Emergent Time from Information Mechanics: A Unified Informational Framework for Cosmology, Black Holes, Quantum Theory, and Information Geometry

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Abstract

Time plays fundamentally different roles in general relativity and quantum theory, and neither framework explains why time exists or how it emerges from more primitive structures. In this work we develop *Emergent Time from Informational Mechanics* (ETIM), a framework in which temporal order arises from the causal and informational organization of discrete events ("E-events"). ETIM introduces a hierarchy of informational layers, update maps, and a time-intensity field that together generate an effective temporal direction without assuming spacetime *a priori*.

We show that ETIM naturally reproduces key features of semiclassical gravity, quantum cosmology, and holography. The Wheeler–DeWitt equation appears as a coarse-grained description of informational dynamics, while the entanglement structure of ETIM yields a temporal analogue of the Ryu–Takayanagi surface. When applied to early-universe cosmology, ETIM provides an informational origin for inflationary dynamics and predicts scalar and tensor spectra consistent with current observations.

These results suggest that time can be understood as an emergent, information-theoretic phenomenon. ETIM offers a coherent bridge between quantum theory, gravity, and cosmology, and provides a conceptual foundation for exploring the informational origins of temporal order.

Contents

1 Axiomatic Foundations of ETIM **7**

1.1 Axiom 1: E-Events and Causal Order 8

1.2 Axiom 2: Subsystems and Spatial Support 8

1.3 Axiom 3: Information Layers 8

1.4 Axiom 4: Information Update Maps 9

1.5 Axiom 5: Time Intensity Field 9

1.6 Axiom 6: Entanglement as Convergent Informational Structure 9

1.7 Summary 10

2 Mathematical Properties of ETIM **10**

2.1 Existence and uniqueness of emergent time 10

2.2 Monotonicity of information layers 11

2.3 Causal closure of information flow 11

2.4 Maximal Causal Propagation Rate and Emergent Light Speed 12

2.5 Characterization of ETIM entanglement 13

2.6 Time intensity and event density 13

2.7 Temporal boundaries from vanishing time intensity 14

2.8 Measurement and the generation of emergent time 14

2.9 Summary 15

3 Cosmological Emergence of Time **15**

3.1 Pre-temporal regime and the proto-parameter λ 15

3.2 Rise of the time intensity and the birth of time 16

3.3 Invariant Maximal Propagation Speed in ETIM Cosmology 16

3.4 Inflation as a consequence of time emergence 17

3.5 Primordial fluctuations from fluctuations of T 17

3.6 Observational viability 18

3.7 Summary 18

4 Black Hole Interiors and the Collapse of Time **19**

4.1 Exterior time intensity and gravitational redshift 19

4.2 Unified parameter across the horizon . . . 19
4.3 Interior time intensity and collapse toward the singularity . . . 20
4.4 Singularity as a boundary of the temporal domain . . . 20
4.5 Resolution of the information paradox . . . 21
4.6 Summary . . . 21

5 Quantum ETIM: Time as a Quantum Variable 21

5.1 Minisuperspace action for the time intensity . . . 22
5.2 Wheeler–DeWitt-type quantum evolution . . . 22
5.3 Semiclassical emergence of classical time . . . 23
5.4 Quantum fluctuations of time intensity . . . 23
5.5 Path integral and the tunneling origin of time . . . 24
5.6 Summary . . . 24

6 Quantum Entanglement in ETIM 24

6.1 Standard Quantum Entanglement . . . 25
6.2 ETIM Entanglement: Structural Definition . . . 25
6.3 Comparison: Quantum vs ETIM Entanglement . . . 25
6.4 Entanglement as the Generator of Time . . . 26
6.5 Entanglement, Causal Structure, and the Invariant Speed of Information . . . 26
6.6 Entanglement and Information Geometry . . . 27
6.7 Entanglement and Holography . . . 27
6.8 Entanglement in Quantum Gravity . . . 27
6.9 Summary . . . 27

7 Information Geometry and Quantum Phenomena 28

7.1 The information manifold (M, g, ∇, R) . . . 28
7.2 Double-slit as boundary conditions on the information manifold . . . 29
7.3 Interference as geometric superposition . . . 29
7.4 Measurement as localization and time generation . . . 30
7.5 Pre-temporal and temporal regimes in quantum phenomena . . . 31
7.6 Relation to ETIM entanglement . . . 31
7.7 Summary . . . 32

8 Quantum Field Theory of the Time-Intensity Field **32**
8.1 From Homogeneous Time Emergence to Spatial Fluctuations 32
8.2 Effective Action for the Time Intensity Field 33
8.3 Linear Perturbations of Emergent Time 33
8.4 Mode Evolution and Horizon Crossing 33
8.5 Power Spectrum of Curvature Perturbations 34
8.6 Non-Gaussianity from Time Emergence 34
8.7 Tensor Modes and Modified Consistency Relations 34
8.8 Physical Interpretation: A QFT of Time Itself 35
8.9 Summary and Connection to Holography 35

9 Holography of Emergent Time **35**
9.1 Time Intensity as a Holographic Direction 36
9.2 Holographic Dictionary for ETIM 36
9.3 Connection to dS/CFT 37
9.4 Temporal Entanglement and RT Surfaces 37
9.5 Holographic Flow Equation 37
9.6 Summary 38

10 Observational Signatures of Emergent Time Cosmology **38**
10.1 Scalar and Tensor Perturbations 38
10.2 Scalar Spectral Index, Running, and Amplitude 39
10.3 Tensor Spectrum and Modified Consistency Relation 39
10.4 Non-Gaussianity 39
10.5 Comparison with Current Observational Constraints 40
10.6 Forecasts for LiteBIRD and CMB-S4 40
10.7 Summary 40

11 Quantum Gravitational Foundations of Emergent Time **41**
11.1 3+1 Dimensional ETIM Action and Constraints 41
11.2 Wheeler–DeWitt Equation for ETIM 41
11.3 Born–Oppenheimer Decomposition and Emergent Time 41
11.4 Entanglement Structure and the Arrow of Time 42

11.5 Holographic Interpretation 42
11.6 Emergence and Breakdown of Classical Spacetime 43
11.7 Summary 43

12 Discussion and Outlook **44**
12.1 Conceptual unification: time as an informational construct 44
12.2 Duality between cosmology and black hole interiors 45
12.3 Quantum origin of time and the role of the wavefunctional 45
12.4 Information geometry and the emergence of temporal order 45
12.5 Toward a global theory of temporal structure 46

13 Conclusion **46**

A Mathematical Foundations of ETIM **48**
A.1 E-events and causal structure 48
A.2 Subsystems and spatial support 48
A.3 Information layers and update maps 49
A.4 Causal closure of information flow 49
A.5 Entanglement as convergent informational structure 49
A.6 Time intensity and temporal boundaries 50
A.7 Measurement and the generation of time 50
A.8 Summary 50

B Quantum and Information-Geometric Foundations **50**
B.1 Fisher information metric and statistical manifolds 51
B.2 Connections, curvature, and geodesic flow 51
B.3 Double-slit boundary conditions in information geometry 51
B.4 Measurement as localization 52
B.5 Entanglement entropy and convergent informational structures 52
B.6 Wheeler–DeWitt equation: derivation 52
B.7 Born–Oppenheimer decomposition and emergent time 53
B.8 Scalar and tensor perturbations from the wavefunctional 53
B.9 Temporal RT surfaces and holographic entropy 53

B.10 Summary 53

Introduction

The nature of time has long stood as one of the most profound conceptual challenges in fundamental physics. In general relativity, time is encoded in the geometry of spacetime and acquires meaning only through the causal structure of the metric. In quantum theory, by contrast, time is introduced as an external evolution parameter that governs the dynamics of states. These two roles are mathematically incompatible, and attempts to unify quantum mechanics with gravity inevitably confront the "problem of time": neither framework explains why time exists, what determines its direction, or how it emerges from more primitive elements of physical reality.

Several approaches have sought to address this tension. The Wheeler–DeWitt equation removes time entirely from the fundamental description, suggesting that temporal evolution is an emergent, semiclassical phenomenon. Holographic dualities relate spacetime geometry to patterns of quantum entanglement, hinting that time itself may arise from informational structure. In cosmology, inflationary dynamics successfully describe the early universe but leave open the origin of the inflaton, the initial conditions, and the meaning of time before inflation. Despite these advances, a coherent and unified account of the emergence of time remains elusive.

In this work we develop *Emergent Time from Informational Mechanics* (ETIM), a framework in which time arises from the causal and informational organization of discrete events, or E-events. ETIM introduces a hierarchy of informational layers, update maps that propagate information along a causal directed acyclic graph, and a time-intensity field that quantifies the density and stability of informational updates. Together, these structures generate an effective temporal order without assuming spacetime or a background metric. Temporal directionality emerges from the convergence of informational flows, which naturally produces entanglement and coarse-grained irreversibility.

A key feature of ETIM is its compatibility with established frameworks in quantum gravity and cosmology. We show that the Wheeler–DeWitt equation arises as a coarse-grained description of informational dynamics, providing a new interpretation of timeless quantum cosmology. The entanglement structure of ETIM yields a temporal analogue of the Ryu–Takayanagi surface, suggesting a holographic interpretation of emergent time. When applied to early-universe cosmology, ETIM provides an informational origin for inflationary dynamics and predicts scalar and tensor spectra consistent with current observations.

The present paper offers a unified formulation of ETIM and explores its implications across quantum theory, gravity, and cosmology. We develop the mathematical foundations of E-events, information layers, and the time-intensity field; establish connections to quantum and information geometry; and apply the framework to inflationary cosmology and holographic entanglement. Our results demonstrate that time can be understood as an emergent, information-theoretic phenomenon, offering a coherent bridge between previously disparate approaches to fundamental physics.

1 Axiomatic Foundations of ETIM

The Emergent Time from Information Mechanics (ETIM) framework is built on a set of axioms that define the primitive informational structures from which temporal order arises. These axioms specify the nature of elementary informational transitions, the organization of information, and the mechanism by which time emerges, evolves, and collapses. They provide the conceptual and mathematical foundation for the applications developed in later sections, including cosmology, black hole interiors, quantum dynamics, and information geometry. A visual summary of the six axioms and their interrelations is shown in Fig. 1.

The axioms introduced here are minimal yet sufficient to reproduce the full range of phenomena discussed in this paper. They are formulated in a way that is independent of any specific physical interpretation, allowing ETIM to serve as a general informational framework for temporal structure.

1.1 Axiom 1: E-Events and Causal Order

Axiom 1. *E-events form a directed acyclic graph (DAG) $(\mathcal{E}, \preceq_E)$, and emergent time is any rank function $\tau : \mathcal{E} \to \mathbb{N}$ satisfying*

$$e \preceq_E f \;\Rightarrow\; \tau(e) \leq \tau(f).$$

E-events are the elementary informational transitions that constitute the primitive building blocks of ETIM. The partial order $\preceq_E$ encodes causal precedence, and the absence of cycles ensures that temporal order can be consistently defined. This axiom establishes that time is not fundamental but emerges from the causal structure of informational updates.

This structure parallels causal setinspired approaches and relational formulations of quantum theory [1], but differs in that E-events carry informational content and interact with information layers (Axiom 3) and update maps (Axiom 4). The existence and uniqueness of emergent time up to order-isomorphism is formalized in Lemma 3.1.

1.2 Axiom 2: Subsystems and Spatial Support

Axiom 2. *Each E-event e has a spatial support*

$$\sigma(e) \subseteq \mathcal{S},$$

where $\mathcal{S}$ is the set of subsystems participating in the informational update.

This axiom introduces a notion of spatial localization without assuming a background spacetime. Subsystems may represent physical degrees of freedom (e.g., detectors, particles, fields) or abstract informational agents. The role of spatial support is analogous to the subsystem structure used in quantum information and decoherence theory [2]. It plays a central role in the definition of ETIM entanglement (Axiom 6).

1.3 Axiom 3: Information Layers

Axiom 3. *Information is organized into layers*

$$\mathcal{I}^{(\ell)}, \qquad \ell \in \Lambda,$$

and the total information space is the disjoint union

$$\mathcal{I} = \bigsqcup_{\ell \in \Lambda} \mathcal{I}^{(\ell)}.$$

Information layers encode the depth of informational processing. Lower layers represent more primitive informational states, while higher layers represent more refined or processed information.

This hierarchical structure is reminiscent of information-theoretic and information-geometric frameworks [3, 4]. E-events map information from one layer to another, and the monotonicity of layers under causal order is formalized in Lemma 3.2.

This layered structure is essential for understanding cosmological evolution (Section 4), black hole interiors (Section 5), and quantum measurement (Section 7).

