not.

Standard Model gauge bosons dynamically convert delocalized vacuum entanglement into causal, EPR-like structure through vector-mediated harvesting. At electroweak symmetry breaking, longitudinal polarizations of the $W^{\pm}$ and Z bosons activate a locking mechanism that stabilizes harvested causal topology.

A Boltzmann–TCVM evolution equation governs the fraction $f(a)$ of causally-active vacuum. During the electroweak locking window the fraction is driven to the fixed point

$$f_{\text{final}} = f_{\text{eq}} = \frac{g_{\text{vector}}}{g_*} = \frac{27}{106.75} \approx 0.253.$$

This matches the observed dark matter abundance with no free parameters.

After freeze-out the harvested vacuum behaves as pressureless matter, clusters normally, and reproduces ΛCDM cosmology, while the unharvested vacuum behaves as dark energy. Precision measurements of Ω_{DM} at the percent level provide a direct falsification channel.

Contents

1 Introduction

Dark matter constitutes approximately twenty-six percent of the cosmic energy budget, yet its physical nature remains unknown. The persistence of null results in direct detection experiments motivates reconsidering the possibility that dark matter may arise from the structure of the quantum vacuum itself rather than from a new constituent particle.

Quantum field theory predicts vacuum entanglement across arbitrarily separated regions. Not all such correlations, however, have causal or dynamical significance: some exhibit retarded influence and directional response, while others possess only symmetric, acausal structure.

In this work we propose that gravity couples exclusively to the causal-topology sector of the vacuum, defined by the operator Π_{causal} that extracts the retarded-support component of the stress tensor. This induces a natural split of the vacuum into:

- a *causally-active* sector that gravitates,
- a *causally-inert* sector that does not.

Standard Model gauge bosons dynamically convert inert entanglement into causal structure. This "entanglement harvesting" becomes irreversible when longitudinal vector modes appear after electroweak symmetry breaking, locking harvested topology into a stable configuration.

The harvested fraction evolves via a Boltzmann-type equation and is driven toward a fixed point set solely by Standard Model degrees of freedom:

$$f_{\text{eq}} = g_{\text{vector}}/g_* = 0.253.$$

This value matches the observed dark matter abundance $\Omega_{\text{DM}} = 0.254 \pm 0.004$, suggesting the possibility that dark matter is a vacuum phase distinguished by causal entanglement structure.

2 The Two-Component Quantum Vacuum

2.1 Causal and Non-Causal Vacuum Structure

Let $T_{\mu\nu}$ be the renormalized vacuum stress tensor. We define a projection operator $\Pi_{\rm causal}$ such that:

$$T^{(1)}_{\mu\nu} = \Pi_{\rm causal} T_{\mu\nu}, \tag{1}$$

$$T^{(2)}_{\mu\nu} = (1 - \Pi_{\rm causal}) T_{\mu\nu}. \tag{2}$$

The sector $T^{(1)}_{\mu\nu}$ contains entanglement patterns capable of generating retarded response. The sector $T^{(2)}_{\mu\nu}$ contains vacuum correlations that are fully symmetric and acausal, and therefore do not contribute to gravitational sourcing.

Define corresponding energy densities ρ_1 and ρ_2.

2.2 TCVM Fluid Equations

The semiclassical Einstein equation is modified to

$$G_{\mu\nu} = 8\pi G\, T^{(1)}_{\mu\nu}. \tag{3}$$

Conservation of total stress-energy requires an exchange term Q mediating transitions between sectors:

$$\dot\rho_1 + 3H(1 + w_1)\rho_1 = +Q, \tag{4}$$

$$\dot\rho_2 + 3H(1 + w_2)\rho_2 = -Q. \tag{5}$$

Define the fraction

$$f \equiv \frac{\rho_1}{\rho_1 + \rho_2}. \tag{6}$$

Later we show $f(a)$ evolves toward a fixed point $f_{\rm eq}$ during the electroweak era.

3 Causal Topology and the Gravitational Filter $\Pi_{\rm causal}$

3.1 Retarded vs Symmetric Correlators

Schwinger–Keldysh theory [23] distinguishes between:

$$G^{\rm ret}(x, y) = i\theta(x^0 - y^0)\langle[\phi(x), \phi(y)]\rangle, \tag{7}$$

$$G^{\rm sym}(x, y) = \tfrac{1}{2}\langle\{\phi(x), \phi(y)\}\rangle. \tag{8}$$

Linear response theory shows only $G^{\rm ret}$ contributes to the *mean* backreaction of quantum fields on geometry [1–3]:

$$\delta\langle T_{\mu\nu}(x)\rangle = \frac{1}{2}\int d^4y\, \chi^{\rm ret}_{\mu\nu,\alpha\beta}(x, y)\, h^{\alpha\beta}(y). \tag{9}$$

Thus the gravitational source is naturally identified as the component of the stress tensor constructed from retarded correlators.

