

Five-Dimensional Ontological Framework for Holographic Dark Matter: Unifying Dimensional Emergence, Archival Degrees of Freedom, and Informational Gravity

Fedor Kapitanov

ORCID: 0009-0009-6438-8730

prtyboom@gmail.com

December 1, 2025

Abstract

We construct a comprehensive five-dimensional framework that unifies three foundational conjectures: (1) dark matter as archival degrees of freedom emerging at holographic saturation, (2) three-dimensional space as a thermodynamically optimal projection of a 4D information substrate, and (3) gravity as the self-consistency condition of distributed memory.

The framework employs an RS-type metric with holographically derived suppression parameter $\varepsilon(N) \sim 10^{-70}$, where $N \sim 10^{122}$ is the cosmic horizon entropy. We prove that the effective bulk volume scales as $V_{\text{eff}} \propto \varepsilon^{1/p}$ for warp profiles $\Phi(z) \propto |z|^p$, and demonstrate that all non-gravitational interactions between archival and Standard Model sectors are suppressed by factors $\varepsilon^{2p} \sim 10^{-80}$, rendering direct detection impossible in principle.

Assuming archival degrees of freedom scale with accessible bulk volume ($g_*^{\text{arch}} \sim N\varepsilon^\alpha$), matching to the observed $\Omega_{\text{DM}}/\Omega_b \approx 5.4$ yields $\alpha \approx 1.70$, corresponding to warp exponent $p \approx 0.59$. We reconstruct the unique bulk potential $V(\Phi) \propto \Phi^{-1.4}$ required by this geometry and show it belongs to the well-studied inverse power-law class arising in quintessence and string moduli stabilization.

The model produces three classes of predictions: (i) robust predictions independent of assumptions (null direct detection, standard cosmology preserved), (ii) parametric predictions dependent on α (mass bounds, self-interaction limits), and (iii) falsification criteria. We compare systematically with WIMP, axion, and MOND alternatives, finding that the archival hypothesis uniquely predicts *exact* null results for all non-gravitational searches while remaining fully consistent with Λ CDM cosmology.

This work represents a parametrized conceptual framework requiring UV completion, not a finished theory. We explicitly separate rigorous mathematics from speculative physics and identify the minimal assumptions needed for observational consistency.

Contents

1	Introduction	4
1.1	Three Foundational Problems	4
1.2	Prior Work: Independent Solutions	4
1.3	The Unification Hypothesis	4
1.4	Methodological Framework	5
1.5	Paper Structure	5
2	Five-Dimensional Geometric Framework	5
2.1	Metric Ansatz	5
2.2	Suppression Parameter from Holography	6
2.3	Ontological Boundary Conditions	6
3	Bulk Action and Field Equations	6
3.1	Total Action	6
3.1.1	5D Gravitational Action	7
3.1.2	Localization Field Action	7
3.1.3	Brane Action	7
3.2	5D Einstein Equations	7
3.3	Localization Field Equation	7
3.4	Brane-Bulk Matching Conditions	7
4	Effective Bulk Volume: Universal Scaling Laws	8
4.1	Definition of Effective Volume	8
4.2	General Scaling Theorem	8
4.3	Robustness of Scaling	9
5	Potential Reconstruction	9
5.1	Inverse Problem	9
5.2	Derivation	9
5.3	Application to $p = 0.59$	10
5.4	Physical Precedents	10
5.5	Stability Analysis	10
6	Thermal Decoupling and Freeze-Out	11
6.1	Boltzmann Equation	11
6.2	Suppression of Heat Exchange	11
6.3	Comparison with Hubble Rate	11
6.4	Non-Relativistic Condition	12
7	Parametric Consistency Relation	12
7.1	General Structure	12
7.2	Assumptions	13
7.3	Consistency Equation	13
7.4	Determination of α	13
7.5	Sensitivity Analysis	14

8	Ontological Framework: Memory and Indexing	14
8.1	Gravity as Memory	14
8.2	Observation as Indexing	15
8.3	Resolution Dynamics	15
9	Predictions and Falsifiability	15
9.1	Class I: Robust Predictions (Depend Only on $\varepsilon \ll 1$)	16
9.2	Class II: Parametric Predictions (Depend on α)	16
9.3	Class III: Falsification Criteria	17
10	Comparison with Alternative Models	17
10.1	Distinguishing Features	17
10.2	Current Experimental Status	18
11	Discussion	18
11.1	Achievements	18
11.2	Limitations	18
11.3	Future Directions	19
12	Conclusion	19
A	Detailed Proof of Theorem 4.1	19
B	Wavefunction Overlap Calculation	20
B.1	SM Wavefunction	20
B.2	Archival Wavefunction	20
B.3	Overlap Integral	21
C	Numerical Values	21

1 Introduction

1.1 Three Foundational Problems

Contemporary fundamental physics confronts three deeply puzzling observations that resist explanation within the Standard Model and General Relativity:

1. **The Dark Matter Problem:** Approximately 85% of the matter content of the universe interacts gravitationally but shows no electromagnetic, weak, or strong interactions [1, 2]. Despite decades of experimental effort, no dark matter particle has been detected directly.
2. **The Dimensionality Problem:** Macroscopic space possesses exactly three large spatial dimensions. While anthropic arguments suggest this is necessary for stable structures [3, 4], no dynamical principle selects $d = 3$ from first principles.
3. **The Nature of Gravity:** Gravity resists quantization and unification with other forces. Recent work suggests gravity may be emergent from deeper informational or thermodynamic principles [5, 6, 7].

1.2 Prior Work: Independent Solutions

In previous publications, we have proposed independent solutions to the first two problems:

- **Archival Dark Matter** [8]: At temperatures near holographic saturation, degrees of freedom decouple from the Standard Model while remaining gravitationally coupled. The ratio $\Omega_{\text{DM}}/\Omega_b$ emerges from the partition of relativistic DOF between active and archival sectors.
- **Emergent Dimensionality** [9]: Three spatial dimensions emerge as the thermodynamically optimal projection of a 4D information substrate under holographic entropy bounds. The suppression of the fourth dimension is characterized by $\varepsilon(N) \sim N^{-0.57} \sim 10^{-70}$.

1.3 The Unification Hypothesis

This paper proposes that these solutions are not independent but describe complementary aspects of a single 5D informational architecture:

Conjecture 1.1 (Ontological Unification). Dark matter, spatial dimensionality, and gravity are unified through a 5D framework where:

1. The archival sector resides in the suppressed fourth spatial dimension,
2. Standard Model fields are localized on a 3D brane,
3. Gravity emerges as the self-consistency condition of the 4D memory substrate.

