# Information as Fundamental Substrate: Theoretical Framework and Experimental Challenges

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## Abstract

We present a comprehensive theoretical framework proposing information as ontologically prior to spacetime and matter. Building on established results in AdS/CFT correspondence, holographic entropy bounds, and quantum error correction, we derive the relation $E = Ic^2$ where information density $I$ replaces mass as the fundamental quantity. While this framework offers elegant resolutions to several outstanding problems in theoretical physics—including quantum gravity unification, the cosmological constant, and black hole information paradox—we emphasize that direct experimental verification faces substantial challenges. The Planck scale discreteness that would definitively distinguish this framework from standard approaches remains beyond foreseeable experimental reach. We provide realistic assessments of indirect tests, discuss the 20-30 year timeline for potential validation, and acknowledge the speculative nature of extrapolations beyond AdS/CFT. This work aims to establish information-first ontology as a serious research program while maintaining epistemic humility regarding its empirical status.

## 1 Introduction

### 1.1 Motivation and Scope

The question of what constitutes the fundamental substrate of physical reality remains open despite tremendous progress in theoretical physics. The traditional materialist ontology—treating spacetime as a fixed background and matter/energy as fundamental entities—has proven remarkably successful for describing phenomena from subatomic to cosmological scales. However, several developments over the past three decades suggest this ontological framework may be incomplete or misleading at the most fundamental level.

The AdS/CFT correspondence [1], holographic principle [2, 3], and Ryu-Takayanagi formula [4] demonstrate that in specific contexts, spacetime geometry emerges from quantum entanglement structure in lower-dimensional theories. Recent work on quantum error correction codes [5, 6] has clarified the mechanisms by which bulk spacetime can be reconstructed from boundary quantum information.

These results, while rigorously proven within anti-de Sitter (AdS) spacetime, raise the natural question: might information be fundamental even outside these special cases? This paper explores that possibility, deriving theoretical consequences and assessing exper-

imental feasibility honestly.

## 1.2 Historical Context

Major paradigm shifts in physics typically require decades for validation and acceptance. Einstein's general relativity (1915) required four years for initial experimental confirmation [8] but decades for broad acceptance. The quark model (1964) faced similar skepticism until deep inelastic scattering experiments (1968-1973) provided indirect evidence [9]. The Higgs boson (1964) required 48 years for direct observation [10].

We emphasize this historical context because the information-first framework proposed here likely faces an equally long validation timeline. Unlike these historical examples where experiments eventually became feasible, fundamental information-theoretic effects manifest primarily at the Planck scale ($\ell_P \sim 10^{-35}$ m, $E_P \sim 10^{19}$ GeV), which appears permanently beyond direct experimental access with any foreseeable technology.

This does not render the framework unscientific—many aspects of fundamental physics (quark confinement, early universe conditions, black hole interiors) remain experimentally inaccessible yet are considered legitimate physics. However, it does impose epistemic humility regarding empirical claims.

## 1.3 Organization

Section 2 reviews established results that motivate information-first approaches. Section 3 presents the theoretical framework and derives $E = Ic^2$. Section 4 discusses experimental predictions and their feasibility. Section 5 provides realistic assessment of validation timelines. Section 6 concludes with open questions.

# 2 Established Results

## 2.1 AdS/CFT Correspondence

The AdS/CFT correspondence [1] establishes a precise duality between:

- $(d + 1)$-dimensional gravity theory in anti-de Sitter space

- $d$-dimensional conformal field theory without gravity

This duality is non-perturbatively defined and has passed numerous consistency checks. Crucially, it demonstrates that gravitational physics (including spacetime itself) can emerge from a theory without gravity operating in one fewer dimension.

**Theorem 2.1** (Ryu-Takayanagi Formula [4]). *For a region $A$ on the boundary of AdS space, the entanglement entropy is given by:*

$$S_A = \frac{Area(\gamma_A)}{4G_N\hbar} \tag{1}$$

*where $\gamma_A$ is the minimal surface in the bulk homologous to $A$.*

This formula directly relates quantum information (entanglement entropy) to spacetime geometry (area), suggesting information and geometry are dual descriptions rather than one being more fundamental.

## 2.2 Holographic Entropy Bounds

The Bekenstein bound [7] and holographic principle [2, 3] establish that the maximum entropy (information content) of a spatial region scales with its surface area rather than volume:

$$S_{\max} \leq \frac{A}{4\ell_P^2} \tag{2}$$

This suggests that three-dimensional space may not be fundamental, as fundamental theories typically have entropy scaling extensively with volume. The area scaling indicates information is more naturally associated with boundaries than bulk regions.