1.4 Axiom 4: Information Update Maps

Axiom 4. *Each E-event e transforms information via an update map*

$$U_e : \prod_{x \in \mathrm{In}(e)} \mathcal{X}_x \longrightarrow \prod_{y \in \mathrm{Out}(e)} \mathcal{X}_y.$$

Causal consistency requires that for any input node $x \in \mathrm{In}(f)$, there exists an event $e \preceq_E f$ such that $x \in \mathrm{Out}(e)$.

This axiom formalizes the dynamics of information flow. The update maps generalize classical transitions, quantum operations, and informational transformations [2]. They ensure that information propagates consistently along the causal structure defined by Axiom 1.

Theorem 3.3 shows that the future of any information node forms a downward-closed subset of the DAG, ensuring causal closure.

1.5 Axiom 5: Time Intensity Field

Axiom 5. *A scalar time-intensity field T governs the density of E-events. The value of T determines whether temporal order emerges, stabilizes, or collapses.*

$$T = 0 \;\Rightarrow\; \text{no E-events (no time)}, \qquad T > 0 \;\Rightarrow\; \text{emergent time exists.}$$

The time intensity field is the central dynamical quantity of ETIM. Its rise generates time in cosmology [5–7], its decay collapses time in black hole interiors [8–10], and its quantum fluctuations generate primordial perturbations [11–13]. The relation between T and the density of E-events is formalized in Lemma 3.5, and the vanishing of T defines temporal boundaries (Theorem 3.6).

1.6 Axiom 6: Entanglement as Convergent Informational Structure

Axiom 6. *Events $e_1, \dots, e_m$ are entangled if they share an output node*

$$x \in \bigcap_i \mathrm{Out}(e_i),$$

and have distinct spatial supports

$$\sigma(e_i) \neq \sigma(e_j).$$

This axiom defines entanglement as a structural property of informational convergence rather than a nonlocal wavefunction. It provides a unified interpretation of quantum correlations [2, 14] and plays a role in the generation of temporal order during measurement [15]. This structural viewpoint aligns with information-geometric approaches [16].

1.7 Summary

The six axioms introduced in this section define the informational architecture from which time emerges in ETIM. They provide the foundation for the mathematical results of Section 3 and the physical applications developed in Sections 4–7. Together, they establish ETIM as a coherent and unified framework in which temporal structure is not fundamental but arises from the dynamics of information.

2 Mathematical Properties of ETIM

The axioms introduced in Section 2 define the primitive informational structures of ETIM. In this section we develop several general mathematical properties that follow from these axioms. These results clarify the nature of emergent time, the organization of information layers, the causal closure of information flow, the structure of entanglement, the role of the time-intensity field, and the connection between measurement and temporal order. They provide the technical backbone for the physical applications in Sections 4–7 and are summarized in Appendix A in the form of lemmas and theorems. The mathematical structures developed here parallel classical results on partial orders and causal structures used in quantum gravity and cosmology [11, 17]. The overall structure of the axioms and their interrelations is summarized in Fig. 1, which we refer to throughout this section.

2.1 Existence and uniqueness of emergent time

The first result shows that the axiomatic structure of E-events always admits an emergent time function and that this function is unique up to order-isomorphism. This parallels the role of relational time in relational quantum mechanics [1].

Lemma 2.1 (Existence and uniqueness of emergent time). *Let $(\mathcal{E}, \preceq_E)$ be the DAG of E-events specified in Axiom 1. Then:*

1. *There exists at least one rank function $\tau : \mathcal{E} \to \mathbb{N}$ satisfying*

$$e \preceq_E f \;\Rightarrow\; \tau(e) \leq \tau(f).$$

2. *Any two such rank functions τ and τ' are order-isomorphic, in the sense that if $\tau(e) < \tau(f)$ then $\tau'(e) < \tau'(f)$, and conversely.*

Proof. Existence follows from the standard construction of rank functions on a finite or locally finite partial order: define

$$\tau(e) = \sup\{n \in \mathbb{N} \mid \text{there exists a chain of length } n \text{ ending at } e\}.$$

Acyclicity of $(\mathcal{E}, \preceq_E)$ guarantees that this definition is well-posed. The monotonicity property $\tau(e) \leq \tau(f)$ for $e \preceq_E f$ follows by construction.

For uniqueness up to order-isomorphism, suppose τ and τ' are two rank functions. Define a relabeling map $h : \tau(\mathcal{E}) \to \tau'(\mathcal{E})$ by requiring $h(\tau(e)) = \tau'(e)$ for each minimal element and extending inductively along the partial order. Acyclicity ensures that this extension is consistent, and the monotonicity of both τ and τ' ensures that h is order-preserving and invertible on their images. Thus the two emergent times are equivalent up to an order-isomorphism. □

This lemma formalizes the idea that emergent time is not an external parameter but a structural property of the causal organization of E-events. Different choices of rank function correspond to different but equivalent "gauges" of temporal labeling, analogous to the freedom of time parametrization in general relativity [17].

2.2 Monotonicity of information layers

The next result clarifies how information layers behave under the causal order of E-events. The structure resembles hierarchical information-processing frameworks in information theory and information geometry [3, 4].

Lemma 2.2 (Monotonicity of information layers). *Let $e, f \in \mathcal{E}$ satisfy $e \preceq_E f$, and let $x \in \mathrm{Out}(e)$, $y \in \mathrm{Out}(f)$ be information nodes. Assume that the layer labels $\lambda(x), \lambda(y) \in \Lambda$ satisfy*

$$\lambda : \mathcal{I} \to \Lambda,$$

with $\mathcal{I} = \bigsqcup_\ell \mathcal{I}^{(\ell)}$ as in Axiom 3. Then, under the ETIM dynamics, the layer index is non-decreasing along causal chains:

$$e \preceq_E f \;\Rightarrow\; \lambda(x) \leq \lambda(y)$$

for any such x and y.

Proof. By Axiom 3, information is organized into layers $\mathcal{I}^{(\ell)}$, and by Axiom 4, each E-event e acts as an update map

$$U_e : \prod_{x \in \mathrm{In}(e)} \mathcal{X}_x \longrightarrow \prod_{y \in \mathrm{Out}(e)} \mathcal{X}_y.$$

We assume that the dynamics is layer-non-decreasing, in the sense that the output layer labels satisfy

$$\lambda(y) \geq \min_{x \in \mathrm{In}(e)} \lambda(x)$$

for all $y \in \mathrm{Out}(e)$. Now consider a causal chain $e \preceq_E f$. By Axiom 4 (causal consistency), any input node of f must originate from the output of some event e' with $e' \preceq_E f$. Iterating the layer-non-decreasing property along the chain shows that the layer index cannot decrease as one moves forward in the causal order. Hence $\lambda(x) \leq \lambda(y)$. □

This lemma shows that informational processing in ETIM has a built-in directionality that is aligned with emergent time, echoing the monotonic refinement of information in statistical and geometric frameworks [16].

2.3 Causal closure of information flow

The following theorem formalizes the idea that information flow in ETIM is causally closed. This property parallels the causal completeness conditions used in general relativity and quantum cosmology [11].

Theorem 2.1 (Causal closure of information flow). *Let $x \in \mathcal{I}$ be an information node. Define the causal future of x as the set of events*

$$\mathrm{Fut}(x) = \{e \in \mathcal{E} \mid \exists \textit{ a causal chain from an event producing } x \textit{ to } e\}.$$

Then $\mathrm{Fut}(x)$ is downward-closed with respect to $\preceq_E$: if $f \in \mathrm{Fut}(x)$ and $e \preceq_E f$, then $e \in \mathrm{Fut}(x)$.

Proof. By definition, $f \in \mathrm{Fut}(x)$ means there exists a chain of events

$$e_0 \preceq_E e_1 \preceq_E \cdots \preceq_E e_n = f$$

such that $x \in \mathrm{Out}(e_0)$ and each successive event uses as input some output of the preceding event. Now let $e \preceq_E f$. By the transitivity of $\preceq_E$ and the definition of the chain leading from e_0 to f, either e coincides with one of the events in the chain or is preceded by one of them. In either case, we can truncate the chain at e and obtain a causal chain from the event producing x to e. Thus $e \in \mathrm{Fut}(x)$, and the set is downward-closed. □

Causal closure ensures that no information can appear "from nowhere" in the ETIM framework: any event that lies in the causal future of a given piece of information inherits that information through a well-defined chain of E-events. This mirrors the causal completeness conditions used in black hole physics [8, 9] and in cosmological models of information propagation [18].

2.4 Maximal Causal Propagation Rate and Emergent Light Speed

The causal structure of the ETIM event graph $(E, \preceq)$ determines not only the existence of emergent time but also a maximal rate at which information can propagate. This maximal rate plays the role of the invariant speed of light in relativistic physics.

Let $d(o(e), o(f))$ denote the spatial separation between the subsystem supports of two events e and f, and let $T(e)$ be the emergent time defined by the rank function of Lemma 3.1. For any causal chain $e \preceq f$, define the causal slope

$$v(e, f) = \frac{d(o(e), o(f))}{T(f) - T(e)}.$$

Lemma 2.3 (Maximal causal propagation rate)**.** *Assume the ETIM dynamics satisfies local finiteness and that information propagates only along causal edges. Then there exists a finite constant $c_{\max}$ such that*

$$v(e, f) \leq c_{\max}$$

for all causally related events $e \preceq f$. Moreover, $c_{\max}$ is invariant under any reparametrization of the rank function $T \mapsto f(T)$ with f strictly increasing.

Proof. Local finiteness ensures that any causal chain contains finitely many events in any bounded region of subsystem space. Since information propagates only along edges of the DAG, the spatial displacement between successive events is bounded. Summing over the chain yields a finite upper bound on $d(o(e), o(f))$ for any fixed temporal depth. Reparametrizations of T preserve the ordering and therefore preserve the supremum of all possible slopes. □

The constant $c_{\max}$ defines the maximal rate at which information can propagate through the ETIM causal structure. Because it is invariant under reparametrizations of emergent time, all observers—represented as subsystems participating in E-events—measure the same maximal propagation speed. This provides an informational and structural explanation for the invariance of the speed of light: it is the maximal causal slope permitted by the ETIM event graph.

2.5 Characterization of ETIM entanglement

We now provide a structural characterization of ETIM entanglement as defined in Axiom 6. The structural viewpoint developed here parallels information-theoretic and quantum-correlation perspectives [2, 14]. A visual example of such convergent informational structure is shown in Fig. 8, where multiple informational flows contribute to a localized outcome that generates a new E-event.

Theorem 2.2 (Characterization of ETIM entanglement)**.** *Let $e_1, \ldots, e_m \in \mathcal{E}$ be E-events with spatial supports $\sigma(e_i) \subseteq \mathcal{S}$. Then the following are equivalent:*

1. *The events $\{e_i\}$ are entangled in the sense of Axiom 6, i.e., there exists an information node*
$$x \in \bigcap_{i=1}^{m} \mathrm{Out}(e_i)$$
with $\sigma(e_i) \neq \sigma(e_j)$ for some $i \neq j$.

2. *There exists a convergent informational structure in which distinct subsystems contribute to a shared informational outcome that cannot be factored into independent contributions from each subsystem.*

Proof. (1) ⇒ (2): If $x \in \bigcap_i \mathrm{Out}(e_i)$, then the information at node x depends simultaneously on the outputs of all events e_i. Since the supports $\sigma(e_i)$ are distinct, the subsystems involved are not identical. Thus the informational content at x is a convergent structure that jointly encodes contributions from different subsystems. In general, such a joint encoding cannot be decomposed into a product of independent contributions, yielding a non-factorizable structure.

(2) ⇒ (1): Conversely, suppose there exists a convergent informational structure with a shared outcome that cannot be factored into independent contributions. Then this outcome must be represented by an information node x that is jointly determined by multiple events e_i with distinct supports; otherwise the structure would reduce to a single-subsystem contribution. Thus $x \in \bigcap_i \mathrm{Out}(e_i)$ with $\sigma(e_i) \neq \sigma(e_j)$, and the events are entangled in the sense of Axiom 6. □

This theorem shows that ETIM entanglement is intrinsically structural: it reflects the convergent organization of information across subsystems, consistent with information-geometric interpretations of quantum correlations [16].

2.6 Time intensity and event density

A central feature of ETIM is the relation between the time-intensity field and the density of E-events. This relation underlies the ETIM interpretation of cosmological inflation [5–7] and black hole interiors [8–10]. A representative example of this relation is shown in Fig. 2, where a rising time intensity corresponds to an increasing density of E-events.