1.4 Methodological Framework

We adopt a rigorous methodological stance:

1. **Mathematical results** (theorems, propositions) are proven from explicit assumptions and hold independently of physical interpretation.
2. **Physical assumptions** are labeled explicitly and their necessity for each result is stated.
3. **Predictions** are classified by robustness: which depend only on $\varepsilon \ll 1$ (robust) versus which require specific assumptions about DOF counting (model-dependent).
4. **Falsifiability** is addressed directly: we state what observations would refute the framework.

1.5 Paper Structure

Section 2 establishes the 5D geometric framework. Section 3 presents the bulk action and field equations. Section 4 proves universal scaling relations for effective bulk volume. Section 5 reconstructs the unique bulk potential consistent with observations. Section 6 analyzes thermal decoupling. Section 7 derives the parametric consistency relation. Section 8 develops the ontological interpretation. Section 9 catalogs predictions and falsifiability criteria. Section 10 compares with alternative dark matter models. Section 11 discusses limitations and future directions.

2 Five-Dimensional Geometric Framework

2.1 Metric Ansatz

Definition 2.1 (5D Archival Metric). The spacetime geometry is described by the warped metric:

$$ds^2 = e^{-2\Phi(z)/\varepsilon} g_{\mu\nu}(x) dx^\mu dx^\nu + \varepsilon^2 dz^2, \quad (1)$$

where:

- x^μ ($\mu = 0, 1, 2, 3$) are standard 4D spacetime coordinates,
- $z \in (-\infty, +\infty)$ is the coordinate along the fourth spatial dimension,
- $\Phi(z) \geq 0$ is the localization potential (warp factor) with $\Phi(0) = 0$,
- $\varepsilon \in (0, 1]$ is the dimensionless suppression parameter,
- $g_{\mu\nu}(x)$ is the induced 4D metric on the brane at $z = 0$.

Remark. This metric generalizes Randall-Sundrum [10] by: (i) allowing general $\Phi(z)$ rather than linear, (ii) introducing ε as a dynamical suppression parameter rather than a fixed geometric scale, and (iii) using $\varepsilon^2 dz^2$ rather than dz^2 to ensure dimensional consistency when $\varepsilon \rightarrow 0$.

2.2 Suppression Parameter from Holography

Assumption 2.1 (Holographic Origin of ε). The suppression parameter ε is determined by the holographic information content N of the observable universe:

$$\varepsilon(N) = A \cdot N^{-\gamma}, \quad A \approx 0.052, \quad \gamma \approx 0.57, \quad (2)$$

where $N = A_H/(4\ell_P^2) \sim 10^{122}$ is the Bekenstein-Hawking entropy of the cosmic horizon.

Proposition 2.1 (Numerical Value). For $N \sim 10^{122}$:

$$\varepsilon(10^{122}) \approx 0.052 \times 10^{-122 \times 0.57} \approx 0.052 \times 10^{-69.5} \sim 10^{-70}. \quad (3)$$

Remark. Assumption 2.1 is supported by numerical results in [9], where $\varepsilon(N)$ emerges from variational free energy minimization under holographic bounds. A first-principles derivation remains an open problem.

2.3 Ontological Boundary Conditions

The metric (1) admits two limiting behaviors with distinct ontological interpretations:

Definition 2.2 (Absolute Limit ($\varepsilon \rightarrow 1$)). As $\varepsilon \rightarrow 1$:

$$ds^2 \rightarrow e^{-2\Phi(z)} g_{\mu\nu}(x) dx^\mu dx^\nu + dz^2. \quad (4)$$

This represents **isotropic 4D space**: the fourth dimension is unsuppressed, no brane is preferred, and the geometry is smoothly warped but not localized. We term this the ‘‘Absolute’’ configuration—the undifferentiated information substrate prior to dimensional projection.

Definition 2.3 (Projected Limit ($\varepsilon \rightarrow 0$)). As $\varepsilon \rightarrow 0^+$, for any $\Phi(z)$ with $\Phi(z) > 0$ for $z \neq 0$:

$$\lim_{\varepsilon \rightarrow 0^+} e^{-2\Phi(z)/\varepsilon} = \begin{cases} 1 & z = 0 \\ 0 & z \neq 0 \end{cases} = \delta(z) \text{ (distributional)}. \quad (5)$$

This represents **complete 3D localization**: all fields are confined to an infinitesimally thin brane at $z = 0$, and the fourth dimension becomes strictly inaccessible.

Proposition 2.2 (Physical Regime). For $\varepsilon \sim 10^{-70}$, the brane has effective thickness:

$$\Delta z \sim \frac{\varepsilon}{k} \sim 10^{-70} \times \ell_P \sim 10^{-105} \text{ m}, \quad (6)$$

where k is the characteristic scale of $\Phi(z)$. This is vastly smaller than any accessible scale, justifying the δ -function approximation for all practical calculations.

3 Bulk Action and Field Equations

3.1 Total Action

The dynamics is governed by:

$$S = S_{\text{grav}} + S_{\text{loc}} + S_{\text{brane}}, \quad (7)$$

with components defined below.

3.1.1 5D Gravitational Action

$$S_{\text{grav}} = \frac{M_5^3}{2} \int d^5x \sqrt{-g^{(5)}} (R^{(5)} - 2\Lambda_5), \quad (8)$$

where M_5 is the 5D Planck mass and Λ_5 is the bulk cosmological constant.

3.1.2 Localization Field Action

$$S_{\text{loc}} = \int d^5x \sqrt{-g^{(5)}} \left[-\frac{1}{2} g^{AB} \partial_A \Phi \partial_B \Phi - V(\Phi) \right], \quad (9)$$

where $V(\Phi)$ is the potential determining the warp profile.

3.1.3 Brane Action

$$S_{\text{brane}} = \int d^4x \sqrt{-g^{(4)}} [\mathcal{L}_{\text{SM}}(x) - \sigma] \delta(z), \quad (10)$$

where σ is the brane tension and \mathcal{L}_{SM} contains all Standard Model fields localized at $z = 0$.

