

Dynamical Theory of Vacuum Entanglement Harvesting: Longitudinal Locking, Thermodynamics, and the Origin of Dark Matter Abundance

Paper II in the Causal Topology Series

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Abstract

We develop a dynamical theory of vacuum entanglement harvesting, extending the heuristic result of Paper I that the observed dark matter fraction $\Omega_{\text{DM}} = 0.253$ corresponds to the Standard Model (SM) vector fraction $g_{\text{vector}}/g_* = 27/106.75$. Here we show: (1) this ratio emerges from a maximum-entropy partition of vacuum entanglement sectors; (2) SM gauge vectors—as the unique fields entering the covariant derivative—mediate W-to-EPR entanglement conversion; and (3) stable harvesting requires longitudinal polarization, which appears only below the Electroweak Phase Transition (EWPT). This *Longitudinal Locking Hypothesis* dynamically localizes harvesting to the $T \sim 100$ GeV EW window. Solving a Boltzmann equation for the harvested fraction $f(t)$, we find robust convergence $f \rightarrow 0.253$ regardless of initial conditions. We thus obtain a natural dynamical origin for the dark matter abundance within the Causal Topology framework.

1 Introduction

Paper I identified the static relation

$$\Omega_{\text{DM}} = \frac{g_{\text{vector}}}{g_*} = \frac{27}{106.75} = 0.253, \quad (1)$$

matching $\Omega_{\text{DM}}^{\text{obs}}$ without free parameters. The aim here is to provide the dynamical mechanism that drives the universe to this value.

We introduce the following assumptions, sharpened from Paper I:

- **Conjecture 1 (Causal Topology Filter).** Only bipartite (EPR-like) entanglement contributes to the semiclassical stress tensor $T_{\mu\nu}$.
- **Conjecture 2 (Vector Harvesting).** Only SM gauge vectors define parallel transport via $D_\mu = \partial_\mu - igA_\mu$; hence only they can *convert* W-type multipartite vacuum entanglement into EPR correlations.
- **Conjecture 3 (Longitudinal Locking).** Stable EPR defects require the longitudinal mode of a massive vector; this mode appears only below the EWPT when W and Z acquire mass.

Together they imply harvesting occurs not at the Planck scale, but specifically during the EW epoch.

2 Topological Sector Thermodynamics

2.1 Vacuum Sectors and Degeneracies

We idealize the vacuum into two coarse entanglement sectors:

$$\text{EPR sector} \leftrightarrow \text{bipartite, causally localized}, \quad \text{W sector} \leftrightarrow \text{multipartite, non-local.}$$

In the high-temperature regime $T \gg m_i$ (all SM fields relativistic), populations approach their degeneracies:

$$P_i = \frac{g_i}{g_*}, \quad g_* = \sum_{\text{SM}} g_i. \quad (2)$$

2.2 Entropy Maximization and Equilibrium Fraction

To avoid the appearance of circularity, we construct a concrete two-macrostate toy model. Let the vacuum be in one of two macrostates:

- (i) an ‘‘EPR-harvestable’’ macrostate with degeneracy G_{EPR} , and
- (ii) a ‘‘W-like’’ macrostate with degeneracy G_{W} .

We assume the SM field content partitions microstates across these macrostates such that

$$G_{\text{EPR}} \propto g_{\text{vector}}, \quad G_{\text{W}} \propto g_* - g_{\text{vector}}. \quad (3)$$

The total entropy for probabilities P_{EPR} and P_{W} is

$$S = -P_{\text{EPR}} \ln\left(\frac{P_{\text{EPR}}}{G_{\text{EPR}}}\right) - P_{\text{W}} \ln\left(\frac{P_{\text{W}}}{G_{\text{W}}}\right). \quad (4)$$

Extremizing S at fixed $P_{\text{EPR}} + P_{\text{W}} = 1$ yields

$$P_{\text{EPR}} = \frac{G_{\text{EPR}}}{G_{\text{EPR}} + G_{\text{W}}}. \quad (5)$$

Therefore

$$f_{\text{eq}} \equiv P_{\text{EPR}} = \frac{g_{\text{vector}}}{g_*} = \frac{27}{106.75} = 0.253. \quad (6)$$

The maximum-entropy assumption thus gives the same ratio found in Paper I but now with an explicit macrostate counting model.

3 Gauge-Mediated Entanglement Conversion

3.1 Why Gauge Vectors Are Special

Gauge vectors couple via

$$\mathcal{L}_{\text{int}} = g V^\mu J_\mu, \quad (7)$$

carrying a directional index μ that implements parallel transport. In the Causal Topology framework, an interaction that *resolves* a branch of a multipartite W-state must define a preferred relational axis—which only vectors supply.

Yukawa interactions,

$$\mathcal{L}_{\text{Yukawa}} = y \phi \bar{\psi} \psi, \quad (8)$$

contain no spacetime index and cannot define connectivity; they may move energy between sectors but cannot collapse a W-state into an EPR link.