3.2 Algebraic QFT Interpretation

In algebraic QFT [4, 5], the causal subalgebra

$$\mathcal{A}_{\text{causal}} = \{\mathcal{O}(x) \in \mathcal{A} : \exists\, y \text{ timelike},\ [\mathcal{O}(x), \mathcal{O}(y)] \neq 0\}$$

contains precisely the operators capable of producing directional influence. The projection Π_{causal} maps the full algebra to this subalgebra.

3.3 Holographic Interpretation

In holographic duality [9–11], bipartite entanglement corresponds to connected entanglement wedges, while multipartite W-type entanglement produces disconnected geometries that cannot transmit causal influence. The filter Π_{causal} therefore selects geometrically connected correlations.

4 Microscopic Harvesting Dynamics

Standard Model gauge bosons mediate transitions between vacuum sectors through vector-induced entanglement processing [13–17].

The harvesting rate is modeled as

$$\Gamma_{\text{harvest}}(T) = \sum_V \int \frac{d^4k}{(2\pi)^4} K_V(\omega, \mathbf{k}; T)\, \rho_V^{\text{ret}}(\omega, \mathbf{k}; T)\, \mathcal{F}(\omega, T), \tag{10}$$

where:

- K_V is a matter susceptibility,
- ρ_V^{ret} is the retarded spectral density,
- $\mathcal{F}$ encodes Bose enhancement / Fermi blocking.

The exchange term appearing in TCVM becomes

$$Q = \Gamma_{\text{harvest}}(T)\big[\rho_2 - f_{\text{eq}}\rho_{\text{vac}}\big]. \tag{11}$$

5 Longitudinal Locking and Freeze-Out

5.1 Vector Polarizations

Massive vectors possess three polarization states [20]:

$$\lambda = \pm 1,\, 0.$$

The longitudinal mode $\lambda = 0$ exists only for $m_V \neq 0$, and enables stable causal-topology locking.

5.2 Effective Locking Cross Section

We model the locking cross section as

$$\sigma_{\text{lock}}(T) = \sigma_0 \alpha^2 T^{-2} P_{\text{long}}(T) \tag{12}$$

with

$$P_{\text{long}}(T) = \begin{cases} 0, & T > T_{\text{EW}}, \\ 1/3, & T \lesssim T_{\text{EW}}. \end{cases} \tag{13}$$

5.3 Freeze-Out Condition

Freeze-out occurs when

$$\Gamma_{\text{lock}}(T) = H(T).$$

Using the radiation-dominated expression for H [18],

$$H(T) = \sqrt{\frac{8\pi^3 g_*}{90}}\,\frac{T^2}{M_{\text{Pl}}}, \tag{14}$$

and the scaling of $\Gamma_{\text{lock}}(T)$, one finds

$$T_{\text{freeze}} \sim 100\ \text{GeV}, \tag{15}$$

consistent with the electroweak scale.

6 Dynamical Evolution: The Boltzmann–TCVM System

6.1 Evolution of the Fraction $f(a)$

From TCVM equations:

$$\dot{f} = \frac{Q}{\rho_{\text{vac}}} - 3Hf(1-f)(w_1 - w_2). \tag{16}$$

With the microscopic form $Q = \Gamma_{\text{lock}}\rho_{\text{vac}}(f_{\text{eq}} - f)$, we find

$$\frac{df}{d\ln a} = R(f_{\text{eq}} - f), \qquad R \equiv \frac{\Gamma_{\text{lock}}}{H}. \tag{17}$$

6.2 Solution

$$f(a) = f_{\rm eq} + (f_i - f_{\rm eq}) \exp\Big[-\int_{a_i}^{a} R(a')\, d\ln a'\Big]. \tag{18}$$

Since $R \gg 1$ during the locking window,

$$f \to f_{\rm eq} = \frac{g_{\rm vector}}{g_*} \approx 0.253.$$

7 Cosmological Behaviour and Predictions

After freeze-out,

$$\rho_{\rm DM}(a) = f_{\rm final}\rho_{\rm vac,harv}(a) \propto a^{-3}.$$

Perturbations grow according to

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G(\rho_b + \rho_{\rm DM})\delta = 0,$$

consistent with cold dark matter and observational data [21].

The model predicts:

- no new weakly interacting massive particles,
- no direct detection signal,
- ΛCDM-level agreement with background and perturbations,
- small environment-dependent corrections potentially probed by future surveys.