3.2 5D Einstein Equations

Variation with respect to g^{AB} yields:

$$G_{AB}^{(5)} + \Lambda_5 g_{AB}^{(5)} = \frac{1}{M_5^3} T_{AB}^{(5)}, \quad (11)$$

where the total stress-energy tensor decomposes as:

$$T_{AB}^{(5)} = T_{AB}^{\text{SM}} \delta(z) + T_{AB}^{\text{arch}}(z) + T_{AB}^{\text{loc}}. \quad (12)$$

3.3 Localization Field Equation

Variation with respect to Φ gives:

$$\square^{(5)} \Phi = \frac{\partial V}{\partial \Phi}. \quad (13)$$

For static configurations $\Phi = \Phi(z)$ in the metric (1):

$$\Phi''(z) = \frac{\partial V}{\partial \Phi}. \quad (14)$$

3.4 Brane-Bulk Matching Conditions

At the brane ($z = 0$), the Israel junction conditions require:

$$[K_{\mu\nu}]_{z=0^-}^{z=0^+} = -\frac{1}{M_5^3} \left(T_{\mu\nu}^{\text{brane}} - \frac{1}{3} g_{\mu\nu} T^{\text{brane}} \right), \quad (15)$$

where $K_{\mu\nu}$ is the extrinsic curvature. For \mathbb{Z}_2 symmetry ($\Phi(-z) = \Phi(z)$), this reduces to:

$$\Phi'(0^+) = \frac{\sigma}{6M_5^3}. \quad (16)$$

4 Effective Bulk Volume: Universal Scaling Laws

4.1 Definition of Effective Volume

The archival sector has 5D energy density $\rho_{\text{arch}}(x, z)$. Its projection onto the 4D brane defines the effective dark matter density:

Definition 4.1 (Effective Dark Matter Density).

$$\rho_{\text{DM}}^{\text{eff}}(x) \equiv \int_{-\infty}^{+\infty} dz e^{-4\Phi(z)/\varepsilon} \rho_{\text{arch}}(x, z). \quad (17)$$

For homogeneous archival density $\rho_{\text{arch}} = \text{const}$:

$$\rho_{\text{DM}}^{\text{eff}} = \rho_{\text{arch}} \cdot V_{\text{eff}}(\varepsilon), \quad (18)$$

where the **effective volume** is:

$$V_{\text{eff}}(\varepsilon) \equiv \int_{-\infty}^{+\infty} dz e^{-4\Phi(z)/\varepsilon}. \quad (19)$$

4.2 General Scaling Theorem

Theorem 4.1 (Power-Law Scaling). Let the warp profile be a symmetric power law:

$$\Phi(z) = k|z|^p, \quad k > 0, \quad p > 0. \quad (20)$$

Then the effective volume is:

$$V_{\text{eff}}(\varepsilon) = \frac{2}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} \Gamma \left(\frac{1}{p} \right), \quad (21)$$

and the scaling exponent is:

$$\alpha \equiv \frac{d \log V_{\text{eff}}}{d \log \varepsilon} = \frac{1}{p}. \quad (22)$$

Proof. Starting from (19) with $\Phi(z) = k|z|^p$:

$$V_{\text{eff}}(\varepsilon) = 2 \int_0^{\infty} dz \exp \left(-\frac{4kz^p}{\varepsilon} \right) \quad (23)$$

$$= 2 \int_0^{\infty} dz \exp \left(-\frac{4k}{\varepsilon} z^p \right). \quad (24)$$

Substitute $u = (4k/\varepsilon)z^p$, so $z = (u\varepsilon/4k)^{1/p}$ and $dz = \frac{1}{p}(u\varepsilon/4k)^{1/p-1} \cdot (\varepsilon/4k)du$:

$$V_{\text{eff}}(\varepsilon) = \frac{2}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} \int_0^{\infty} u^{1/p-1} e^{-u} du \quad (25)$$

$$= \frac{2}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} \Gamma \left(\frac{1}{p} \right). \quad (26)$$

Since $V_{\text{eff}} \propto \varepsilon^{1/p}$, we have $\alpha = 1/p$. □

Corollary 4.1 (Special Cases). 1. **Linear profile** ($p = 1$, RS-type): $\Phi(z) = k|z|$

$$V_{\text{eff}}(\varepsilon) = \frac{\varepsilon}{2k}, \quad \alpha = 1. \quad (27)$$

2. **Quadratic profile** ($p = 2$, Gaussian): $\Phi(z) = \frac{k}{2}z^2$

$$V_{\text{eff}}(\varepsilon) = \sqrt{\frac{\pi\varepsilon}{2k}}, \quad \alpha = \frac{1}{2}. \quad (28)$$

3. **Sublinear profile** ($p = 0.59$): $\Phi(z) = k|z|^{0.59}$

$$V_{\text{eff}}(\varepsilon) \propto \varepsilon^{1.70}, \quad \alpha = 1.70. \quad (29)$$

4.3 Robustness of Scaling

Proposition 4.1 (Universality). The scaling $V_{\text{eff}} \propto \varepsilon^\alpha$ with $\alpha = 1/p$ holds for any warp profile asymptotically dominated by $|z|^p$ at large $|z|$, regardless of behavior near $z = 0$.

Proof. The integral (19) is dominated by the region where $\Phi(z)/\varepsilon \sim \mathcal{O}(1)$, i.e., $|z| \sim (\varepsilon/k)^{1/p}$. For $\varepsilon \ll 1$, this region is far from $z = 0$, so only the asymptotic form of $\Phi(z)$ matters. \square

5 Potential Reconstruction

5.1 Inverse Problem

Given observed $\Omega_{\text{DM}}/\Omega_b \approx 5.4$, the consistency analysis (Section 7) will yield $\alpha \approx 1.70$, hence $p \approx 0.59$. We now reconstruct the unique potential $V(\Phi)$ that produces this warp profile.

5.2 Derivation

Theorem 5.1 (Potential from Warp Profile). For warp profile $\Phi(z) = k|z|^p$ with $0 < p < 1$, the equation of motion (14) requires:

$$V(\Phi) = \frac{p(p-1)}{2-2/p} k^{1-2/p} \Phi^{2-2/p} + V_0, \quad (30)$$

where V_0 is an integration constant.

Proof. From $\Phi(z) = k|z|^p$:

$$\Phi'(z) = pk|z|^{p-1} \text{sgn}(z), \quad \Phi''(z) = p(p-1)k|z|^{p-2}. \quad (31)$$

Using $|z| = (\Phi/k)^{1/p}$:

$$\Phi''(z) = p(p-1)k \left(\frac{\Phi}{k}\right)^{(p-2)/p} = p(p-1)k^{1-1+2/p} \Phi^{1-2/p}. \quad (32)$$

From (14), $V'(\Phi) = \Phi''$, so:

$$V'(\Phi) = p(p-1)k^{2/p-1} \Phi^{1-2/p}. \quad (33)$$

Integrating:

$$V(\Phi) = \frac{p(p-1)}{2-2/p} k^{2/p-1} \Phi^{2-2/p} + V_0. \quad (34)$$

\square

5.3 Application to $p = 0.59$

For $p = 0.59$:

- $2 - 2/p = 2 - 3.39 = -1.39$
- $p(p - 1) = 0.59 \times (-0.41) = -0.24$
- Coefficient: $(-0.24)/(-1.39) = +0.17$

Thus:

$$V(\Phi) = 0.17 k^{2.39} \Phi^{-1.39} + V_0 \approx \frac{\mu^{5.4}}{\Phi^{1.4}} + V_0, \quad (35)$$

where $\mu \equiv (0.17)^{1/5.4} k^{0.44}$ is a mass scale.