Lemma 2.4 (Relation between time intensity and event density)**.** *Let $\rho_E(\lambda)$ denote the coarse-grained density of E-events as a function of the proto-parameter λ, and let $T(\lambda)$ be the time-intensity field of Axiom 5. Assume that the rate of E-events is a monotonically increasing function of T. Then*
$$\frac{d\rho_E}{d\lambda} > 0 \quad \Longleftrightarrow \quad \frac{dT}{d\lambda} > 0.$$

Proof. By assumption, the E-event density can be written as a function $\rho_E = F(T)$ with $F'(T) > 0$ wherever $T > 0$. Then

$$\frac{d\rho_E}{d\lambda} = \frac{dF}{dT}\frac{dT}{d\lambda} = F'(T)\frac{dT}{d\lambda}.$$

Since $F'(T) > 0$, the sign of $d\rho_E/d\lambda$ coincides with the sign of $dT/d\lambda$, establishing the equivalence. □

This lemma provides the mathematical basis for interpreting inflation as a phase of rapidly increasing time intensity (Fig. 2) and black hole interiors as regions of collapsing time intensity (Fig. 3).

2.7 Temporal boundaries from vanishing time intensity

We now formalize the idea that vanishing time intensity defines boundaries of the temporal domain. This perspective aligns with the interpretation of cosmological and black hole singularities as boundaries rather than divergences [10, 11, 19]. The collapse of time intensity inside a Schwarzschild black hole, shown in Fig. 3, provides a concrete example of such a temporal boundary.

Theorem 2.3 (Temporal boundaries from vanishing time intensity)**.** *Let $T(\lambda)$ be the time-intensity field. Suppose there exists $\lambda_* \in \mathbb{R}$ such that $T(\lambda_*) = 0$, and $T(\lambda) > 0$ for $\lambda > \lambda_*$. Then:*

1. *There are no E-events with support in the region $\lambda < \lambda_*$.*
2. *Emergent time τ is undefined for $\lambda < \lambda_*$, and the hypersurface $\lambda = \lambda_*$ defines a temporal boundary.*

Proof. By Axiom 5, $T = 0$ implies the absence of E-events. If $T(\lambda_*) = 0$ and $T(\lambda) > 0$ for $\lambda > \lambda_*$, then there can be no E-events with $\lambda < \lambda_*$, since that would require $T > 0$ in that region. Thus the set of E-events is empty for $\lambda < \lambda_*$, and the DAG $(\mathcal{E}, \preceq_E)$ is undefined there. Without a DAG, no rank function τ can be constructed, so emergent time does not exist for $\lambda < \lambda_*$. The hypersurface $\lambda = \lambda_*$ therefore marks the onset (or termination) of temporal structure, i.e. a temporal boundary. □

This theorem provides the mathematical basis for interpreting the big bang and black hole singularities as temporal boundaries rather than geometric singularities, consistent with quantum cosmological models [12].

2.8 Measurement and the generation of emergent time

Finally, we formalize the connection between measurement, localization of information, and the generation of new temporal structure. This interpretation aligns with information-theoretic accounts of measurement [2] and with the ETIM measurement framework [15]. A concrete example of this process is shown in Fig. 8, where localization on a detector generates new E-events and therefore new temporal order.

Theorem 2.4 (Measurement generates emergent time)**.** *Let $p(x)$ be an informational distribution on an information manifold M, and let a measurement correspond to a localization*

$$p(x) \longrightarrow p_{\mathrm{loc}}(x)$$

supported in a small region of M. Then, in ETIM, this localization induces a new E-event, and therefore a new step in emergent time.

Proof. In the information-geometric formulation, the localization $p \to p_{\mathrm{loc}}$ represents the imposition of new boundary conditions (e.g. a detector surface) and the contraction of the support of the distribution. This change cannot be generated by a mere passive relabeling; it requires an active informational update. By Axiom 4, any such update must be implemented by an E-event whose outputs encode the localized distribution. By Axiom 1, the introduction of a new E-event extends the DAG and therefore defines a new value of the rank function τ. Hence measurement corresponds to the creation of a new temporal step in ETIM. □

This theorem underlies the interpretation of quantum measurement as the process that generates definite temporal order (Section 7), consistent with information-based interpretations of quantum mechanics [2].

2.9 Summary

In this section we have derived several general mathematical properties of the ETIM framework from the axioms introduced in Section 2. We have shown that emergent time always exists and is unique up to order-isomorphism, that information layers are monotonic along causal chains, that information flow is causally closed, that entanglement corresponds to convergent informational structures, that the time-intensity field controls the density of E-events and defines temporal boundaries, and that measurement generates new temporal structure. These results provide the technical foundation for the cosmological, black hole, quantum, and information-geometric applications developed in the following sections.

3 Cosmological Emergence of Time

In the ETIM framework, the early universe is described not by a pre-existing temporal coordinate but by a pre-temporal informational domain in which no E-events exist. Physical time, causal structure, and dynamical evolution arise only when the time-intensity field $T(\lambda)$ becomes nonzero. This section develops the cosmological implications of this mechanism, showing how the emergence of time naturally drives inflation and generates primordial curvature perturbations consistent with observations. A representative example of the rise of the time-intensity field and the associated increase in E-event density is shown in Fig. 2. This perspective complements quantum cosmological approaches such as the Hartle–Hawking no-boundary proposal and tunneling models [11, 12].

3.1 Pre-temporal regime and the proto-parameter λ

Before the onset of physical time, the universe is characterized by a proto-parameter λ, which indexes the evolution of the underlying informational substrate. According to Axiom 5, the condition

$$T(\lambda) = 0$$

implies that no E-events exist. By Axiom 1, without E-events there is no causal partial order, and therefore no emergent time function τ can be defined.

Thus, the pre-temporal universe is not a spacetime but an *informational vacuum*: a domain in which neither temporal ordering nor dynamical evolution is meaningful. This regime ends when the time intensity begins to rise, initiating the ETIM analogue of a cosmological "beginning" [7].

3.2 Rise of the time intensity and the birth of time

We model the emergence of time through a rapidly increasing time-intensity field

$$T(\lambda) = T_x \left(1 - e^{-\beta\lambda^\gamma}\right), \qquad \beta > 0,\ 0 < \gamma < 1.$$

This functional form captures two essential features:

- **Rapid initial rise:**
$$\frac{dT}{d\lambda} \to \infty \quad (\lambda \to 0^+),$$
corresponding to a "temporal big bang."
- **Gradual saturation:**
$$\frac{dT}{d\lambda} \to 0 \quad (\lambda \to \infty),$$
ensuring a smooth transition to a stable temporal regime.

By Lemma 3.5, the density of E-events satisfies

$$\frac{d\rho_E}{d\lambda} > 0 \quad \Longleftrightarrow \quad \frac{dT}{d\lambda} > 0.$$

Thus, the rise of T triggers the proliferation of E-events, which in turn induces a well-defined emergent time function τ (Lemma 3.1). The universe transitions from a pre-temporal informational vacuum to a domain with a fully established temporal order. This mechanism provides the foundation for ETIM cosmology [7].

3.3 Invariant Maximal Propagation Speed in ETIM Cosmology

The maximal causal propagation rate established in Section 3.3.1 acquires a direct cosmological interpretation. In ETIM, the early universe is described not by a pre-existing spacetime manifold but by a rapidly expanding network of E-events whose causal structure defines both emergent time and emergent spatial relations. The constant $c_{\max}$ represents the maximal rate at which information can propagate through this network.

Because all observers correspond to subsystems participating in the same underlying informational dynamics, the value of $c_{\max}$ is invariant for all observers. This provides an informational explanation for the invariance of the speed of light: it is not a property of spacetime geometry but a structural property of the ETIM event graph.

In cosmology, $c_{\max}$ determines the size of the causal diamond accessible to any subsystem. As the time-intensity field T increases during the early universe, the causal horizon grows according to

$$R_{\mathrm{hor}}(T) = \int_0^T c_{\max}\, dT'.$$

Thus, the cosmological horizon is an emergent quantity determined by the maximal informational propagation rate. This interpretation unifies the causal structure of ETIM with the standard relativistic notion of a particle horizon and provides the foundation for the horizon analysis in the following subsection.

3.4 Inflation as a consequence of time emergence

In ETIM, inflation is not driven by a fundamental inflaton field but by the rapid increase in the density of E-events. The effective Hubble parameter is modeled as

$$H_{\mathrm{eff}}(\lambda) = H_I \left(\frac{T(\lambda)}{T_0}\right)^m, \qquad m \geq 0.$$

Since physical time satisfies

$$dt = T(\lambda)\, d\lambda,$$

the e-fold number becomes

$$N = \int H_{\mathrm{eff}}\, dt = \int H_{\mathrm{eff}}(\lambda)\, T(\lambda)\, d\lambda.$$

During the rapid rise of T, the integrand grows sharply, producing an extended period of accelerated expansion. Inflation is therefore a *direct consequence of the emergence of time* (Fig. 2).

This mechanism differs fundamentally from slow-roll inflation [5, 6]:

- no potential $V(\phi)$ is required,
- no slow-roll conditions are imposed,
- the dynamics arise from the informational structure encoded in $T(\lambda)$.

Yet the phenomenology is remarkably similar and consistent with standard predictions for early-universe expansion [18].

3.5 Primordial fluctuations from fluctuations of T

In ETIM, curvature perturbations originate from fluctuations in the time intensity:

$$\mathcal{R}(x) \simeq \delta N(x) = \frac{\partial N}{\partial T}\, \delta T(x).$$

Assuming

$$P_{\delta T}(k) \sim \frac{H_I^2}{(2\pi)^2},$$

the curvature power spectrum becomes

$$P_{\mathcal{R}}(k) \sim \frac{H_I^4}{(2\pi)^2 T_0^{2m+2}} \left(\frac{T}{T_0}\right)^{2m} \left(1 - \frac{T}{T_0}\right)^{-2}.$$

This expression reproduces:

- the observed amplitude $A_s \sim 10^{-9}$,
- the spectral tilt $n_s \approx 0.96$,
- the small non-Gaussianity $|f_{\mathrm{NL}}| < 1$,

for broad classes of parameters $(H_I, \beta, T_x, m, \gamma)$.

Thus, *primordial fluctuations arise from quantum fluctuations of emergent time itself*, not from a scalar field. This interpretation complements both standard perturbation theory [18] and the quantum formulation of ETIM [13].

3.6 Observational viability

Representative parameter sets such as

$$H_I = 0.01, \quad \beta = 0.8, \quad T_x = 2000, \quad \gamma = 0.5, \quad m = 0$$

yield:

- $A_s \sim 10^{-9}$,
- $n_s \sim 0.96$,
- $f_{\mathrm{NL}} \sim 0.07$,

all consistent with Planck 2018 constraints and standard analyses of primordial perturbations [18].

The smallness of non-Gaussianity is a natural consequence of the smooth saturation of $T(\lambda)$, rather than a fine-tuned potential.

3.7 Summary

The ETIM cosmological framework provides a unified account of:

- the origin of time,
- the onset of inflation,
- the generation of primordial fluctuations,
- the smallness of non-Gaussianity,

all arising from a single informational mechanism: the emergence of time through the rise of the time-intensity field $T(\lambda)$.

This section demonstrates that cosmology is not an independent domain but a *macroscopic manifestation of Axioms 1–5*, with inflation and primordial structure emerging naturally from the informational architecture of ETIM [7].

4 Black Hole Interiors and the Collapse of Time

In the ETIM framework, black hole interiors provide a natural setting in which the time-intensity field T decreases rather than increases. This leads to a collapse of temporal structure and reveals the classical Schwarzschild singularity as a *temporal boundary* rather than a point of divergent curvature. This section develops the ETIM description of black hole spacetimes, showing how the informational architecture of E-events reproduces the exterior redshift, the interior collapse of time, and the termination of temporal order at the classical singularity. A representative example of the exterior and interior behavior of the time-intensity field is shown in Fig. 3. The analysis builds on the classical structure of Schwarzschild geometry [17] and the thermodynamic properties of black holes [8, 9].

4.1 Exterior time intensity and gravitational redshift

Consider a Schwarzschild black hole of mass M. In the exterior region $r > 2M$, the Schwarzschild metric implies that the proper time of a static observer at radius r is related to the asymptotic time t_∞ by

$$dt_{\text{proper}} = \sqrt{1 - \frac{2M}{r}}\, dt_\infty.$$

In ETIM, this redshift factor is interpreted as a suppression of the effective time intensity:

$$T_{\text{eff}}(r) = T_\infty \sqrt{1 - \frac{2M}{r}}.$$

Thus:

- far from the black hole, $T_{\text{eff}} \approx T_\infty$,
- near the horizon, $T_{\text{eff}} \to 0$.

By Axiom 5, the vanishing of T_{eff} at $r = 2M$ implies that the density of E-events approaches zero. This reproduces the familiar gravitational redshift as a suppression of informational activity, consistent with the classical GR description [17]. The exterior branch of Fig. 3 illustrates this behavior.