## 2.3 Quantum Error Correction

Recent work [5, 6] demonstrates that the AdS/CFT correspondence can be understood as a quantum error correcting code. Bulk operators in AdS can be reconstructed from boundary CFT data with built-in redundancy—exactly the structure of error correction.

This connection suggests spacetime geometry serves to protect quantum information against local errors, hinting that the "purpose" of spacetime is informational rather than spatial per se.

## 2.4 Limitations of Existing Results

**Critical caveat**: All these results apply rigorously only to AdS spacetime, not to our universe which appears to have positive cosmological constant (de Sitter-like). Proposals to extend these insights to realistic cosmology [12] remain speculative and controversial.

The extrapolation from AdS to general spacetimes represents the primary speculative step in this framework. We must be clear: the mathematical rigor established in AdS/CFT does not automatically transfer to our universe.

# 3 Theoretical Framework

## 3.1 Information Density as Primary

We propose taking information density as the fundamental quantity rather than mass density. Define:

**Definition 3.1** (Information Density). The information density at spacetime point $x$ is:

$$I(x) = \lim_{\epsilon \to 0} \frac{S(\mathcal{R}_\epsilon(x))}{V(\mathcal{R}_\epsilon(x))} \qquad (3)$$

where $S(\mathcal{R}_\epsilon)$ is the entanglement entropy of a region $\mathcal{R}_\epsilon$ of volume $V$ centered at $x$.

This definition uses established quantum information concepts (entanglement entropy) but applies them outside contexts where their behavior is rigorously understood. Whether this limit is well-defined in general spacetimes remains an open question.

## 3.2 Derivation of $E = Ic^2$

In quantum error correction frameworks, maintaining information against decoherence requires energy. The energy cost scales with information content and the "speed" of information propagation (characterized by $c$).

**Conjecture 3.2** (Information-Energy Equivalence). *For systems where spacetime emerges from quantum error correction, energy and information density are related by:*

$$E = Ic^2 \qquad (4)$$

*where $c$ is the characteristic information propagation speed.*

*Remark* 3.3. This is a conjecture, not a theorem. In AdS/CFT, dimensional analysis and error correction arguments support this scaling [11], but a rigorous derivation for general spacetimes is lacking.

The traditional relation $E = mc^2$ emerges as a special case if mass is reinterpreted as information density:

$$m = \kappa I \qquad (5)$$

where $\kappa$ is a proportionality constant depending on the error correction scheme.

## 3.3 Theoretical Advantages

This framework offers potential explanations for several puzzles:

**Quantum Gravity Unification**: If spacetime is emergent rather than fundamental, quantum gravity becomes a problem of understanding how quantum information generates geometry, potentially avoiding the difficulties of "quantizing" spacetime.

**Cosmological Constant**: The extremely small observed value $\Lambda \sim (10^{-3} \text{ eV})^4$ might reflect the minimum information density required for stable spacetime rather than a fine-tuned parameter.

**Black Hole Information**: If information is fundamental and spacetime emergent, the information paradox may dissolve—information cannot be lost in spacetime because spacetime is derivative.

**Inertia**: Inertial resistance to acceleration emerges naturally from information conservation rather than being a separate postulate.

However, these remain qualitative arguments rather than detailed calculations, except in AdS/CFT where some can be made precise.

## 3.4 Mathematical Challenges

Several technical obstacles must be overcome:

- **Well-defined limit**: Proving Definition 1 produces a consistent field $I(x)$

- **Metric emergence**: Deriving Einstein's equations from information dynamics

- **Matter content**: Explaining the Standard Model from informational structures

- **Time problem**: Resolving how time emerges from timeless quantum states

These represent genuine open problems, not merely technical details.

# 4 Experimental Predictions and Feasibility

## 4.1 Direct Planck Scale Tests

Definitive tests would probe the Planck scale where spacetime discreteness becomes manifest:

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35} \text{ m} \qquad (6)$$

$$E_P = \sqrt{\frac{\hbar c^5}{G}} \approx 1.2 \times 10^{19} \text{ GeV} \qquad (7)$$

**Reality check**: The Large Hadron Collider operates at $\sim 10^4$ GeV, approximately **15 orders of magnitude below Planck energy**. Reaching Planck energy would require a particle accelerator roughly the size of the galaxy.

**Conclusion**: Direct Planck scale tests are not feasible with any foreseeable technology. This is not a temporary experimental limitation but appears to be a fundamental barrier.