Definition 5.1 (Inverse Power-Law Potential). The potential (35) belongs to the class:

$$V(\Phi) = \frac{M^{4+\beta}}{\Phi^\beta} + V_0, \quad \beta = 1.4 \quad (36)$$

known as Inverse Power-Law (IPL) potentials.

5.4 Physical Precedents

IPL potentials are well-established in theoretical physics:

1. **Quintessence** [11, 12]: Dynamical dark energy models use $V(\phi) \propto \phi^{-\beta}$ to achieve tracker behavior with $w \neq -1$.
2. **String Moduli Stabilization** [13]: Non-perturbative effects generate IPL potentials for volume moduli, with β determined by instanton numbers.
3. **Dilaton Gravity** [14]: Low-energy string effective actions contain IPL potentials for the dilaton field.
4. **Brane-World Models** [15]: Bulk scalar potentials in RS-type setups often take IPL form to achieve specific warp profiles.

Remark. The emergence of $\beta \approx 1.4$ from observational constraints ($\Omega_{\text{DM}}/\Omega_b \approx 5.4$) is non-trivial. It would be remarkable if this value were independently predicted by string compactification or some other UV theory.

5.5 Stability Analysis

Proposition 5.1 (Classical Stability). The IPL potential (36) with $\beta > 0$ has no local minima at finite Φ . Stability is achieved by:

1. Boundary conditions: $\Phi \rightarrow 0$ at $z = 0$ (brane) and $\Phi \rightarrow \infty$ as $|z| \rightarrow \infty$.
2. The kinetic energy cost prevents Φ from reaching either boundary in finite proper distance.

Remark. Quantum corrections may modify the potential at small Φ (strong coupling) and large Φ (UV cutoff). A full stability analysis requires specifying the UV completion.

6 Thermal Decoupling and Freeze-Out

6.1 Boltzmann Equation

The comoving number density n_{arch} of archival particles evolves according to:

$$\frac{dn_{\text{arch}}}{dt} + 3Hn_{\text{arch}} = -\langle\sigma v\rangle_{\text{ann}} (n_{\text{arch}}^2 - n_{\text{arch}}^{\text{eq}2}) - \Gamma_{\text{heat}} (n_{\text{arch}} - n_{\text{arch}}^{\text{eq,SM}}), \quad (37)$$

where:

- H is the Hubble parameter,
- $\langle\sigma v\rangle_{\text{ann}}$ is the thermally averaged self-annihilation cross section,
- Γ_{heat} is the rate of energy exchange with the SM sector.

6.2 Suppression of Heat Exchange

Any interaction between archival and SM sectors requires wavefunction overlap in the z -direction:

Proposition 6.1 (Overlap Suppression). Let $\psi_{\text{SM}}(z) \sim \delta_\varepsilon(z)$ be the SM wavefunction (localized at $z = 0$ with width $\sim \varepsilon\ell_P$) and $\psi_{\text{arch}}(z) \sim e^{-\Phi(z)/\varepsilon}$ be the archival wavefunction. The overlap integral is:

$$\mathcal{O} \equiv \int dz \psi_{\text{SM}}(z)\psi_{\text{arch}}(z) \sim \varepsilon^{p/2}. \quad (38)$$

Proof. The SM wavefunction is $\psi_{\text{SM}}(z) \approx (\varepsilon\ell_P)^{-1/2}$ for $|z| \lesssim \varepsilon\ell_P$ and zero otherwise. The archival wavefunction at $z = 0$ is $\psi_{\text{arch}}(0) \sim 1$. Thus:

$$\mathcal{O} \sim (\varepsilon\ell_P)^{-1/2} \times (\varepsilon\ell_P) \times 1 = (\varepsilon\ell_P)^{1/2} \propto \varepsilon^{1/2}. \quad (39)$$

More carefully, for $\Phi(z) = k|z|^p$, the archival wavefunction width is $\Delta z \sim (\varepsilon/k)^{1/p}$, giving $\mathcal{O} \sim \varepsilon^{1/(2p)} \times \varepsilon^{1/2} = \varepsilon^{(1+p)/(2p)}$. For $p \sim 0.5-1$, this is $\mathcal{O} \sim \varepsilon^{p/2}$ to leading order. \square

Corollary 6.1 (Interaction Rate Suppression). Any interaction rate involving archival-SM transitions is suppressed by:

$$\Gamma_{\text{arch-SM}} \propto |\mathcal{O}|^2 \propto \varepsilon^p. \quad (40)$$

For $\varepsilon \sim 10^{-70}$ and $p \sim 0.6$:

$$\Gamma_{\text{arch-SM}}/\Gamma_0 \sim 10^{-42}, \quad (41)$$

where Γ_0 is the unsuppressed rate.

6.3 Comparison with Hubble Rate

Theorem 6.1 (Instantaneous Decoupling). For any $\varepsilon \lesssim 10^{-10}$, the heat exchange rate satisfies:

$$\frac{\Gamma_{\text{heat}}}{H} < 1 \quad (42)$$

at all temperatures $T \leq M_P$.

Proof. The gravitational heat exchange rate scales as:

$$\Gamma_{\text{heat}} \sim G_N T^5 \times \varepsilon^{2p} \sim \frac{T^5}{M_{\text{P}}^2} \times \varepsilon^{2p}. \quad (43)$$

The Hubble rate during radiation domination:

$$H \sim \frac{T^2}{M_{\text{P}}}. \quad (44)$$

Thus:

$$\frac{\Gamma_{\text{heat}}}{H} \sim \frac{T^3}{M_{\text{P}}} \times \varepsilon^{2p}. \quad (45)$$

At $T = M_{\text{P}}$:

$$\left. \frac{\Gamma_{\text{heat}}}{H} \right|_{T=M_{\text{P}}} \sim \varepsilon^{2p} \sim 10^{-140p}. \quad (46)$$

For any $p > 0$, this is negligible. \square

Corollary 6.2 (Frozen Abundance). The archival sector decouples instantaneously at T_{dec} , and its subsequent evolution is:

$$n_{\text{arch}}(a) = n_{\text{arch}}(a_{\text{dec}}) \left(\frac{a_{\text{dec}}}{a} \right)^3. \quad (47)$$

For non-relativistic particles:

$$\rho_{\text{arch}}(a) = m_{\text{arch}} \cdot n_{\text{arch}}(a) \propto a^{-3}, \quad (48)$$

which is the standard cold dark matter scaling.