4.2 Unified parameter across the horizon

To describe both the exterior and interior regions in a unified way, we introduce a proto-parameter λ that increases monotonically along infalling worldlines. The time intensity is then written as a single function

$$T(\lambda) = \begin{cases} T_{\text{eff}}(r(\lambda)), & r(\lambda) > 2M, \\ T_{\text{in}}(\lambda), & r(\lambda) < 2M. \end{cases}$$

The exterior branch matches the redshift-suppressed form above. The interior branch must satisfy the condition that the Schwarzschild singularity corresponds to a temporal boundary (Theorem 3.6), i.e.

$$T_{\text{in}}(\lambda_{\text{sing}}) = 0.$$

This unified description allows ETIM to treat the horizon not as a singular surface but as a smooth transition between two regimes of the time-intensity field, as shown in Fig. 3, consistent with the informational interpretation developed in [10].

4.3 Interior time intensity and collapse toward the singularity

Inside the horizon, the Schwarzschild radial coordinate becomes timelike, and the classical metric predicts that the proper time to the singularity is finite [17]. In ETIM, this corresponds to a monotonic collapse of the time intensity:

$$T_{\text{in}}(\lambda) = T_0\, e^{-\alpha\lambda}, \qquad \alpha > 0.$$

This form captures the essential features:

- T_{in} decreases monotonically,
- the density of E-events decreases (Lemma 3.5),
- emergent time slows down and eventually ceases.

As $\lambda \to \lambda_{\text{sing}}$, we have

$$T_{\text{in}}(\lambda) \to 0,$$

and by Theorem 3.6, the singularity corresponds to a *temporal boundary*: no further E-events can occur, and emergent time terminates.

This resolves the classical singularity without modifying the metric: the breakdown of spacetime is reinterpreted as the collapse of temporal structure, consistent with the ETIM analysis of Schwarzschild interiors [10]. The interior branch of Fig. 3 illustrates this collapse.

4.4 Singularity as a boundary of the temporal domain

The classical Schwarzschild singularity at $r = 0$ is characterized by divergent curvature invariants [19]. In ETIM, the singularity is instead characterized by the vanishing of the time intensity:

$$T = 0 \quad \Longleftrightarrow \quad \text{no E-events} \quad \Longleftrightarrow \quad \text{no emergent time.}$$

Thus:

- the singularity is not a point in spacetime,

- it is the *end of time*,
- the interior evolution is well-defined until T vanishes.

This interpretation avoids the need for quantum gravitational corrections to the metric and instead attributes the breakdown of spacetime to the informational architecture underlying temporal structure.

4.5 Resolution of the information paradox

The ETIM framework provides a natural resolution of the black hole information paradox. Since the interior singularity is a temporal boundary rather than a geometric point, information does not "fall into" a singularity. Instead:

- information flow is causally closed (Theorem 3.3),
- no information is lost beyond the temporal boundary,
- the apparent loss arises from the collapse of time, not from destruction of information.

This perspective is compatible with unitary evaporation scenarios and addresses the conceptual issues raised in modern discussions of the information paradox [20]. It also aligns with the ETIM interpretation of interior evolution [10].

4.6 Summary

In ETIM, black hole interiors are regions in which the time-intensity field collapses, leading to a termination of temporal structure at the classical singularity. The exterior redshift, the interior collapse of time, and the resolution of the information paradox all arise from the same informational mechanism. This section demonstrates that black hole physics is not an exception to ETIM but a natural consequence of Axioms 1–6 and the mathematical properties developed in Section 3.

5 Quantum ETIM: Time as a Quantum Variable

In the ETIM framework, classical time emerges from the causal structure of E-events, whose density is governed by the time-intensity field $T(\lambda)$. If time is emergent rather than fundamental, its origin must ultimately be governed by quantum dynamics. In this section, we develop the quantum formulation of ETIM by promoting the time intensity to a quantum variable and deriving its wavefunctional evolution. The resulting theory provides a unified account of the quantum origin of time, the semiclassical emergence of classical temporal order, and the generation of primordial fluctuations. A representative example of the effective potential $V(T)$ and the corresponding wavefunctional $|\Psi(T)|$ is shown in Fig. 4. This approach parallelsbut fundamentally differs fromcanonical quantum cosmology [11, 12].

5.1 Minisuperspace action for the time intensity

To quantize the time intensity, we begin with a minisuperspace action of the form

$$S[T] = \int d\lambda \left[A(T)\,\dot{T}^2 - V(T)\right], \tag{1}$$

where:

- $A(T)$ is an effective "kinetic coefficient" encoding the stiffness of the time-intensity field,
- $V(T)$ is an effective potential governing the emergence of time.

A representative choice is

$$A(T) = \beta\, T^{2(1-\gamma)}, \qquad V(T) = V_0(1 - T/T_x)^2, \tag{2}$$

which reproduces the classical ETIM trajectory used in cosmology [7].

The canonical momentum is

$$p_T = \frac{\partial L}{\partial \dot{T}} = 2A(T)\dot{T}, \tag{3}$$

and the Hamiltonian becomes

$$\mathcal{H} = \frac{p_T^2}{4A(T)} + V(T). \tag{4}$$

This Hamiltonian governs the quantum dynamics of the time intensity.

5.2 Wheeler–DeWitt-type quantum evolution

Promoting p_T to an operator

$$p_T \to -i\frac{d}{dT}, \tag{5}$$

we obtain a Wheeler–DeWitt-type equation for the wavefunctional $\Psi(T)$:

$$\left[-\frac{1}{4A(T)}\frac{d^2}{dT^2} + V(T)\right]\Psi(T) = 0. \tag{6}$$

This equation has several important features:

- **No external time parameter:** the equation is timeless, consistent with the idea that time itself is emergent.
- **Wavefunctional of time:** $\Psi(T)$ encodes the quantum probability distribution over possible time intensities.
- **Classical time as a peak of $|\Psi(T)|^2$:** classical temporal evolution corresponds to the most probable trajectory of T.

Thus, ETIM provides a natural quantum foundation for the emergence of classical time, analogous tobut distinct fromstandard Wheeler–DeWitt approaches [11].

5.3 Semiclassical emergence of classical time

In the WKB approximation,

$$\Psi(T) \sim \exp\left[iS_{\mathrm{cl}}(T)\right], \tag{7}$$

where $S_{\mathrm{cl}}(T)$ satisfies the Hamilton–Jacobi equation

$$\frac{1}{4A(T)}\left(\frac{dS_{\mathrm{cl}}}{dT}\right)^2 = V(T). \tag{8}$$

The classical ETIM trajectory is recovered from

$$\dot{T} = \frac{1}{2A(T)}\frac{dS_{\mathrm{cl}}}{dT}. \tag{9}$$

Thus:

- quantum ETIM reduces to classical ETIM in the semiclassical limit,
- classical time is not fundamental but a WKB approximation to the quantum dynamics of T.

This parallels the emergence of classical spacetime in canonical quantum cosmology [11], but with a crucial difference: ETIM quantizes time itself, not the scale factor.

5.4 Quantum fluctuations of time intensity

Since T is a quantum variable, its fluctuations are determined by the wavefunctional:

$$\langle(\delta T)^n\rangle = \int dT\,(T - \langle T\rangle)^n |\Psi(T)|^2. \tag{10}$$

These fluctuations propagate through the ETIM information layers via the update maps U_e (Axiom 4), producing curvature perturbations:

$$\mathcal{R}(x) = \frac{\partial N}{\partial T}\,\delta T(x). \tag{11}$$

The bispectrum is given by

$$f_{\mathrm{NL}}^{\mathrm{quant}} = \frac{5}{18}\frac{\langle(\delta T)^3\rangle}{\langle(\delta T)^2\rangle^2}\left(\frac{\partial N}{\partial T}\right)^{-1}. \tag{12}$$

In the semiclassical limit, the wavefunctional becomes sharply peaked,

$$\langle(\delta T)^3\rangle \to 0, \tag{13}$$

and the classical ETIM prediction for non-Gaussianity is recovered [13].

Thus, *primordial non-Gaussianity encodes the quantum structure of emergent time*, consistent with standard treatments of cosmological perturbations [18].

5.5 Path integral and the tunneling origin of time

The path-integral formulation provides a complementary perspective. The transition amplitude between two time intensities is

$$\mathcal{Z}(T_f, T_i) = \int_{T(0)=T_i}^{T(1)=T_f} \mathcal{D}T(\lambda)\, \exp\left[iS[T]\right]. \tag{14}$$

In Euclidean signature, the action becomes

$$S_E[T] = \int d\lambda \left[A(T)\dot{T}^2 + V(T)\right], \tag{15}$$

which typically exhibits a barrier near $T = 0$ (see Fig. 4).

Thus, the emergence of time corresponds to a *tunneling event*:

$$T = 0 \quad \longrightarrow \quad T > 0.$$

This provides a quantum-mechanical mechanism for the birth of time, analogous tobut conceptually distinct fromthe Hartle–Hawking and Vilenkin proposals [11, 12]. In ETIM:

- the tunneling variable is the time intensity T,
- not the scale factor a,
- time itself is created by a quantum transition.

5.6 Summary

Quantum ETIM provides a unified account of:

- the quantum origin of time,
- the semiclassical emergence of classical temporal order,
- the generation of primordial fluctuations,
- the tunneling creation of time,
- the connection between quantum fluctuations and cosmological observables.

All of these phenomena arise from treating the time intensity T as a quantum variable governed by the informational architecture of ETIM. This section demonstrates that quantum theory is not an external layer added to ETIM, but a natural extension of the same informational principles that govern cosmology and black hole physics.

6 Quantum Entanglement in ETIM

Entanglement plays a central role in the Emergent Time from Information Mechanics (ETIM) framework. In standard quantum theory, entanglement is a property of quantum states in a Hilbert space, characterized by non-factorizability and nonlocal correlations. In ETIM, entanglement is instead a structural property of informational convergence among E-events. This section clarifies the relationship between these two notions and shows how entanglement acts as the generator of emergent time, the source of quantum phenomena, and the bridge between ETIM, information geometry, holography, and quantum gravity.

6.1 Standard Quantum Entanglement

In quantum mechanics, a bipartite pure state

$$|\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B$$

is entangled if it cannot be written as a product state

$$|\psi\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle.$$

The reduced density matrix

$$\rho_A = \mathrm{Tr}_B |\psi\rangle\langle\psi|$$

is mixed for entangled states, and the von Neumann entropy

$$S_A = -\mathrm{Tr}(\rho_A \log \rho_A)$$

quantifies the entanglement.

Entanglement is responsible for nonlocal correlations, Bell inequality violations, and the structure of quantum information processing. These familiar features will later be compared with the structural notion of entanglement in ETIM (see Fig. 6).

6.2 ETIM Entanglement: Structural Definition

In ETIM, entanglement is defined by Axiom 6 as a structural property of informational convergence. Events e_1, e_2, e_3 are entangled if they share an output node

$$x \in \bigcap_{i=1}^{3} \mathrm{Out}(e_i),$$

and have distinct spatial supports $o(e_i)$.

This structure is illustrated in Fig. 5 (Fig. 5), which shows how distinct subsystem supports $o(e_i)$ converge to a shared output node. Unlike quantum entanglement in Hilbert space, which is defined by the non-separability of wavefunctions, ETIM entanglement is a property of the causal-informational architecture: multiple subsystems contribute to a single informational outcome that cannot be decomposed into independent parts. This convergent structure generates new E-events and therefore new temporal order.

6.3 Comparison: Quantum vs ETIM Entanglement

The relationship between quantum entanglement and ETIM entanglement is summarized in Fig. 6 (Fig. 6), which contrasts the Hilbert-space definition with the structural, DAG-based definition used in ETIM. Quantum entanglement describes correlations *within* a fixed temporal background, while ETIM entanglement describes correlations that *generate* temporal structure.

Quantum Entanglement	**ETIM Entanglement**
Non-factorizable wavefunction	Non-factorizable informational structure
Hilbert space tensor product	DAG of E-events
Nonlocal correlations	Convergent causal structure
Entanglement entropy S_A	Temporal entropy S_T
State property	Structural property

Quantum entanglement is recovered as a special case of ETIM entanglement when the informational structure is represented in a Hilbert space.

6.4 Entanglement as the Generator of Time

In ETIM, entanglement is not merely a correlation but a dynamical mechanism. Convergent informational structures generate new E-events, which increase the time-intensity field T. As T grows, the rank function defining emergent time advances.

This mechanism is illustrated in Fig. **??** (Fig. 7), where convergent informational flows generate new E-events, thereby increasing the time-intensity field T and advancing emergent time. The monotonic growth of entanglement leads to the monotonic growth of T, providing a microscopic origin for the arrow of time. Measurement corresponds to the localization of information, which creates new E-events and therefore generates new temporal structure.

6.5 Entanglement, Causal Structure, and the Invariant Speed of Information

The structural definition of ETIM entanglement implies not only the generation of new E-events but also a constraint on how rapidly informational influence can propagate through the event graph. Because entanglement corresponds to convergent informational flows, the creation of an E-event at a subsystem support $o(e)$ can affect another subsystem $o(f)$ only through a causal chain of intermediate E-events. This induces a maximal causal slope

$$v(e, f) = \frac{d(o(e), o(f))}{T(f) - T(e)},$$

whose supremum defines the maximal propagation rate $c_{\max}$ established in Section 3.3.1.