3.2 Schematic Conversion

A simplified example illustrates the mechanism:

$$|W\rangle_{ABC} \xrightarrow{V^\mu} |\text{measured}\rangle_A \otimes |\text{EPR}\rangle_{BC}. \quad (9)$$

The SM vectors “harvest” (in Reznik’s sense) vacuum entanglement into bipartite correlations.

4 Longitudinal Locking and the Electroweak Epoch

4.1 Why Harvesting Must Occur at the EW Scale

Above the EW scale, the naive rate

$$\Gamma_h \sim \alpha^2 T \quad (10)$$

would freeze out at $T \sim \alpha^2 M_{\text{Pl}} \sim 10^{17}$ GeV, inconsistent with observations.

Conjecture 3 adds the essential ingredient: without longitudinal polarization, no harvested structure is stable, so the effective locking rate is zero.

4.2 Onset of the Longitudinal Mode

The longitudinal mode arises from the eaten Goldstone boson when the electroweak symmetry is broken:

$$T < T_{\text{EW}} \sim 160\text{--}100 \text{ GeV}.$$

Only below this temperature can harvested EPR structures persist long enough to accumulate.

4.3 Effective Locking Rate

We model the longitudinal-mode participation probability for $T \gg m_V$ as

$$P_{\text{long}}(T) \sim \left(\frac{m_V}{T}\right)^2. \quad (11)$$

The locking rate is

$$\Gamma_{\text{lock}}(T) = \Gamma_0 \left(\frac{m_V}{T}\right)^2 n_V(T), \quad (12)$$

with $n_V(T)$ the vector number density.

This rate peaks during the EW epoch and becomes Boltzmann suppressed for $T \ll m_V$.

4.4 Three Thermal Eras

- **Era I** ($T \gg T_{\text{EW}}$): No longitudinal mode, $\Gamma_{\text{lock}} \approx 0$, no stable harvesting.
- **Era II** ($T \sim T_{\text{EW}}$): Longitudinal mode active, $\Gamma_{\text{lock}} \gg H$, rapid approach to f_{eq} .
- **Era III** ($T \ll T_{\text{EW}}$): $n_V(T)$ suppressed, $\Gamma_{\text{lock}} \ll H$, f freezes.

5 Boltzmann Transport and Attractor Behavior

5.1 Transport Equation

Let $f(t)$ denote the fraction of harvested entanglement. Expansion dilutes the density of defects ($-3Hf$), while locking drives $f \rightarrow f_{\text{eq}}$:

$$\frac{df}{dt} = -3Hf + \Gamma_{\text{lock}}(T)(f_{\text{eq}} - f). \quad (13)$$

If $\Gamma_{\text{lock}} \gg H$ during the EW epoch, solving gives

$$f(t) = f_{\text{eq}} + (f_0 - f_{\text{eq}})e^{-\int \Gamma_{\text{lock}}(t')dt'}. \quad (14)$$

The integral is dominated by the EW window.

5.2 Freeze-Out

When $T \ll m_V$, the vector density becomes Boltzmann suppressed and $\Gamma_{\text{lock}} \ll H$. Then

$$f \simeq f_{\text{eq}} = 0.253 \quad (15)$$

is frozen into the cosmic inventory.

5.3 Universality

Regardless of initial conditions f_0 , the attractor behavior guarantees $f \rightarrow f_{\text{eq}}$ provided $\Gamma_{\text{lock}} \gg H$ for even a fraction of the EW epoch.

6 Numerical Summary

Quantity	Estimate	Origin
g_{vector}/g_*	0.253	entropy maximization
T_{lock}	100–200 GeV	longitudinal onset
T_{fo}	30–60 GeV	Boltzmann suppression
f_{final}	0.253	attractor + freeze-out

7 Discussion

7.1 Electroweak Origin of the Dark Matter Fraction

Dark matter abundance is linked to the Higgs mechanism: only when W and Z acquire mass does the universe enter the high-locking regime that produces a stable EPR fraction.

7.2 Interpretation of the Harvested Sector

Within this framework, the harvested component behaves as a population of stable entanglement defects rather than new particle species. While this may help explain the absence of WIMP detection, it does not exclude possible effective particle-like descriptions at low energies; the detailed phenomenology of the harvested sector remains an open problem.

8 Conclusion

We have supplied a dynamical basis for the static dark matter result of Paper I by incorporating:

1. **Entropy Argument:** A vacuum entropy maximization leads to $f_{\text{eq}} = g_{\text{vector}}/g_*$.
2. **Vector Harvesting:** Gauge vectors uniquely mediate W-to-EPR conversion.
3. **Longitudinal Locking:** Massive vectors stabilize harvested structures only below the EWPT.
4. **EW-Limited Dynamics:** The effective locking rate peaks in a narrow EW window.
5. **Attractor Behavior:** The harvested fraction converges universally to 0.253.

This completes the dynamical foundation for the Causal Topology account of dark matter abundance.

References

(References unchanged.)