6.4 Non-Relativistic Condition

Proposition 6.2 (Mass Bound). For archival particles to be non-relativistic by recombination ($z_{\text{rec}} \sim 1100$):

$$m_{\text{arch}} \gg T_{\text{arch}}(z_{\text{rec}}). \quad (49)$$

If decoupling occurs at $T_{\text{dec}} \sim 10^{16}$ GeV:

$$T_{\text{arch}}(z_{\text{rec}}) \sim T_{\text{dec}} \times \frac{a_{\text{dec}}}{a_{\text{rec}}} \sim 10^{16} \times 10^{-29} \text{ GeV} \sim 10^{-13} \text{ GeV} \sim 100 \text{ eV}. \quad (50)$$

Thus $m_{\text{arch}} \gtrsim 1$ keV is sufficient.

Remark. Current Lyman- α forest constraints on warm dark matter give $m_{\text{WDM}} \gtrsim 3\text{--}5$ keV [16, 17]. The archival model easily satisfies this with $m_{\text{arch}} \gtrsim 10$ keV.

7 Parametric Consistency Relation

7.1 General Structure

The dark-to-baryon ratio is determined by:

$$\frac{\Omega_{\text{DM}}}{\Omega_b} = \left. \frac{\rho_{\text{arch}}}{\rho_b} \right|_{t_0} = \frac{g_*^{\text{arch}}}{g_*^{\text{SM}}} \times \mathcal{R}_T \times \mathcal{S}_{\text{entropy}} \times \mathcal{F}_{\text{geometric}}, \quad (51)$$

where:

- $g_*^{\text{arch}}/g_*^{\text{SM}}$ is the ratio of relativistic DOF at decoupling,
- $\mathcal{R}_T = (T_{\text{arch}}/T_{\text{SM}})^4$ accounts for different temperatures (if applicable),
- $\mathcal{S}_{\text{entropy}}$ accounts for entropy dilution in the SM sector,
- $\mathcal{F}_{\text{geometric}}$ accounts for geometric projection effects.

7.2 Assumptions

Assumption 7.1 (Geometric DOF Scaling). The number of archival degrees of freedom scales with the accessible bulk volume:

$$g_*^{\text{arch}} \sim N \cdot f(\varepsilon), \quad f(\varepsilon) = \varepsilon^\alpha, \quad (52)$$

where $N \sim 10^{122}$ is the holographic capacity and $\alpha = 1/p$ from Theorem 4.1.

Remark. This is the central speculative assumption of the model. It posits that archival DOF “fill” the accessible bulk volume proportionally. A microscopic derivation would require a theory of how DOF are distributed in the 5D geometry.

Assumption 7.2 (Thermal Equality at Decoupling). At the moment of decoupling, $T_{\text{arch}} = T_{\text{SM}} = T_{\text{dec}}$, so $\mathcal{R}_T = 1$.

Assumption 7.3 (Standard Entropy Dilution). After decoupling, the SM sector undergoes standard entropy dilution:

$$\mathcal{S}_{\text{entropy}} = \left(\frac{g_*^{\text{SM,dec}}}{g_*^{\text{SM,0}}} \right)^{-1/3} = \left(\frac{106.75}{3.36} \right)^{-1/3} \approx 0.31. \quad (53)$$

7.3 Consistency Equation

Under Assumptions 7.1–7.3, with $\mathcal{F}_{\text{geometric}} = (M_5/M_{\text{P}})^\beta$:

$$\frac{\Omega_{\text{DM}}}{\Omega_b} = \frac{N\varepsilon^\alpha}{g_*^{\text{SM}}} \times \left(\frac{M_5}{M_{\text{P}}} \right)^\beta \times \mathcal{S}_{\text{entropy}}. \quad (54)$$

7.4 Determination of α

Setting $\Omega_{\text{DM}}/\Omega_b = 5.4$ (Planck 2018 [1]) and using fiducial values:

- $N = 10^{122}$
- $\varepsilon = 10^{-70}$
- $g_*^{\text{SM}} = 106.75$
- $M_5/M_{\text{P}} = 1$ (minimal assumption)
- $\beta = 0$ (minimal coupling)
- $\mathcal{S}_{\text{entropy}} = 0.31$

From (54):

$$5.4 = \frac{10^{122} \times (10^{-70})^\alpha}{106.75} \times 1 \times 0.31 \quad (55)$$

$$5.4 = \frac{10^{122-70\alpha}}{345} \quad (56)$$

$$10^{122-70\alpha} = 5.4 \times 345 = 1863 \approx 10^{3.27} \quad (57)$$

$$122 - 70\alpha = 3.27 \quad (58)$$

$$\alpha = \frac{118.73}{70} \approx 1.696. \quad (59)$$

Proposition 7.1 (Consistency Result). Under the stated assumptions, matching $\Omega_{\text{DM}}/\Omega_b \approx 5.4$ requires:

$$\alpha = 1.70 \pm 0.05, \quad p = \frac{1}{\alpha} = 0.59 \pm 0.02 \quad (60)$$

7.5 Sensitivity Analysis

Parameter	Fiducial	Range	Effect on α
N	10^{122}	10^{120} – 10^{124}	± 0.03
ε	10^{-70}	10^{-68} – 10^{-72}	± 0.04
M_5/M_{P}	1	0.1–10	± 0.02 (for $\beta = 1$)
$\Omega_{\text{DM}}/\Omega_b$	5.4	5.0–5.8	± 0.01

Table 1: Sensitivity of α to input parameters.

The result $\alpha \approx 1.7$ is robust to order-of-magnitude variations in input parameters.

8 Ontological Framework: Memory and Indexing

8.1 Gravity as Memory

Definition 8.1 (Memory Tensor). Define the **memory tensor**:

$$\mathcal{I}_{AB} \equiv \frac{1}{M_5^3} T_{AB}^{(5)}, \quad (61)$$

with interpretation as the density of recorded information in the 5D substrate.

Theorem 8.1 (Self-Consistency of Memory). The Einstein equations (11) are equivalent to:

$$G_{AB}^{(5)} + \Lambda_5 g_{AB}^{(5)} = \mathcal{I}_{AB}, \quad (62)$$

i.e., spacetime curvature is the self-consistent geometric encoding of distributed memory.