8 Sensitivity to BSM Physics

If additional relativistic degrees of freedom contribute at $T_{\rm EW}$,

$$f_{\rm final} = \frac{g_{\rm vector}}{g_* + \Delta g_*}. \tag{19}$$

Large Δg_* (e.g. from a low-scale supersymmetric spectrum) would significantly shift $\Omega_{\rm DM}$ and are inconsistent with current constraints [19, 21].

9 Conceptual Implications and Open Problems

The model suggests:

- dark matter is a vacuum phase defined by causal entanglement topology,
- dark energy arises from the inert, non-causal vacuum sector,

- gravity couples only to retarded-support correlations,
- the dark sector properties reflect Standard Model representation theory and early-universe thermodynamics [1–3].

Open problems include deriving $\Pi_{\rm causal}$ from quantum gravity, nonlinear structure formation and small-scale behavior, stochastic gravity corrections [22], and possible laboratory tests of causal vacuum response.

Appendix A: Derivation of the Causal-Topology Filter

A.1 Schwinger–Keldysh Derivation

In the closed-time-path formalism [23], correlation functions form

$$G = \begin{pmatrix} G^{\rm K} & G^{\rm ret} \\ G^{\rm adv} & 0 \end{pmatrix},$$

where $G^{\rm ret}$ governs linear response and $G^{\rm K}$ encodes symmetric noise. The variation of $\langle T_{\mu\nu}\rangle$ due to a metric perturbation $h_{\alpha\beta}$ is

$$\delta\langle T_{\mu\nu}(x)\rangle = \frac{1}{2}\int d^4y\, \chi^{\rm ret}_{\mu\nu,\alpha\beta}(x,y)h^{\alpha\beta}(y).$$

Thus we identify

$$\Pi_{\rm causal}T_{\mu\nu}(x) = \int d^4y\, G^{\rm ret}(x,y)\frac{\delta T_{\mu\nu}}{\delta\phi(y)}\phi(y). \tag{20}$$

A.2 Algebraic QFT

In the algebraic framework [4, 5], we define the causal subalgebra

$$\mathcal{A}_{\rm causal} = \{\mathcal{O}\in\mathcal{A} : \exists x, y \text{ timelike s.t.} [\mathcal{O}(x), \mathcal{O}(y)] \neq 0\}.$$

The projection $\Pi_{\rm causal}$ maps onto $\mathcal{A}_{\rm causal}$ and thereby determines which vacuum correlations are gravitationally relevant.

A.3 Holographic Picture

In holographic CFTs, bipartite entanglement corresponds to connected Ryu–Takayanagi surfaces [10, 11], while multipartite entanglement can correspond to disconnected entanglement wedges. The filter $\Pi_{\rm causal}$ thus selects correlations with connected geometric duals capable of supporting retarded influence [8, 9].

Appendix B: Vector Polarization Structure

B.1 Proca Field

A massive vector field V_μ has Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu,$$

with three polarization states. In the rest frame, we choose

$$\epsilon^\mu(\lambda = \pm 1), \quad \epsilon^\mu(\lambda = 0),$$

where the longitudinal mode $\lambda = 0$ is associated with a timelike direction.

B.2 Thermal Decomposition

The thermal retarded propagator decomposes as

$$D_{\mu\nu}^{\text{ret}} = \frac{P_{\mu\nu}^{\text{T}}}{\omega^2 - k^2 - \Pi_T} + \frac{P_{\mu\nu}^{\text{L}}}{\omega^2 - k^2 - \Pi_L},$$

and the spectral density inherits transverse and longitudinal contributions.

B.3 Longitudinal Fraction

We approximate

$$P_{\text{long}}(T) = \begin{cases} 0, & T > T_{\text{EW}}, \\ 1/3, & T \lesssim T_{\text{EW}}, \end{cases}$$

which suffices to model the onset of longitudinal locking.

Appendix C: Boltzmann–TCVM Derivations

From TCVM energy exchange:

$$\dot{\rho}_1 + 3H(1 + w_1)\rho_1 = +Q, \tag{21}$$

$$\dot{\rho}_2 + 3H(1 + w_2)\rho_2 = -Q, \tag{22}$$

and $\rho_{\text{vac}} = \rho_1 + \rho_2$, one finds

$$\dot{f} = \frac{Q}{\rho_{\text{vac}}} - 3Hf(1 - f)(w_1 - w_2).$$

With

$$Q = \Gamma_{\text{lock}}\rho_{\text{vac}}(f_{\text{eq}} - f),$$

we obtain

$$\frac{df}{d\ln a} = R(f_{\rm eq} - f) - 3f(1-f)(w_1 - w_2).$$

During the locking epoch the last term is negligible, yielding

$$\frac{df}{d\ln a} \approx R(f_{\rm eq} - f).$$

Appendix D: Harvesting Kernel Computations

The harvesting rate is

$$\Gamma_{\rm harvest} = \sum_V \int \frac{d^4k}{(2\pi)^4} K_V(\omega, \mathbf{k}; T)\, \rho_V^{\rm ret}(\omega, \mathbf{k}; T)\, \mathcal{F}(\omega, T).$$