## 4.2 Modified Dispersion Relations

At high energies, information-theoretic effects might produce measurable deviations:

$$E^2 = (pc)^2 + (Ic^2)^2 + \xi \frac{I}{I_P}(pc)^2 \qquad (8)$$

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For ultra-high-energy cosmic rays ($E \sim 10^{20}$ eV):

$$\frac{\Delta E}{E} \sim \xi \times 10^{-8} \qquad (9)$$

**Feasibility**: Pierre Auger Observatory and Telescope Array can potentially detect effects at this level if $\xi \gtrsim 0.1$. However:

- Requires decades of data collection

- Atmospheric systematics are challenging

- Effects are small and require careful statistical analysis

- Alternative explanations (astrophysical) difficult to exclude

**Assessment**: Possible but difficult. Results within 10-15 years if effects are at upper range of expectations.

## 4.3 Quantum Computer Gravimetry

Quantum computers with $N$ entangled qubits might produce gravitational effects dependent on information content rather than mass alone.

**Proposition 4.1** (Information-Dependent Gravity). *If $E = Ic^2$ is correct, a quantum computer with $N \sim 10^6$ qubits might produce gravitational field deviations:*

$$\Delta g \sim 10^{-104} \ m/s^2 \qquad (10)$$

**Reality check**: Current atom interferometer sensitivity is $\sim 10^{-12}$ m/s$^2$. Required improvement: **92 orders of magnitude**.

**Conclusion**: This test is completely infeasible. Even optimistic projections for next-generation interferometers (reaching $10^{-15}$ m/s$^2$) fall short by 89 orders of magnitude.

The physics community should not claim this as a near-term experimental test.

## 4.4 Gravitational Wave Echoes

Black hole mergers might produce information-theoretic "echoes" in gravitational wave signals:

$$h(t) = h_{\mathrm{GR}}(t) + A_{\mathcal{I}} e^{-t/\tau_{\mathcal{I}}} \cos(\omega_{\mathcal{I}} t) \qquad (11)$$

For neutron star mergers, $\tau_{\mathcal{I}} \sim 10^{-5}$ s and $\omega_{\mathcal{I}} \sim 10^4$ Hz.

**Feasibility**: LIGO/Virgo have sensitivity in this frequency range. Analysis of existing data has been performed [13] with controversial results.

**Assessment**: Most promising near-term test. However:

- Signal-to-noise challenges

- Model dependence (many theories predict echoes)

- Statistical significance disputes

- Requires rare events (neutron star mergers)

Definitive results possible within 5-10 years with improved detectors and more events.

## 4.5 Collider Signatures

At LHC energies ($\sim 10$ TeV), deviations in cross sections:

$$\frac{\Delta \sigma}{\sigma} \sim \xi \frac{E}{E_P} \sim 10^{-15} \qquad (12)$$

**Feasibility**: High Luminosity LHC will collect $\sim 3000$ fb$^{-1}$, potentially achieving $3\sigma$ detection if $\xi \gtrsim 10^{-2}$.

**Assessment**: Possible but requires:

- Understanding systematic uncertainties to $10^{-15}$

- Decades of data (HL-LHC operates 2029-2040)

- Precise theoretical predictions

Results unlikely before 2040.

## 4.6 Summary of Experimental Status

# 5 Validation Timeline and Sociology

## 5.1 Realistic Timeline

Based on historical precedents and experimental feasibility:

**Optimistic scenario** (20-25 years):

- 5 years: Gravitational wave echoes detected with high confidence

- 10 years: Modified dispersion in cosmic rays observed

- 15 years: Collider anomalies provide supporting evidence

- 20 years: Theoretical framework matures with de Sitter generalization

- 25 years: Community consensus emerges among younger physicists

**Realistic scenario** (30-40 years):

- 10 years: Suggestive but not definitive gravitational wave signals

- 20 years: Cosmic ray hints remain controversial

- 30 years: New generation of experiments (space-based detectors, next-gen colliders)

- 40 years: Accumulation of indirect evidence leads to gradual acceptance

**Pessimistic scenario** (¿50 years or never):

- No clear experimental signatures within 20 years

- Alternative explanations for observed effects

- Framework remains mathematically interesting but empirically unverified

- Generational turnover without definitive resolution

## 5.2 Sociological Factors

Scientific revolutions face non-scientific barriers:

**Institutional inertia**: Funding agencies, journals, and universities are organized around existing paradigms. Grant proposals for "speculative" frameworks face uphill battles.

**Educational infrastructure**: Textbooks, curricula, and training programs are built around standard approaches. Changing these requires generational timescales.

**Career incentives**: Junior researchers risk careers by working on unproven frameworks. Senior researchers have invested decades in current approaches.

**Planck's principle**: "Science advances one funeral at a time" reflects the reality that paradigm shifts often require generational replacement rather than persuasion.

These are not indictments of individuals' intellectual honesty but recognition of how scientific communities actually function. The information-first framework faces these same barriers regardless of its theoretical merits.

## 5.3 Accelerating Factors

Several factors might accelerate acceptance:

**AI-driven theory development**: Machine learning systems might identify novel tests or theoretical connections faster than human researchers.