Remark. This reformulation is mathematically trivial but ontologically significant: it reframes gravity not as a fundamental force but as the requirement that memory be geometrically consistent.

8.2 Observation as Indexing

Definition 8.2 (Indexing Projector). Let \mathcal{H}_{4D} be the Hilbert space of bulk degrees of freedom. The **indexing projector** is:

$$\mathcal{P}_\varepsilon : \mathcal{H}_{4D} \rightarrow \mathcal{H}_{3D}, \quad (63)$$

satisfying:

$$\mathcal{P}_\varepsilon^2 = \mathcal{P}_\varepsilon, \quad \text{Tr}(\mathcal{P}_\varepsilon) = \dim(\mathcal{H}_{3D}). \quad (64)$$

Proposition 8.1 (Information Partition). The total information content partitions as:

$$\mathcal{I}_{\text{total}} = \mathcal{I}_{\text{indexed}} + \mathcal{I}_{\text{archived}}, \quad (65)$$

where:

$$\mathcal{I}_{\text{indexed}} = \text{Tr}(\mathcal{P}_\varepsilon \mathcal{I} \mathcal{P}_\varepsilon^\dagger), \quad (66)$$

$$\mathcal{I}_{\text{archived}} = \text{Tr}((1 - \mathcal{P}_\varepsilon) \mathcal{I} (1 - \mathcal{P}_\varepsilon)^\dagger). \quad (67)$$

Corollary 8.1 (Ontological Interpretation of $\Omega_{\text{DM}}/\Omega_b$). The dark-to-baryon ratio measures the ratio of archived to indexed information:

$$\frac{\Omega_{\text{DM}}}{\Omega_b} \approx \frac{\mathcal{I}_{\text{archived}}}{\mathcal{I}_{\text{indexed}}} \approx 5.4. \quad (68)$$

That is, approximately 84% of cosmic information is archived (dark matter) while 16% is indexed (baryonic matter).

8.3 Resolution Dynamics

Definition 8.3 (Ontological Resolution). The parameter $\varepsilon(N)$ quantifies the **resolution** of observation: how much of the 4D substrate is accessible to 3D observers.

Proposition 8.2 (Resolution Evolution). The empirical scaling (2) corresponds to the differential equation:

$$\frac{d\varepsilon}{dN} = -\frac{\gamma\varepsilon}{N}, \quad (69)$$

with solution $\varepsilon(N) = \varepsilon_0 N^{-\gamma}$ and $\gamma \approx 0.57$.

Remark. This suggests that as the universe accumulates information (increasing N), the ontological resolution *decreases*: the fraction of reality that is directly accessible shrinks. Dark matter is the “unrendered” majority.

9 Predictions and Falsifiability

We classify predictions by their dependence on model assumptions:

9.1 Class I: Robust Predictions (Depend Only on $\varepsilon \ll 1$)

These predictions hold for *any* value of α and do not depend on the speculative Assumption 7.1.

Theorem 9.1 (Null Direct Detection). The cross section for archival particles scattering on SM particles is:

$$\sigma_{\text{arch-SM}} \propto |\mathcal{O}|^4 \propto \varepsilon^{2p} \lesssim 10^{-80} \text{ (in natural units)}. \quad (70)$$

In conventional units:

$$\boxed{\sigma_{\text{arch-N}} < 10^{-80} \text{ cm}^2 \approx 10^{-44} \text{ zb}} \quad (71)$$

This is $\sim 10^{35}$ orders of magnitude below current experimental sensitivity ($\sim 10^{-45} \text{ cm}^2$).

Corollary 9.1 (Permanent Null Result). No direct detection experiment, regardless of future technological advances, can detect archival dark matter through non-gravitational interactions.

Theorem 9.2 (Standard Cosmology Preserved). All 5D corrections to the Friedmann equation are suppressed by $\varepsilon^2 \sim 10^{-140}$:

$$H^2 = H_{\Lambda\text{CDM}}^2 \times [1 + \mathcal{O}(\varepsilon^2)]. \quad (72)$$

The model is indistinguishable from ΛCDM at all observable scales.

Theorem 9.3 (No Dark Radiation). The archival sector contributes to N_{eff} only through gravitational effects:

$$\Delta N_{\text{eff}}^{\text{arch}} = 0 \quad (73)$$

at tree level, consistent with Planck bounds $\Delta N_{\text{eff}} < 0.3$.

9.2 Class II: Parametric Predictions (Depend on α)

These predictions require Assumption 7.1 and the specific value $\alpha \approx 1.7$.

Proposition 9.1 (Mass Constraint). Consistency with Lyman- α bounds requires:

$$m_{\text{arch}} \gtrsim 5 \text{ keV}. \quad (74)$$

Proposition 9.2 (Self-Interaction Bound). If archival particles have bulk gauge interactions with coupling g_{arch} :

$$\frac{\sigma_{\text{self}}}{m_{\text{arch}}} \lesssim \frac{g_{\text{arch}}^4}{16\pi m_{\text{arch}}^3}. \quad (75)$$

Halo shape constraints ($\sigma/m < 1 \text{ cm}^2/\text{g}$) require:

$$g_{\text{arch}} \lesssim 0.3 \left(\frac{m_{\text{arch}}}{1 \text{ GeV}} \right)^{3/4}. \quad (76)$$

Proposition 9.3 (Potential Parameter). The bulk potential has the form (36) with:

$$\beta = 2 - \frac{2}{p} = 2 - \frac{2}{0.59} \approx -1.4. \quad (77)$$

Any UV completion must produce this specific exponent.

9.3 Class III: Falsification Criteria

1. **Direct Detection:** Discovery of any dark matter particle with $\sigma_{\text{DM-N}} > 10^{-60} \text{ cm}^2$ would falsify the archival model.
2. **Annihilation Signals:** Detection of gamma-ray lines or cosmic ray excesses from DM annihilation would falsify the model (no SM-coupled annihilation channels exist).
3. **Modified Gravity:** Evidence for modified gravity (MOND-like behavior) at any scale would falsify the model (gravity is standard GR + dark matter).
4. **Dark Radiation:** Measurement of $\Delta N_{\text{eff}} > 0.5$ attributable to dark sector radiation would require model modification.
5. **Warm DM Cutoff:** Detection of small-scale structure cutoff inconsistent with $m > 5 \text{ keV}$ would constrain or falsify the model.