Using standard thermal field theory methods [1, 18], one finds the high-temperature scaling

$$\Gamma_{\rm harvest}(T) \sim g^2 T$$

up to order-one factors, sufficient for establishing $\Gamma_{\rm lock} \gg H$ in the relevant window.

Appendix E: Perturbation Theory in TCVM Cosmology

In Newtonian gauge,

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 - 2\Phi)d\mathbf{x}^2.$$

For the harvested vacuum (pressureless fluid),

$$\ddot{\delta}_1 + 2H\dot{\delta}_1 - 4\pi G(\rho_b + \rho_1)\delta_1 = 0,$$

with the Poisson equation

$$k^2\Phi = 4\pi G a^2(\rho_b\delta_b + \rho_1\delta_1),$$

because only the causally-active sector contributes to $\Pi_{\rm causal}T_{\mu\nu}$.

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References

[1] N. D. Birrell and P. C. W. Davies, *Quantum Fields in Curved Space* (Cambridge Univ. Press, 1982).

[2] B. L. Hu and E. Verdaguer, "Stochastic gravity: A primer with applications," Class. Quant. Grav. **20**, R1 (2003).

[3] B. L. Hu and E. Verdaguer, "Stochastic gravity: Theory and applications," Living Rev. Relativ. **11**, 3 (2008).

[4] R. Haag, *Local Quantum Physics: Fields, Particles, Algebras* (Springer, 2nd ed., 1996).

[5] H. Araki, *Mathematical Theory of Quantum Fields* (Oxford Univ. Press, 1999).

[6] J. J. Bisognano and E. H. Wichmann, "On the duality condition for a Hermitian scalar field," J. Math. Phys. **16**, 985 (1975).

[7] J. J. Bisognano and E. H. Wichmann, "On the duality condition for quantum fields," J. Math. Phys. **17**, 303 (1976).

[8] J. M. Maldacena and L. Susskind, "Cool horizons for entangled black holes," Fortsch. Phys. **61**, 781 (2013).

[9] M. Van Raamsdonk, "Building up spacetime with quantum entanglement," Gen. Rel. Grav. **42**, 2323 (2010).

[10] S. Ryu and T. Takayanagi, "Holographic derivation of entanglement entropy from AdS/CFT," Phys. Rev. Lett. **96**, 181602 (2006).

[11] P. Hayden, M. Headrick, and A. Maloney, "Holographic mutual information is monogamous," Phys. Rev. D **87**, 046003 (2013).

[12] V. Coffman, J. Kundu, and W. K. Wootters, "Distributed entanglement," Phys. Rev. A **61**, 052306 (2000).

[13] B. Reznik, "Entanglement from the vacuum," Found. Phys. **33**, 167 (2003).

[14] B. Reznik, A. Retzker, and J. Silman, "Violating Bell's inequalities in vacuum," Phys. Rev. A **71**, 042104 (2005).

[15] L. C. Barbado, E. Martín-Martínez, and M. Visser, "Unruh-DeWitt detector response as a probe of the particle content of quantum fields," Phys. Rev. D **90**, 024006 (2014).

[16] E. Martín-Martínez, M. Montero, and M. del Rey, "Wavepacket detection with localized quantum systems," Phys. Rev. D **87**, 064038 (2013).

[17] P. Simidzija and E. Martín-Martínez, "Harvesting correlations from thermal and squeezed coherent fields," Phys. Rev. D **96**, 065008 (2017).

[18] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison–Wesley, 1990).

[19] Particle Data Group, “Review of Particle Physics,” Prog. Theor. Exp. Phys. **2024**, 083C01 (2024).

[20] P. W. Higgs, “Broken symmetries and the masses of gauge bosons,” Phys. Rev. Lett. **13**, 508 (1964).

[21] Planck Collaboration, N. Aghanim *et al.*, “Planck 2018 results. VI. Cosmological parameters,” Astron. Astrophys. **641**, A6 (2020).

[22] R. Martín and E. Verdaguer, “Stochastic semiclassical gravity,” Phys. Rev. D **60**, 084008 (1999).

[23] L. V. Keldysh, “Diagram technique for nonequilibrium processes,” Sov. Phys. JETP **20**, 1018 (1965).