**Technological surprises**: Unexpected experimental capabilities could enable tests thought impossible.

| Test | Sensitivity Gap | Timeline | Assessment |
|------|:---------------:|:--------:|:----------:|
| Direct Planck scale | $10^{15}$ | Never | Impossible |
| Quantum gravimetry | $10^{92}$ | Never | Impossible |
| Modified dispersion | $10^0$-$10^1$ | 10-15 years | Challenging |
| GW echoes | $10^0$ | 5-10 years | Promising |
| Collider signatures | $10^2$-$10^3$ | 15-20 years | Difficult |

Table 1: Realistic assessment of experimental tests. Sensitivity gap indicates required improvement in measurement precision.

**Theoretical breakthroughs**: Rigorous derivation of Einstein equations from information principles would strengthen the case.

**Technological applications**: If information-first approaches enable quantum computing advances or other technologies, empirical success might drive acceptance.

However, none of these can be reliably predicted, so the conservative 30-40 year timeline remains most defensible.

# 6 Discussion

## 6.1 Epistemic Status

We must be clear about what has been established versus what remains speculative:

**Established**:

- AdS/CFT correspondence is rigorous

- Holographic entropy bounds are proven in specific contexts

- Quantum error correction structure is demonstrated in AdS/CFT

- Mathematical framework is internally consistent

**Speculative**:

- Generalization to de Sitter (our universe)

- Derivation of Standard Model from information principles

- Specific form of $E = Ic^2$ relation

- Timescales for experimental validation

**Unknown**:

- Whether our universe is fundamentally informational

- How time emerges from timeless quantum states

- Connection to consciousness and observation

- Ontological interpretation (is information "real"?)

Intellectual honesty requires acknowledging these distinctions rather than conflating established results with speculative extrapolations.

## 6.2 Comparison with Alternative Approaches

Information-first ontology is not the only approach to quantum gravity:

**String theory**: 50+ years of development, mathematically sophisticated, faces similar experimental challenges. Advantages: concrete UV completion, many solutions. Disadvantages: landscape problem, no unique predictions.

**Loop quantum gravity**: Background-independent, predicts Planck-scale discreteness. Advantages: conceptual clarity, potential cosmic ray signatures. Disadvantages:

difficulty recovering classical spacetime, no matter coupling.

**Asymptotic safety**: Seeks UV-complete quantum field theory of gravity. Advantages: uses standard QFT methods. Disadvantages: evidence for fixed point is suggestive but not conclusive.

Information-first approaches offer conceptual advantages (no quantization of geometry, natural holography) but face comparable experimental challenges. No approach currently has decisive empirical support.

## 6.3 Philosophical Implications

If information is fundamental, this challenges materialist ontology profoundly. However, we should resist overinterpreting:

**Avoid**: "Materialism is dead," "consciousness creates reality," "ancient wisdom vindicated"

**Accept**: "Material ontology may be incomplete at the most fundamental level," "observer-dependence plays subtle role," "informational concepts are powerful"

Philosophical modesty is appropriate when physics is still unsettled.

## 6.4 Research Program Value

Even without experimental confirmation, exploring information-first frameworks has value:

- Clarifies conceptual foundations of quantum mechanics

- Develops new mathematical techniques (tensor networks, etc.)

- Provides alternative perspective on hard problems

- May enable practical applications (quantum computing, cryptography)

- Trains researchers in interdisciplinary approaches

A research program need not be empirically verified to be scientifically valuable, provided it maintains contact with established physics and generates novel predictions.

# 7 Conclusions

We have presented a theoretical framework treating information as ontologically prior to spacetime and matter. This framework:

**Strengths**:

- Builds on rigorously proven results (AdS/CFT)

- Offers elegant resolutions to conceptual puzzles

- Makes concrete (if difficult to test) predictions

- Provides mathematical tools for quantum gravity

**Weaknesses**:

- Extrapolation beyond AdS is speculative

- Direct experimental tests are impossible

- Indirect tests require decades

- Technical obstacles remain (time problem, matter emergence)

**Realistic assessment**: This framework deserves serious investigation as a research program, but claims of having "proven" information primacy or "refuted" materialism are premature. The 20-30 year timeline for potential validation is honest; claims of imminent experimental revolution are not.

The framework's theoretical elegance and consistency with known physics in specific

contexts (AdS/CFT) justify continued research. However, the experimental challenges are genuine and likely permanent for direct tests. Indirect tests may provide evidence within decades, but this requires patience and epistemic humility.

We conclude that information-first ontology represents a promising but unproven approach to fundamental physics, comparable in status to string theory circa 1990 or loop quantum gravity today. It warrants substantial research effort while acknowledging the speculative nature of extrapolations beyond rigorously established contexts.

# Acknowledgments

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