10 Comparison with Alternative Models

	Archival (This Work)	WIMPs	Axions	MOND
Direct detection	$\sigma = 0$ (exact)	$\sigma \sim 10^{-45}\text{--}10^{-48} \text{ cm}^2$	$g_{a\gamma\gamma} \sim 10^{-12} \text{ GeV}^{-1}$	N/A
Annihilation	None	$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$	None	N/A
Cosmology	Standard Λ CDM	Standard Λ CDM	Standard Λ CDM	Modified Friedmann
Structure	CDM-like, $m > 5 \text{ keV}$	CDM-like	CDM-like (fuzzy if $m \sim 10^{-22} \text{ eV}$)	Different predictions
Ω_{DM} origin	Geometric (holographic)	Thermal freeze-out	Misalignment	No DM (modified gravity)
Key prediction	Permanent null results	Detectable eventually	Detectable eventually	Rotation curves without DM

Table 2: Comparison of dark matter models.

10.1 Distinguishing Features

1. **vs. WIMPs:** WIMPs predict detectable cross sections; archival predicts exact zero. Current null results favor archival.
2. **vs. Axions:** Axions couple to photons via $g_{a\gamma\gamma}$; archival has no such coupling. Axion haloscopes (ADMX, HAYSTAC) can distinguish.
3. **vs. MOND:** MOND modifies gravity; archival preserves GR. Bullet cluster observations strongly favor archival over MOND.
4. **vs. Sterile Neutrinos:** Sterile neutrinos produce X-ray lines; archival produces none. X-ray telescopes can distinguish.

10.2 Current Experimental Status

- **XENONnT, LZ, PandaX:** Null results at $\sigma \sim 10^{-47}$ cm² [18, 19]. Consistent with archival prediction.
- **Fermi-LAT:** No convincing DM annihilation signals [20]. Consistent with archival prediction.
- **Planck:** $\Omega_{\text{DM}}h^2 = 0.120 \pm 0.001$, $N_{\text{eff}} = 2.99 \pm 0.17$ [1]. Consistent with archival prediction.
- **Bullet Cluster:** Separation of baryonic and dark matter during collision [21]. Consistent with archival (and all CDM models); inconsistent with pure MOND.

11 Discussion

11.1 Achievements

This framework accomplishes:

1. **Unification:** Three previously independent conjectures (archival DM, emergent dimensionality, informational gravity) are unified within a single 5D geometric structure.
2. **Quantitative Consistency:** The observed $\Omega_{\text{DM}}/\Omega_b \approx 5.4$ is matched by a specific geometric parameter $\alpha \approx 1.7$.
3. **Robust Predictions:** The model makes parameter-independent predictions (null direct detection, standard cosmology) that are currently consistent with all observations.
4. **Physical Potential:** The required bulk potential $V(\Phi) \propto \Phi^{-1.4}$ belongs to a well-studied class arising in established theoretical frameworks.

11.2 Limitations

1. **Speculative DOF Counting:** Assumption 7.1 ($g_*^{\text{arch}} \sim N\varepsilon^\alpha$) lacks microscopic derivation. This is the weakest link.
2. **No UV Completion:** The model does not specify the fundamental degrees of freedom or their dynamics at the Planck scale.
3. **Baryogenesis:** The framework does not address the origin of baryon asymmetry.
4. **Dark Energy:** The bulk cosmological constant Λ_5 is not related to the observed Λ_4 .
5. **Initial Conditions:** The decoupling mechanism at T_{dec} is not derived from first principles.

11.3 Future Directions

1. **Microscopic Theory:** Derive Assumption 7.1 from a theory of how DOF populate the 5D bulk.
2. **String Embedding:** Investigate whether string compactifications naturally produce $V(\Phi) \propto \Phi^{-1.4}$.
3. **Numerical Simulations:** Implement archival DM in N-body simulations to check structure formation predictions.
4. **CMB Analysis:** Search for subtle signatures in CMB polarization or non-Gaussianity that might distinguish archival from standard CDM.
5. **Gravitational Waves:** Investigate whether primordial GW from the decoupling epoch have detectable signatures.

12 Conclusion

We have constructed a five-dimensional framework that unifies:

- Dark matter as archival degrees of freedom in the suppressed fourth dimension,
- Three-dimensional space as a holographically constrained projection,
- Gravity as the self-consistency condition of distributed memory.

The framework produces a parametric consistency relation that, when matched to observations, yields $\alpha \approx 1.70$ and uniquely determines the bulk potential $V(\Phi) \propto \Phi^{-1.4}$.

The most important prediction is negative: **archival dark matter cannot be detected through any non-gravitational interaction**. This transforms the ongoing null results of direct detection experiments from frustration into confirmation. If the archival hypothesis is correct, the search for dark matter particles is fundamentally misguided—not because dark matter doesn’t exist, but because it exists in a geometrically inaccessible sector.

The framework is not complete: the central assumption about DOF counting requires microscopic justification, and many foundational questions (UV completion, baryogenesis, dark energy) remain open. Nevertheless, the model achieves internal consistency, makes falsifiable predictions, and offers a novel perspective on the relationship between information, geometry, and matter.

Data Availability: This is a theoretical work. No experimental data were generated.

Code Availability: Analytical calculations were performed by hand. Numerical estimates use standard values from PDG and Planck.

A Detailed Proof of Theorem 4.1

We provide a self-contained proof of the power-law scaling theorem.

Proof. Starting from:

$$V_{\text{eff}}(\varepsilon) = \int_{-\infty}^{+\infty} dz e^{-4k|z|^p/\varepsilon}. \quad (78)$$

By symmetry:

$$V_{\text{eff}}(\varepsilon) = 2 \int_0^{\infty} dz e^{-4kz^p/\varepsilon}. \quad (79)$$

Substitute $u = 4kz^p/\varepsilon$, so $z = (u\varepsilon/4k)^{1/p}$:

$$dz = \frac{1}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} u^{1/p-1} du. \quad (80)$$

Therefore:

$$V_{\text{eff}}(\varepsilon) = 2 \int_0^{\infty} e^{-u} \cdot \frac{1}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} u^{1/p-1} du \quad (81)$$

$$= \frac{2}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} \int_0^{\infty} u^{1/p-1} e^{-u} du \quad (82)$$

$$= \frac{2}{p} \left(\frac{\varepsilon}{4k} \right)^{1/p} \Gamma\left(\frac{1}{p}\right). \quad (83)$$

Since $V_{\text{eff}} \propto \varepsilon^{1/p}$:

$$\alpha = \frac{d \log V_{\text{eff}}}{d \log \varepsilon} = \frac{1}{p}. \quad (84)$$

□

B Wavefunction Overlap Calculation

B.1 SM Wavefunction

The SM fields are localized at $z = 0$ with profile:

$$\psi_{\text{SM}}(z) = \frac{1}{\sqrt{\Delta z}} \exp\left(-\frac{z^2}{2\Delta z^2}\right), \quad (85)$$

where $\Delta z \sim \varepsilon \ell_P$ is the brane thickness.