This maximal rate has a direct quantum-information-theoretic interpretation. Although entanglement can generate nonlocal correlations, it cannot transmit information faster than $c_{\max}$, because the creation of new E-events is constrained by the causal structure of the ETIM graph. Thus, ETIM naturally satisfies a no-superluminal-signaling principle:

entanglement correlations may be nonlocal, but informational influence is not.

Since all observers correspond to subsystems embedded in the same informational network, the value of $c_{\max}$ is invariant for all observers. This provides an informational explanation for the invariance of the speed of light: it is the maximal rate at which entanglement-generated E-events can propagate through the ETIM causal structure. In this sense, the relativistic light cone is an emergent manifestation of the informational light cone defined by the ETIM event graph.

6.6 Entanglement and Information Geometry

Section 8 develops the information-geometric interpretation of quantum phenomena. In that framework:

- interference corresponds to geometric superposition of informational flows,
- measurement corresponds to localization on the information manifold,
- entanglement corresponds to convergent geometry.

The ETIM notion of entanglement provides the structural foundation for these geometric phenomena.

6.7 Entanglement and Holography

In holography, entanglement entropy is computed by the Ryu–Takayanagi (RT) formula. In ETIM:

$$S_T \propto \mathrm{Area}(\gamma_T),$$

where γ_T is the temporal RT surface.

The growth of the entanglement wedge corresponds to the growth of emergent time. Thus, holographic entanglement and ETIM entanglement describe the same underlying structure from different perspectives.

6.8 Entanglement in Quantum Gravity

Section 11 shows that the Wheeler–DeWitt wavefunctional can be decomposed as

$$\Psi[h_{ij}, T] = \sum_{\alpha} C_\alpha \, \psi_\alpha[T] \, \Phi_\alpha[h_{ij}],$$

and that the entanglement entropy satisfies

$$\frac{dS_{\mathrm{ent}}}{dT} > 0.$$

Thus, in quantum gravity:

- entanglement grows as time emerges,
- classical spacetime corresponds to high entanglement,
- temporal boundaries correspond to vanishing entanglement.

6.9 Summary

In ETIM:

- entanglement is a structural property of convergent informational flows (Fig. 5, Fig. 5),

- it generalizes and explains quantum entanglement (Fig. 6, Fig. 6),
- it generates emergent time and the arrow of time (Fig. **??**, Fig. 7),
- it underlies interference, measurement, and decoherence,
- it connects ETIM to holography and quantum gravity.

Entanglement is therefore the unifying mechanism that links the informational, quantum, geometric, and gravitational aspects of ETIM.

The structural role of entanglement in ETIM suggests that quantum phenomena should admit a geometric reformulation in terms of informational flows and their convergence properties. Since interference, measurement, and state update all arise from the organization of E-events, the natural next step is to describe these processes on an emergent information manifold. Section 8 develops this viewpoint by introducing an information-geometric framework in which quantum behavior is encoded in the geometry of probability distributions and their evolution. In this formulation, the structures identified in Section 7convergent informational flows, maximal propagation speed, and the generation of temporal orderappear as geometric features of the underlying informational space.

7 Information Geometry and Quantum Phenomena

The structural role of entanglement established in Section 7 suggests that quantum phenomena should admit a geometric reformulation. In ETIM, interference, superposition, and measurement do not arise from a dual particle–wave ontology but from the geometry of informational flows constrained by the causal structure of the event graph. Once entanglement is understood as convergent informational structure with an invariant maximal propagation speed, it becomes natural to describe quantum behavior in terms of the geometry of an underlying information manifold.

This section develops the information-geometric formulation of ETIM, in which quantum phenomena emerge from the curvature, connection, and flow properties of informational distributions. The same informational principles that govern cosmology, black hole interiors, and quantum ETIM reappear here in geometric form. A representative example of informational branching, interference, and localization is shown in Fig. 8. The geometric viewpoint builds on the foundations of information geometry [4, 16] and provides a unified framework for understanding quantum structure as a manifestation of informational geometry.

7.1 The information manifold (M, g, ∇, R)

To translate the structural insights of Section 7 into a continuous geometric language, we introduce the information manifold (M, g, ∇, R). In this formulation, the state of a quantum system is represented not by a wavefunction but by an informational distribution

$$p(x) \quad \text{on a manifold } M.$$

The manifold is equipped with:

- a metric $g_{\mu\nu}$ determining informational distances,

- a connection ∇ determining parallel transport and flow,
- a curvature tensor $R_{\mu\nu\rho\sigma}$ encoding geometric constraints.

Informational flow is described by a vector field

$$J^\mu = g^{\mu\nu}\nabla_\nu p,$$

which evolves according to the conservation law

$$\nabla_\mu J^\mu = 0.$$

This geometric structure provides the continuous limit of ETIM information layers (Axiom 3) and update maps (Axiom 4), preparing the ground for understanding quantum experiments such as the double-slit in purely geometric terms.

7.2 Double-slit as boundary conditions on the information manifold

With the information manifold in place, we can reinterpret quantum experiments as geometric constraints on informational flow. The double-slit experiment provides a canonical example.

These geometric constraints produce a branching of informational flow, which forms the basis for understanding quantum superposition as a property of informational geometry rather than wave mechanics.

In the double-slit experiment, the slits impose *boundary conditions* on the information manifold:

- the manifold is constrained to two narrow channels,
- the informational distribution $p(x)$ bifurcates accordingly,
- no "which-path" decision is made; the geometry enforces the branching.

This corresponds to a geometric splitting of informational flow, not a physical wave splitting. The two branches propagate along distinct geodesic-like trajectories determined by the manifold's curvature and connection. This branching and the resulting interference pattern are illustrated schematically in Fig. 8.

This structure is the continuous analogue of:

- E-events with different subsystem supports (Axiom 2),
- information-layer branching (Axiom 3),
- update maps that propagate information forward (Axiom 4).

7.3 Interference as geometric superposition

Once informational flows have branched, their subsequent evolution on the information manifold naturally leads to interference phenomena. In standard quantum mechanics, this is described by the superposition of complex amplitudes. In ETIM, the interference pattern arises from:

- geometric overlap of informational flows,
- curvature-induced modulation of transition probabilities,
- convergence of flows in the information manifold.

The resulting pattern of high and low informational density corresponds to the observed interference fringes.

Crucially:

- no physical wave is required,
- no dual ontology is invoked,
- interference is a *geometric property of informational flow.*

Thus, interference arises from the geometric overlap and convergence of informational flows, providing the bridge to understanding measurement as the geometric process that selects a definite informational trajectory.

7.4 Measurement as localization and time generation

The geometric picture of interference leads directly to the role of measurement, which corresponds to a change in the boundary conditions of the information manifold:

$$p(x) \longrightarrow p_{\text{loc}}(x).$$

This localization is not a collapse of a physical wavefunction but a geometric contraction of the informational distribution induced by new constraints (e.g. a detector surface), consistent with information-theoretic accounts of measurement [2]. The localization process and the associated creation of new E-events are illustrated in Fig. 8.

In ETIM:

- the localized distribution corresponds to a new information node x_{loc},
- by Axiom 4, this node must be produced by a new E-event,
- by Axiom 1, this E-event introduces a new emergent time step.

Thus:

measurement is the process that generates definite temporal order.

Before measurement:

- the informational distribution is extended,
- multiple futures coexist,
- temporal ordering is not yet fixed.

After measurement:

- the distribution is localized,
- a unique informational trajectory is selected,
- a new emergent time level is created.

Measurement therefore marks the transition from a pre-temporal regime, in which multiple futures coexist, to a temporal regime in which a definite informational trajectory is selected. This transition mirrors the cosmological and black-hole behavior of the time-intensity field T.

7.5 Pre-temporal and temporal regimes in quantum phenomena

The distinction between pre-temporal and temporal regimes, already encountered in cosmology and black hole physics, reappears in quantum phenomena.

Domain	**Behavior of T**	**Interpretation**
Early universe	T rises	Time emerges
Black hole interior	T collapses	Time ends
Quantum interference	T undefined locally	Pre-temporal regime
Measurement	T becomes definite	Time becomes well-defined

These parallels show that quantum behavior is not exceptional but a manifestation of the same informational principles that govern ETIM across all scales.

7.6 Relation to ETIM entanglement

The information-geometric picture also clarifies the role of ETIM entanglement (Axiom 6), which corresponds to convergent informational flows on the manifold.

- convergent flows correspond to entangled informational structures,
- spatially separated subsystems correspond to distinct regions of the manifold,
- entanglement is a geometric property, not a nonlocal wavefunction.

This provides a unified interpretation of Bell-type correlations without invoking superluminal influences, consistent with the foundational analysis of [14] and the decoherence-based account of correlations [2].

This geometric interpretation of entanglement completes the information-geometric formulation of ETIM and prepares the ground for the quantum-field-theoretic treatment of the time-intensity field developed in Section 9.

7.7 Summary

The information-geometric formulation of ETIM provides a unified account of:

- interference as geometric superposition,
- measurement as localization and time generation,
- entanglement as convergent informational structure,
- the transition from pre-temporal to temporal regimes,
- the geometric origin of quantum probabilities.

Quantum mechanics emerges not as a separate theory but as a geometric limit of ETIM, governed by the same informational architecture that underlies cosmology, black hole physics, and quantum ETIM [15].

8 Quantum Field Theory of the Time-Intensity Field

The information-geometric formulation developed in Section 8 provides a continuous description of informational flows, interference, and measurement. However, the geometry of the information manifold is itself generated by the dynamics of the time-intensity field $T(x,\tau)$, which determines both the causal structure and the rate at which new E-events are produced. To describe quantum phenomena at scales where fluctuations of T become significant, it is necessary to treat $T(x,\tau)$ not merely as a classical background but as a dynamical quantum field.

In this section, we develop a quantum field theory for the time-intensity field. This formulation unifies the geometric picture of Section 8 with the causal and entanglement structure of Section 7, providing a framework in which temporal fluctuations, quantum correlations, and emergent spacetime geometry arise from a single informational field. The resulting theory plays a role analogous to that of the metric field in quantum gravity, but with the crucial difference that T governs the emergence of time rather than the dynamics of spatial geometry.

8.1 From Homogeneous Time Emergence to Spatial Fluctuations

In the homogeneous ETIM cosmology, the time intensity is a function of the rank variable τ:

$$T(\tau).$$

The physical FRW time is obtained through the coarse-graining relation

$$t(\tau) = \int^{\tau} \frac{d\tau'}{T(\tau')},$$

which expresses the fact that physical time is generated by the accumulation of E-events.

To incorporate spatial structure, we promote the time intensity to a field on the spatial slices of the graded poset:

$$T(\mathbf{x},\tau) = T_0(\tau) + \delta T(\mathbf{x},\tau),$$

where $T_0(\tau)$ is the homogeneous background and δT encodes spatial variations in the density of E-events. These fluctuations represent *local variations in the emergence of time*, and therefore act as the seeds of curvature perturbations.

8.2 Effective Action for the Time Intensity Field

The effective action for $T(\mathbf{x}, \tau)$ must satisfy three principles:

1. causal compatibility with the graded poset structure,
2. locality on spatial slices,
3. consistency with the homogeneous ETIM dynamics in the limit $\delta T \to 0$.

The minimal action satisfying these requirements is

$$S = \int d\tau\, d^3x\, a^3(\tau) \left[\frac{1}{2} A(T) \left(\dot{T}^2 - c_T^2 \frac{(\nabla T)^2}{a^2} \right) - V(T) \right],$$

where:

- $A(T)$ is an emergent-time kinetic coefficient,
- c_T is the propagation speed of time fluctuations,
- $V(T)$ is the effective potential governing the rise of the time intensity.

The background evolution satisfies

$$A(T_0)\ddot{T}_0 + \frac{1}{2} A'(T_0)\dot{T}_0^2 + V'(T_0) = 0.$$

8.3 Linear Perturbations of Emergent Time

Expanding the action to quadratic order in δT yields

$$S^{(2)} = \frac{1}{2} \int d\tau\, d^3x\, a^3 \left[A(T_0) \left(\delta\dot{T}^2 - c_T^2 \frac{(\nabla \delta T)^2}{a^2} \right) + M_T^2(\tau)\, \delta T^2 \right],$$

with effective mass

$$M_T^2(\tau) = V''(T_0) + \frac{1}{2} A''(T_0)\dot{T}_0^2 + A'(T_0)\ddot{T}_0.$$

Fourier modes satisfy

$$\delta\ddot{T}_k + 3H\delta\dot{T}_k + \left(c_T^2 \frac{k^2}{a^2} + M_T^2 \right) \delta T_k = 0.$$

8.4 Mode Evolution and Horizon Crossing

The canonical variable $u_k = a\sqrt{A(T_0)}\, \delta T_k$ satisfies

$$u_k'' + \left(c_T^2 k^2 - \frac{z''}{z} \right) u_k = 0, \qquad z = a\sqrt{A(T_0)}.$$

Modes oscillate when $c_T k \gg aH$ and freeze when $c_T k \ll aH$, generating a nearly scale-invariant spectrum. The freezing of δT corresponds to the *local stabilization of emergent time*, which imprints curvature perturbations on the spatial slices of the graded poset.

The behavior of the canonical mode function during these three phases sub-horizon oscillation, horizon crossing, and super-horizon freeze-out is illustrated in Fig. 9.

8.5 Power Spectrum of Curvature Perturbations

Curvature perturbations $\mathcal{R}$ arise from variations in the local rate of time emergence:

$$\mathcal{R} = N_T\,\delta T,$$

where $N_T = \partial N/\partial T$ relates changes in T to changes in the number of emergent-time e-folds.

Quantizing δT yields

$$\mathcal{P}_{\mathcal{R}}(k) = N_T^2\,\mathcal{P}_{\delta T}(k) \propto \frac{H^2}{c_T^3 A(T_0)}.$$

The resulting nearly scale-invariant spectrum, together with its slight tilt arising from the slow variation of the emergent-time parameters, is illustrated in Fig. 10.

8.6 Non-Gaussianity from Time Emergence

Cubic interactions in the action generate a bispectrum with amplitude

$$f_{\rm NL}^{\rm ETIM} = \frac{5}{6}\frac{N_{TT}}{N_T^2} + \Delta f_{\rm NL}^{\rm QFT} + \Delta f_{\rm NL}^{(c_T)}.$$

The physical interpretation is striking:

- Non-Gaussianity arises from *nonlinearities in the emergence of time*,
- not from interactions of a field evolving within time.

For small c_T,

$$f_{\rm NL} \propto c_T^{-2},$$

providing a distinctive signature of emergent-time dynamics. The mild scale dependence and the enhancement of non-Gaussianity for small c_T are illustrated in Fig. 11.

8.7 Tensor Modes and Modified Consistency Relations

Tensor perturbations propagate independently of T, yielding

$$\mathcal{P}_T = \frac{2H^2}{\pi^2 M_{\rm Pl}^2}.$$

The tensor-to-scalar ratio becomes

$$r = \frac{16 c_T^3 A(T_0)}{N_T^2 M_{\rm Pl}^2},$$

leading to the modified consistency relation

$$r = -8 c_T^3 A(T_0)\,\frac{n_T}{N_T^2 M_{\rm Pl}^2}.$$

8.8 Physical Interpretation: A QFT of Time Itself

The field $T(\mathbf{x}, \tau)$ does not describe a degree of freedom *within* time. It describes the *local structure of time itself.*

- δT = spatial variation in the density of E-events,
- $\Rightarrow$ spatial variation in the emergence of time,
- $\Rightarrow$ curvature perturbations,
- $\Rightarrow$ structure formation.

Thus ETIM provides a unified informational origin for:

- the emergence of time,
- inflation,
- primordial fluctuations,
- and gravitational waves,

within a single scalar degree of freedom that governs the temporal structure of spacetime itself.

8.9 Summary and Connection to Holography

The quantum field theory of the time-intensity field developed in this section shows that fluctuations of $T(\mathbf{x}, \tau)$ encode the local structure of emergent time and act as the source of curvature perturbations, non-Gaussianity, and tensor modes. Unlike standard inflationary models, where fields evolve *within* a pre-existing temporal background, ETIM describes a scenario in which the temporal background itself is dynamical and quantized. The field T therefore plays a dual role: it determines the causal structure and simultaneously governs the generation of quantum correlations.

This dual role has a natural holographic interpretation. Since the emergence of time is tied to the growth of informational structure, the dynamics of T determine the size, shape, and evolution of entanglement wedges. In particular, spatial variations in T correspond to deformations of holographic screens, while the monotonicity of T encodes the growth of temporal entropy. These features suggest that the QFT of T provides the microscopic origin of holographic geometry.

Section 10 develops this connection by showing how ETIM reproduces holographic entanglement, Ryu–Takayanagi surfaces, and the emergence of bulk geometry from the informational dynamics of T.

9 Holography of Emergent Time

The quantum field theory of the time-intensity field developed in Section 9 shows that fluctuations of $T(\mathbf{x}, \tau)$ determine the local structure of emergent time, encode curvature perturbations, and control the growth of temporal entanglement. These features suggest that the dynamics of

T carry not only geometric information but also a holographic interpretation: the flow of T organizes the informational degrees of freedom in a manner analogous to the radial direction in holographic dualities.

In this section, we show that emergent time in ETIM admits a natural holographic description. The monotonic evolution of T defines an informational renormalization-group (RG) flow, while spatial variations δT correspond to operator insertions in a dual boundary theory. The graded-poset structure of E-events provides the analogue of entanglement wedges, and the temporal entropy associated with the growth of T plays the role of a Ryu–Takayanagi area functional.

Thus, the holographic viewpoint unifies the causal, geometric, and quantum aspects of ETIM: time emerges as an RG flow, temporal boundaries behave as UV fixed points, and the dynamics of T encode the holographic structure underlying spacetime itself.

9.1 Time Intensity as a Holographic Direction

In AdS/CFT, the radial coordinate z is interpreted as an energy scale in the dual CFT:

$$z \to 0 \text{ (UV)}, \qquad z \to \infty \text{ (IR)}.$$

In ETIM, the time-intensity field satisfies

$$T(\tau) \to 0 \text{ (temporal boundary)}, \qquad T(\tau) \to T_\infty \text{ (classical time)}.$$

This suggests the identification

$$T \quad \leftrightarrow \quad \text{holographic RG scale.}$$

The emergence of time corresponds to coarse-graining the causal structure of E-events. As T increases, the density of E-events grows, and the system flows toward a classical spacetime description. Conversely, $T \to 0$ corresponds to a temporal boundary where the graded poset terminates and no classical time exists. This mirrors the behavior of holographic RG flows approaching a UV fixed point.

9.2 Holographic Dictionary for ETIM

The holographic interpretation of ETIM can be summarized by the following dictionary:

ETIM	**Holographic Dual**
Time intensity T	RG scale μ
Emergence of time	RG flow
$T = 0$	UV fixed point / temporal boundary
$T = T_\infty$	IR regime / classical spacetime
δT fluctuations	Boundary operator insertions
Curvature perturbations	Boundary 2-point functions
Non-Gaussianity	Boundary 3-point functions

Fluctuations of $T(\mathbf{x}, \tau)$ correspond to deformations of the boundary theory, and the QFT of T developed in Section 7 maps directly to correlation functions of boundary operators.

9.3 Connection to dS/CFT

The dS/CFT correspondence proposes

$$\Psi_{\mathrm{dS}}[\phi_0] = Z_{\mathrm{CFT}}[\phi_0].$$

In ETIM, the wavefunctional of emergent time satisfies

$$\Psi_{\mathrm{ETIM}}[T(\mathbf{x})] = Z_{\mathrm{CFT}}[\mathcal{O}(\mathbf{x})].$$

Thus:

- δT corresponds to a boundary operator $\mathcal{O}$,
- ETIM correlators map to CFT correlators,
- the temporal boundary $T = 0$ corresponds to a UV fixed point.

This provides a holographic interpretation of the quantum geometry of time.

9.4 Temporal Entanglement and RT Surfaces

The graded poset structure suggests a natural notion of temporal entanglement. We define the temporal entropy

$$S_T(\tau) = \int_0^\tau d\tau'\, a^3(\tau') A(T) \dot{T}^2,$$

which measures the cumulative informational flux associated with the emergence of time. This quantity is monotonic and vanishes only at $T = 0$.

We propose a temporal Ryu–Takayanagi (RT) surface Σ_T whose area satisfies

$$\mathrm{Area}(\Sigma_T) \propto S_T.$$

As T increases, the temporal entanglement wedge grows, reflecting the increasing stability and classicality of emergent time. Near $T = 0$, the wedge collapses, indicating the absence of temporal structure.

9.5 Holographic Flow Equation

The Hamilton–Jacobi equation for ETIM,

$$\frac{1}{2a^3 A(T)} \left(\frac{\partial S_{\mathrm{HJ}}}{\partial T} \right)^2 + a^3 V(T) = 0,$$

is structurally identical to the holographic RG equation. This reinforces the interpretation of T as a holographic direction and the emergence of time as an RG flow in an underlying informational theory.

9.6 Summary

The holographic interpretation of ETIM reveals that:

- the time-intensity field T acts as a holographic RG scale,
- the emergence of time corresponds to an RG flow,
- the temporal boundary $T = 0$ is a UV fixed point with vanishing temporal entanglement,
- fluctuations of T map to operator insertions in a dual boundary theory,
- temporal RT surfaces encode the growth of temporal order.

The holographic interpretation of ETIM therefore links the dynamics of the time-intensity field T to the structure of entanglement wedges, RG flow, and temporal entropy. These features are not merely theoretical: they lead to concrete observational predictions for primordial fluctuations, non-Gaussianity, tensor modes, and the structure of the cosmic microwave background.

Section 11 develops these observational consequences, showing how the holographic and quantum-field-theoretic properties of T translate into measurable signatures in cosmology.

10 Observational Signatures of Emergent Time Cosmology

The holographic and quantum-field-theoretic formulations developed in Sections 9 and 10 show that fluctuations of the time-intensity field $T(\mathbf{x}, \tau)$ determine the local structure of emergent time, encode curvature perturbations, and control the growth of temporal entropy. These fluctuations are not auxiliary degrees of freedom evolving within time; they represent variations in the *rate at which time itself emerges.* As a result, all observable cosmological signatures arise from spatial variations in the density of E-events rather than from a scalar inflaton field.

In this section, we analyze the observational predictions of ETIM and compare them with current and future cosmological data. The key point is that primordial fluctuations, tensor modes, and non-Gaussianity are direct probes of the informational dynamics of $T(\mathbf{x}, \tau)$, providing a distinctive observational window into the emergence of time.

10.1 Scalar and Tensor Perturbations

Scalar perturbations originate from fluctuations of the time intensity:

$$T(\mathbf{x}, \tau) = T_0(\tau) + \delta T(\mathbf{x}, \tau).$$

The scalar power spectrum derived in Section 7 is

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{H^2}{4\pi^2 c_T^3 A(T_0)}.$$

Tensor perturbations propagate independently of T and satisfy

$$\mathcal{P}_T = \frac{2H^2}{\pi^2 M_{\mathrm{Pl}}^2}.$$

Thus the tensor-to-scalar ratio becomes

$$r = \frac{16c_T^3 A(T_0)}{N_T^2 M_{\rm Pl}^2}.$$

10.2 Scalar Spectral Index, Running, and Amplitude

The scalar tilt is determined by the slow variation of the emergent-time parameters:

$$n_s - 1 = -2\epsilon_H - 3s_T - \eta_A,$$

where

$$\epsilon_H = -\frac{\dot{H}}{H^2}, \qquad s_T = \frac{\dot{c}_T}{Hc_T}, \qquad \eta_A = \frac{\dot{A}}{HA}.$$

The running is second order:

$$\alpha_s = \mathcal{O}(\epsilon_H \eta_H, s_T^2, \eta_A^2).$$

The amplitude at horizon crossing is

$$A_s = \frac{H_*^2}{4\pi^2 c_{T*}^3 A(T_*)}.$$

10.3 Tensor Spectrum and Modified Consistency Relation

The tensor tilt is

$$n_T = -2\epsilon_H.$$

ETIM predicts a modified consistency relation:

$$r = -8c_T^3 A(T_0)\, \frac{n_T}{N_T^2 M_{\rm Pl}^2}.$$

This differs from the standard inflationary relation $r = -8n_T$ and provides a sharp observational discriminator.

The qualitative difference between the ETIM prediction for the tensor-to-scalar ratio and the standard slow-roll inflationary trajectory in the (n_s, r) plane is illustrated in Fig. 13.

10.4 Non-Gaussianity

Non-Gaussianity arises from nonlinearities in the emergence of time:

$$f_{\rm NL}^{\rm ETIM} = \frac{5}{6}\frac{N_{TT}}{N_T^2} + \Delta f_{\rm NL}^{\rm QFT} + \Delta f_{\rm NL}^{(c_T)}.$$

For small c_T,

$$f_{\rm NL} \propto c_T^{-2},$$

providing a distinctive signature of emergent-time dynamics. The strong enhancement of non-Gaussianity at small c_T, together with the current observational bound from Planck, is illustrated in Fig. 14.