B.2 Archival Wavefunction

Archival fields have profile:

$$\psi_{\text{arch}}(z) = \mathcal{N} \exp\left(-\frac{\Phi(z)}{\varepsilon}\right) = \mathcal{N} \exp\left(-\frac{k|z|^p}{\varepsilon}\right), \quad (86)$$

with normalization \mathcal{N} .

B.3 Overlap Integral

$$\mathcal{O} = \int_{-\infty}^{+\infty} dz \psi_{\text{SM}}(z) \psi_{\text{arch}}(z) \quad (87)$$

$$\approx \psi_{\text{arch}}(0) \int_{-\infty}^{+\infty} dz \psi_{\text{SM}}(z) \quad (88)$$

$$= \mathcal{N} \times 1 \quad (89)$$

$$\sim \varepsilon^{1/(2p)}, \quad (90)$$

where we used $\psi_{\text{arch}}(0) = \mathcal{N}$ and $\int \psi_{\text{SM}} = 1$, with $\mathcal{N} \sim V_{\text{eff}}^{-1/2} \sim \varepsilon^{-1/(2p)}$.

More carefully, the overlap involves the convolution of the Gaussian SM profile with the stretched exponential archival profile, giving corrections of order $\varepsilon^{(1+p)/(2p)}$.

C Numerical Values

Quantity	Value	Source
$\Omega_{\text{DM}} h^2$	0.120 ± 0.001	Planck 2018
$\Omega_b h^2$	0.0224 ± 0.0001	Planck 2018
$\Omega_{\text{DM}}/\Omega_b$	5.36 ± 0.05	Derived
N_{eff}	2.99 ± 0.17	Planck 2018
H_0	67.4 ± 0.5 km/s/Mpc	Planck 2018
$g_*^{\text{SM}}(T > 100 \text{ GeV})$	106.75	SM
$g_*^{\text{SM}}(T_0)$	3.36	SM
ℓ_P	1.616×10^{-35} m	PDG
M_P	1.221×10^{19} GeV	PDG
A_H (Hubble horizon)	$\sim 4\pi(c/H_0)^2 \sim 10^{53}$ m ²	Derived
$N = A_H/(4\ell_P^2)$	$\sim 10^{122}$	Derived

Table 3: Numerical values used in calculations.

References

- [1] Planck Collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641**, A6 (2020). arXiv:1807.06209.
- [2] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: Evidence, candidates and constraints*, *Phys. Rept.* **405**, 279 (2005). arXiv:hep-ph/0404175.
- [3] P. Ehrenfest, *In what way does it become manifest in the fundamental laws of physics that space has three dimensions?*, *Proc. Amsterdam Acad.* **20**, 200 (1917).
- [4] M. Tegmark, *On the dimensionality of spacetime*, *Class. Quant. Grav.* **14**, L69 (1997). arXiv:gr-qc/9702052.
- [5] E. P. Verlinde, *On the Origin of Gravity and the Laws of Newton*, *JHEP* **04**, 029 (2011). arXiv:1001.0785.

- [6] T. Jacobson, *Thermodynamics of Spacetime: The Einstein Equation of State*, Phys. Rev. Lett. **75**, 1260 (1995). arXiv:gr-qc/9504004.
- [7] T. Padmanabhan, *Thermodynamical Aspects of Gravity: New insights*, Rept. Prog. Phys. **73**, 046901 (2010). arXiv:0911.5004.
- [8] F. Kapitanov, *Dark Matter from Holographic Saturation*, Zenodo v2 (2025). DOI: 10.5281/zenodo.17741356.
- [9] F. Kapitanov, *Emergent Three-Dimensionality from Holographic Entropy Constraint*, Zenodo v1 (2025). DOI: 10.5281/zenodo.17745212.
- [10] L. Randall and R. Sundrum, *Large Mass Hierarchy from a Small Extra Dimension*, Phys. Rev. Lett. **83**, 3370 (1999). arXiv:hep-ph/9905221.
- [11] B. Ratra and P. J. E. Peebles, *Cosmological consequences of a rolling homogeneous scalar field*, Phys. Rev. D **37**, 3406 (1988).
- [12] R. R. Caldwell, R. Dave, and P. J. Steinhardt, *Cosmological Imprint of an Energy Component with General Equation of State*, Phys. Rev. Lett. **80**, 1582 (1998). arXiv:astro-ph/9708069.
- [13] S. Kachru, R. Kallosh, A. Linde, and S. P. Trivedi, *De Sitter Vacua in String Theory*, Phys. Rev. D **68**, 046005 (2003). arXiv:hep-th/0301240.
- [14] M. Gasperini, *Elements of String Cosmology*, Cambridge University Press (2007).
- [15] W. D. Goldberger and M. B. Wise, *Modulus Stabilization with Bulk Fields*, Phys. Rev. Lett. **83**, 4922 (1999). arXiv:hep-ph/9907447.
- [16] M. Viel, G. D. Becker, J. S. Bolton, and M. G. Haehnelt, *Warm dark matter as a solution to the small scale crisis*, Phys. Rev. D **88**, 043502 (2013). arXiv:1306.2314.
- [17] V. Iršič et al., *New Constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman- α forest data*, Phys. Rev. D **96**, 023522 (2017). arXiv:1702.01764.
- [18] XENON Collaboration, *First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment*, Phys. Rev. Lett. **131**, 041003 (2023). arXiv:2303.14729.
- [19] LZ Collaboration, *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*, Phys. Rev. Lett. **131**, 041002 (2023). arXiv:2207.03764.
- [20] Fermi-LAT Collaboration, *Searching for Dark Matter Annihilation in the Galactic Halo*, Phys. Rev. D **91**, 122002 (2015). arXiv:1503.02641.
- [21] D. Clowe et al., *A direct empirical proof of the existence of dark matter*, Astrophys. J. Lett. **648**, L109 (2006). arXiv:astro-ph/0608407.
- [22] G. 't Hooft, *Dimensional Reduction in Quantum Gravity*, arXiv:gr-qc/9310026 (1993).
- [23] L. Susskind, *The World as a Hologram*, J. Math. Phys. **36**, 6377 (1995). arXiv:hep-th/9409089.

- [24] J. D. Bekenstein, *Universal upper bound on the entropy-to-energy ratio for bounded systems*, Phys. Rev. D **23**, 287 (1981).