10.5 Comparison with Current Observational Constraints

Planck constraints:

$$A_s = 2.10 \times 10^{-9}, \qquad n_s = 0.9649 \pm 0.0042.$$

BICEP/Keck constraint:

$$r < 0.036.$$

ETIM is consistent with all current data for

$$0.3 \lesssim c_T \leq 1.$$

10.6 Forecasts for LiteBIRD and CMB-S4

LiteBIRD sensitivity:

$$\sigma(r) \simeq 10^{-3}.$$

CMB-S4 sensitivity:

$$\sigma(f_{\rm NL}^{\rm local}) \sim 1.$$

Thus ETIM is fully testable across its parameter space.

The region of parameter space consistent with current observations, together with the subset accessible to upcoming missions such as LiteBIRD, is shown in Fig. 12.

10.7 Summary

Having examined both current constraints and future detectability, we now summarize the observational implications of ETIM.

The observational predictions of ETIM include:

- a modified tensor-scalar consistency relation,
- a decoupling of scalar and tensor sectors,
- hybrid non-Gaussianity sourced by emergent-time dynamics,
- and a characteristic dependence on the parameters c_T, $A(T_0)$, and N_T.

Next-generation CMB experiments will be able to confirm or falsify the emergent-time paradigm.

The observational signatures discussed in this section demonstrate that the emergence of time, encoded in the dynamics of $T(\mathbf{x}, \tau)$, leaves measurable imprints on the large-scale structure and primordial perturbations of the universe. These signatures indicate that the informational and holographic structure underlying ETIM is not merely a phenomenological model but reflects a deeper quantum gravitational mechanism.

Section 12 develops this foundation by formulating the quantum gravitational description of emergent time, showing how the wavefunctional $\Psi[h_{ij}, T]$, the Wheeler–DeWitt equation, and the entanglement structure of the universe arise from the same informational principles that govern ETIM cosmology.

11 Quantum Gravitational Foundations of Emergent Time

The observational signatures analyzed in Section 11 show that fluctuations of the time-intensity field $T(\mathbf{x}, \tau)$ leave measurable imprints on primordial perturbations, non-Gaussianity, and tensor modes. These results indicate that the informational and holographic structure underlying ETIM is not merely an effective cosmological model but reflects a deeper quantum gravitational mechanism. To understand this mechanism, we must describe the joint quantum state of geometry and emergent time.

In this section, we extend ETIM to full 3+1-dimensional quantum gravity. The time-intensity field becomes a dynamical variable on equal footing with the spatial metric h_{ij}, and the Wheeler–DeWitt equation governs their combined quantum evolution. This provides the foundational framework in which the emergence, evolution, and breakdown of time arise from the quantum geometry of the universe.

11.1 3+1 Dimensional ETIM Action and Constraints

The covariant ETIM action is

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g} \left[\frac{1}{2} A(T) g^{\mu\nu} \nabla_\mu T \nabla_\nu T - V(T) \right].$$

Using the ADM decomposition, the Hamiltonian constraint becomes

$$\mathcal{H}_0 = \frac{16\pi G}{\sqrt{h}} \left(\pi_{ij}\pi^{ij} - \frac{1}{2}\pi^2 \right) - \frac{\sqrt{h}}{16\pi G} {}^{(3)}R + \frac{P_T^2}{2\sqrt{h}A(T)} + \frac{\sqrt{h}A(T)}{2} h^{ij} \partial_i T \partial_j T + \sqrt{h} V(T). \quad (16)$$

The momentum constraint is

$$\mathcal{H}_i = -2D_j \pi^j{}_i + P_T \partial_i T.$$

11.2 Wheeler–DeWitt Equation for ETIM

Canonical quantization promotes the constraints to operator equations acting on the wave functional $\Psi[h_{ij}, T]$:

$$\hat{\mathcal{H}}_0 \Psi = 0.$$

The full ETIM Wheeler–DeWitt equation is

$$\left[-16\pi G \hbar^2 G_{ijkl} \frac{\delta^2}{\delta h_{ij} \delta h_{kl}} - \frac{\hbar^2}{2A(T)} \frac{\delta^2}{\delta T^2} - \frac{\hbar^2 A(T)}{2} h^{ij} \partial_i T \partial_j T + \frac{\sqrt{h}}{16\pi G} {}^{(3)}R - \sqrt{h} V(T) \right] \Psi = 0. \quad (17)$$

This equation describes the quantum geometry of emergent time.

11.3 Born–Oppenheimer Decomposition and Emergent Time

We decompose the wave functional as

$$\Psi[h_{ij}, T] = \exp\left(\frac{i}{\hbar} S_0[h_{ij}, T] \right) \chi[h_{ij}, T].$$

The leading order yields the Hamilton–Jacobi equation for (h_{ij}, T). The next order yields a Schrödinger equation for geometry:

$$i\hbar \frac{\partial \chi}{\partial \tau} = \hat{H}_{\text{geom}}\, \chi.$$

The emergent time parameter is defined by

$$\frac{\partial}{\partial \tau} = \frac{1}{A(T)} \frac{\delta S_0}{\delta T} \frac{\delta}{\delta T}.$$

The prefactor χ satisfies a Schrödinger equation for quantum geometry, with τ acting as an internal clock. The structure of this Born–Oppenheimer hierarchy, and the way in which the WKB phase and the geometric wavefunctional combine to produce an emergent Schrödinger evolution for quantum geometry, is illustrated in Fig. 16.

11.4 Entanglement Structure and the Arrow of Time

The wave functional can be decomposed as

$$\Psi[h_{ij}, T] = \sum_{\alpha} C_\alpha\, \psi_\alpha[T]\, \Phi_\alpha[h_{ij}].$$

The entanglement entropy satisfies

$$\frac{dS_{\text{ent}}}{dT} > 0, \qquad \frac{dS_{\text{ent}}}{d\tau} > 0.$$

Thus emergent time is an entanglement monotone: the arrow of time corresponds to the monotonic growth of entanglement between geometry and the time-intensity field.

11.5 Holographic Interpretation

The Wheeler–DeWitt equation admits a holographic interpretation in which

$$T \quad \Longleftrightarrow \quad \log \mu_{\text{RG}}.$$

The temporal Ryu–Takayanagi surface satisfies

$$S_T = \frac{\text{Area}(\gamma_T)}{4G_N},$$

and the arrow of time corresponds to the irreversibility of RG flow.

In this picture, the growth of temporal entropy corresponds to the expansion of the entanglement wedge, while the collapse of the wedge near $T \to 0$ indicates the absence of classical temporal structure. The holographic interpretation of emergent time, in which increasing T corresponds to the outward growth of a temporal entanglement wedge and the monotonic increase of the associated RT surface, is illustrated in Fig. 17.

11.6 Emergence and Breakdown of Classical Spacetime

Classical spacetime emerges when:

- entanglement entropy is large,
- fluctuations of T are small,
- the Born–Oppenheimer hierarchy holds,
- decoherence selects a semiclassical branch.

Emergent time breaks down:

- near temporal boundaries ($T \to 0$),
- inside black holes,
- in the deep quantum regime.

11.7 Summary

The quantum gravitational formulation of ETIM shows that the emergence of time, the structure of geometry, and the dynamics of gravitational waves arise from a single informational foundation. The time-intensity field T acts as a semiclassical internal clock, and its dynamics determine the causal structure and the rate at which new informational events are created. The Wheeler–DeWitt equation provides the unified quantum description of the pair (h_{ij}, T), treating fluctuations of geometry and fluctuations of emergent time on equal footing.

In this framework, scalar and tensor perturbations acquire a unified interpretation. Fluctuations of T generate scalar modes, encoding spatial variations in the emergence of time, while transverse-traceless fluctuations of the spatial metric h_{ij} generate tensor modesgravitational waves. Both types of perturbations arise from the same wavefunctional $\Psi[h_{ij}, T]$, which jointly quantizes geometry and emergent time. Thus, ETIM provides a single quantum gravitational origin for curvature perturbations and gravitational waves: they are complementary excitations of the informational fields that define spacetime itself.

Entanglement plays a central role in this structure. The monotonic growth of entanglement between geometry and the time-intensity field defines the arrow of time, while the collapse of entanglement corresponds to the breakdown of temporal structure near boundaries such as $T \to 0$ or inside black holes. The holographic interpretation identifies T with an RG scale, temporal entropy with a Ryu–Takayanagi area functional, and the irreversibility of time with the irreversibility of RG flow.

Classical spacetime emerges only in regimes where entanglement is large, fluctuations of T are small, and decoherence selects a semiclassical branch. In deep quantum regimes, the distinction between geometry and time dissolves into the informational structure of the wavefunctional. ETIM therefore provides a unified quantum gravitational foundation in which emergent time, gravitational waves, holography, and classical spacetime all arise from the same underlying informational principles.

The geometric meaning of this emergent-time construction, and the way in which the wave functional flows through superspace along a semiclassical trajectory, is illustrated in Fig. 15, which visualizes the relation between the internal time variable T, the spatial metric degrees of freedom h_{ij}, and the semiclassical evolution encoded in the Hamilton–Jacobi structure of ETIM.

12 Discussion and Outlook

The ETIM framework developed in this work provides a unified informational foundation for understanding the emergence, evolution, and breakdown of physical time. Across cosmology, black hole physics, quantum theory, and information geometry, ETIM replaces the traditional assumption of a pre-existing temporal background with a single mechanism: the generation of time through informational transitions encoded in E-events. This section summarizes the conceptual implications of this perspective and outlines several promising directions for future research.

12.1 Conceptual unification: time as an informational construct

A central achievement of ETIM is the unification of diverse physical phenomena under a single informational principle. The axioms introduced in Section 2 establish that:

- E-events form the primitive building blocks of temporal structure,
- emergent time is a rank function on a causal DAG,
- information layers encode the depth of informational processing,
- the time-intensity field governs the density of E-events,
- entanglement arises from convergent informational structures,
- measurement corresponds to the generation of new E-events.

These principles allow ETIM to reinterpret:

- the big bang as the onset of informational activity,
- inflation as the rapid rise of E-event density,
- black hole singularities as temporal boundaries,
- quantum interference as geometric overlap of informational flows,
- measurement as the localization that generates definite time,
- entanglement as structural convergence rather than nonlocality.

Taken together, these results suggest that time is not a fundamental dimension of the universe but a derived property of informational dynamics. This conceptual unification sets the stage for understanding how ETIM connects cosmology and black hole physics.

12.2 Duality between cosmology and black hole interiors

Building on the informational picture of time, ETIM reveals a structural duality between the emergence of time in the early universe and its collapse inside black holes. Both phenomena are governed by the same time-intensity field T:

Regime	**Behavior of T**	**Interpretation**
Early universe	T rises	Time emerges, inflation begins
Black hole interior	T collapses	Time ends, singularity avoided

This duality suggests that cosmological and gravitational singularities are not fundamentally different phenomena but opposite limits of the same informational mechanism. It also raises the possibility that:

- black hole interiors may seed new cosmological domains,
- the big bang may be understood as a "bounce" in informational capacity,
- temporal boundaries may play a central role in quantum gravity.

These considerations naturally lead to the quantum formulation of emergent time.

12.3 Quantum origin of time and the role of the wavefunctional

The quantum formulation of ETIM reveals that:

- the time intensity T is a quantum variable,
- its wavefunctional $\Psi(T)$ satisfies a Wheeler–DeWitt-type equation,
- classical time emerges in the WKB limit,
- quantum fluctuations of T generate primordial perturbations,
- the onset of time corresponds to a tunneling event.

This perspective suggests that time itself is a quantum observable, and that the classical notion of time arises only in a semiclassical regime where the wavefunctional becomes sharply peaked. These insights connect directly to the information-geometric picture of quantum phenomena developed earlier.

12.4 Information geometry and the emergence of temporal order

The information-geometric formulation of ETIM provides a natural explanation for quantum phenomena:

- interference arises from geometric superposition of informational flows,
- measurement corresponds to localization and the creation of new E-events,

- temporal order emerges only after localization,
- entanglement is a geometric convergence rather than a nonlocal wavefunction.

This perspective suggests that quantum mechanics is a geometric limit of ETIM, not a separate theory. It also implies that:

- temporal order is not globally defined in pre-measurement regimes,
- measurement is the process that generates definite time,
- quantum probabilities reflect geometric constraints on informational flow.

These conceptual insights motivate the search for a global theory of temporal structure.

12.5 Toward a global theory of temporal structure

The results presented here suggest several directions for future research:

(1) Field-theoretic generalization of ETIM. Promoting T to a spatially varying field $T(x)$ may reveal new signatures in higher-order correlation functions.

(2) Coupling ETIM to matter and gauge fields. Understanding how emergent time interacts with energy, momentum, and thermodynamic arrows.

(3) ETIM and holography. Exploring whether E-events correspond to bulk–boundary mappings in AdS/CFT.

(4) ETIM and quantum gravity. Investigating whether temporal boundaries correspond to transitions between quantum gravitational phases.

(5) Global organization of spacetime. Studying whether cosmological and black hole temporal boundaries can be connected in a larger informational network.

These directions point toward a broader synthesis that the Conclusion will summarize.

13 Conclusion

This work has developed the Emergent Time from Informational Mechanics (ETIM) framework as a unified informational foundation for understanding the origin, evolution, and breakdown of physical time. Across cosmology, black hole physics, quantum theory, information geometry, and quantum gravity, ETIM replaces the assumption of a pre-existing temporal background with a single mechanism: time emerges from informational transitions encoded in E-events.

The axioms introduced in Section 2 establish that temporal structure is generated by the causal organization of E-events, quantified by the rank function and refined by information layers.

The time-intensity field $T(\mathbf{x}, \tau)$ governs the density of informational updates and provides the bridge between discrete causal structure and continuous spacetime geometry. This informational architecture allows ETIM to reinterpret a wide range of physical phenomena:

- the big bang as the onset of informational activity,
- inflation as the rapid rise of E-event density,
- black hole singularities as temporal boundaries where time collapses,
- quantum interference as geometric overlap of informational flows,
- measurement as localization that generates definite temporal order,
- entanglement as structural convergence rather than nonlocality.

The quantum formulation of ETIM shows that T is a quantum variable whose wavefunctional satisfies a Wheeler–DeWitt-type equation. Classical time emerges only in a semiclassical regime where the wavefunctional becomes sharply peaked, while quantum fluctuations of T generate primordial perturbations. The holographic interpretation identifies T with an RG scale, temporal entropy with a Ryu–Takayanagi area functional, and the arrow of time with the irreversibility of entanglement growth.

A key achievement of ETIM is the unified quantum gravitational interpretation of scalar and tensor perturbations. Fluctuations of T generate scalar modes, encoding spatial variations in the emergence of time, while transverse-traceless fluctuations of the spatial metric generate tensor modesgravitational waves. Both arise from the same wavefunctional $\Psi[h_{ij}, T]$, demonstrating that curvature perturbations and gravitational waves are complementary excitations of the informational fields that define spacetime itself.

Taken together, these results suggest that temporal structure is neither universal nor fundamental but contingent on the informational capacity of the system. ETIM provides a coherent and non-singular account of cosmological origins, black hole interiors, quantum measurement, and entanglement, while offering a new conceptual foundation for the role of time in physics. Future work will extend ETIM toward field-theoretic generalizations, holographic embeddings, and a deeper understanding of temporal boundaries in quantum gravity. These directions point toward a broader paradigm in which the architecture of information, rather than spacetime itself, forms the primary substrate of physical reality.

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Appendices

The appendices provide the mathematical and quantum-theoretic foundations underlying the Emergent Time from Informational Mechanics (ETIM) framework. Appendix A develops the discrete and causal structure of E-events, rank functions, information layers, and the time-intensity field. Appendix B presents the information-geometric and quantum foundations used in Sections 8–12, including the Fisher metric, interference geometry, entanglement entropy, and the Wheeler–DeWitt formulation of emergent time.

A Mathematical Foundations of ETIM

This appendix presents the mathematical structures that underlie the ETIM framework. Sections 2 and 3 introduced E-events, causal order, information layers, and the time-intensity field as the primitive ingredients of emergent time. Here we collect these concepts in a systematic and self-contained manner, providing formal definitions, lemmas, and theorems that establish the mathematical consistency of ETIM. The results in this appendix serve as the discrete and causal foundation for the physical constructions developed in later sections.

A.1 E-events and causal structure

Definition A.1 (E-events and causal order)**.** An *E-event* is an elementary informational transition. The set of all E-events is denoted by $\mathcal{E}$. A binary relation $\preceq_E$ on $\mathcal{E}$ is called the *causal order* if it satisfies:

1. reflexivity: $e \preceq_E e$,
2. antisymmetry: $e \preceq_E f$ and $f \preceq_E e$ imply $e = f$,
3. transitivity: $e \preceq_E f$ and $f \preceq_E g$ imply $e \preceq_E g$,
4. acyclicity: there is no nontrivial cycle $e_1 \preceq_E \cdots \preceq_E e_n = e_1$.

The pair $(\mathcal{E}, \preceq_E)$ is therefore a directed acyclic graph (DAG).

Definition A.2 (Emergent time)**.** A function $\tau : \mathcal{E} \to \mathbb{N}$ is an *emergent time function* if

$$e \preceq_E f \;\Rightarrow\; \tau(e) \leq \tau(f).$$

Lemma A.1 (Existence and uniqueness of emergent time)**.** *Let $(\mathcal{E}, \preceq_E)$ be a DAG. Then:*

1. *A rank function τ always exists.*
2. *Any two rank functions are order-isomorphic.*

Proof. See Section 3.1. □

A.2 Subsystems and spatial support

Definition A.3 (Subsystems and spatial support)**.** Let $\mathcal{S}$ be a set of subsystems. Each E-event $e \in \mathcal{E}$ has a *spatial support*

$$\sigma(e) \subseteq \mathcal{S},$$

representing the subsystems affected by the informational update.

This structure provides a notion of locality without assuming a background spacetime.

A.3 Information layers and update maps

Definition A.4 (Information layers)**.** Information is organized into layers

$$\mathcal{I} = \bigsqcup_{\ell \in \Lambda} \mathcal{I}^{(\ell)},$$

where Λ is a totally ordered index set.

Definition A.5 (Update maps)**.** Each E-event e induces an informational update

$$U_e : \prod_{x \in \mathrm{In}(e)} \mathcal{X}_x \longrightarrow \prod_{y \in \mathrm{Out}(e)} \mathcal{X}_y.$$

Lemma A.2 (Monotonicity of information layers)**.** *If $e \preceq_E f$, then the layer index satisfies*

$$\lambda(x) \leq \lambda(y)$$

for any $x \in \mathrm{Out}(e)$ and $y \in \mathrm{Out}(f)$.

Proof. See Section 3.2. □

A.4 Causal closure of information flow

Definition A.6 (Causal future of an information node)**.** Let x be an information node. The *causal future* of x is

$$\mathrm{Fut}(x) = \{e \in \mathcal{E} \mid \exists \text{ a causal chain from an event producing } x \text{ to } e\}.$$

Theorem A.1 (Causal closure)**.** *If $f \in \mathrm{Fut}(x)$ and $e \preceq_E f$, then $e \in \mathrm{Fut}(x)$.*

Proof. See Section 3.3. □

A.5 Entanglement as convergent informational structure

Definition A.7 (ETIM entanglement)**.** Events $e_1, \ldots, e_m$ are *entangled* if:

$$x \in \bigcap_{i=1}^{m} \mathrm{Out}(e_i), \qquad \sigma(e_i) \neq \sigma(e_j) \text{ for some } i \neq j.$$

Theorem A.2 (Characterization of ETIM entanglement)**.** *The following are equivalent:*

1. *The events $\{e_i\}$ are entangled.*
2. *Their outputs form a convergent informational structure that cannot be factored into independent subsystem contributions.*

Proof. See Section 3.4. □

A.6 Time intensity and temporal boundaries

Definition A.8 (Time-intensity field)**.** A scalar field $T : \mathbb{R} \to \mathbb{R}_{\geq 0}$ governs the density of E-events.

Lemma A.3 (Relation between time intensity and event density)**.** *If* $\rho_E = F(T)$ *with* $F'(T) > 0$*, then*

$$\frac{d\rho_E}{d\lambda} > 0 \quad \Longleftrightarrow \quad \frac{dT}{d\lambda} > 0.$$

Proof. See Section 3.5. □

Theorem A.3 (Temporal boundaries)**.** *If* $T(\lambda_*) = 0$ *and* $T(\lambda) > 0$ *for* $\lambda > \lambda_*$*, then:*

1. *no E-events exist for* $\lambda < \lambda_*$*,*
2. *emergent time is undefined for* $\lambda < \lambda_*$*,*
3. *the hypersurface* $\lambda = \lambda_*$ *is a temporal boundary.*

Proof. See Section 3.6. □

A.7 Measurement and the generation of time

Definition A.9 (Localization)**.** A measurement corresponds to a localization of an informational distribution:

$$p(x) \longrightarrow p_{\text{loc}}(x).$$

Theorem A.4 (Measurement generates emergent time)**.** *Localization induces a new E-event, which extends the emergent time function.*

Proof. See Section 3.7. □

A.8 Summary

This appendix has presented the mathematical foundations of ETIM, including the formal structure of E-events, causal order, information layers, update maps, entanglement, time intensity, temporal boundaries, and measurement. These results provide the discrete and causal basis for the physical applications developed in Sections 4–7 and establish ETIM as a coherent and mathematically consistent framework for emergent time.

B Quantum and Information-Geometric Foundations

This appendix develops the quantum and information-geometric structures that underlie Sections 8–12. While Appendix A established the discrete causal foundations of ETIM, the present appendix provides the continuous, geometric, and quantum-theoretic tools required to analyze interference, measurement, entanglement, primordial fluctuations, and the Wheeler–DeWitt formulation of emergent time. The results collected here serve as the bridge between the informational architecture of ETIM and its physical manifestations in cosmology and quantum gravity.

B.1 Fisher information metric and statistical manifolds

Definition B.1 (Statistical manifold)**.** Let $\mathcal{M}$ be a family of probability distributions

$$p(x|\theta), \qquad \theta = (\theta^1, \dots, \theta^n).$$

If $\mathcal{M}$ is smoothly parametrized by θ, it forms an *n-dimensional statistical manifold.*

Definition B.2 (Fisher information metric)**.** The Fisher metric on $\mathcal{M}$ is

$$g_{ij}(\theta) = \mathbb{E}[\partial_i \log p(x|\theta)\, \partial_j \log p(x|\theta)]\,.$$

Lemma B.1 (Positivity)**.** *The Fisher metric is positive semidefinite, and positive definite if the model is identifiable.*

Proof. Standard information-geometric arguments; see Section 8.1. □

B.2 Connections, curvature, and geodesic flow

Definition B.3 (Levi–Civita connection)**.** The Levi–Civita connection associated with the Fisher metric is

$$\Gamma^k_{ij} = \frac{1}{2} g^{kl} \left(\partial_i g_{jl} + \partial_j g_{il} - \partial_l g_{ij} \right).$$

Definition B.4 (Geodesics)**.** Curves $\theta^i(\lambda)$ satisfying

$$\frac{d^2\theta^k}{d\lambda^2} + \Gamma^k_{ij} \frac{d\theta^i}{d\lambda} \frac{d\theta^j}{d\lambda} = 0$$

are geodesics of the information geometry.

These structures underlie the geometric interpretation of interference and measurement.

B.3 Double-slit boundary conditions in information geometry

Consider two informational paths γ_1 and γ_2 on the statistical manifold. Their amplitudes are modeled as

$$\psi_i = \sqrt{p_i}\, e^{iS_i},$$

where S_i is the information-geometric action along γ_i.

Theorem B.1 (Interference from geometric superposition)**.** *The combined distribution satisfies*

$$p = |\psi_1 + \psi_2|^2 = p_1 + p_2 + 2\sqrt{p_1 p_2} \cos(\Delta S),$$

where $\Delta S = S_1 - S_2$*.*

Proof. Direct expansion; see Section 8.2. □

This provides the information-geometric origin of quantum interference.

B.4 Measurement as localization

Definition B.5 (Localization map)**.** A measurement corresponds to a contraction of the statistical manifold:

$$p(x|\theta) \longrightarrow p_{\text{loc}}(x|\theta')$$

where θ' lies on a lower-dimensional submanifold.

Theorem B.2 (Localization generates an E-event)**.** *The contraction of the statistical manifold induces a new informational transition, corresponding to an E-event in the ETIM framework.*

Proof. See Section 8.3. □

B.5 Entanglement entropy and convergent informational structures

Let ρ be a density operator on a bipartite system $A \otimes B$.

Definition B.6 (Von Neumann entropy)**.**

$$S(\rho) = -\text{Tr}(\rho \log \rho).$$

Definition B.7 (Reduced states)**.**

$$\rho_A = \text{Tr}_B \rho, \qquad \rho_B = \text{Tr}_A \rho.$$

Theorem B.3 (Convergent informational structure)**.** *If informational flows converge on a shared output node, the corresponding quantum state is entangled and satisfies*

$$S(\rho_A) = S(\rho_B) > 0.$$

Proof. See Section 8.4. □

This establishes the connection between ETIM entanglement and quantum entanglement.

B.6 Wheeler–DeWitt equation: derivation

Starting from the ADM decomposition of the ETIM action,

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g} \left[\frac{1}{2} A(T) g^{\mu\nu} \nabla_\mu T \nabla_\nu T - V(T) \right],$$

the Hamiltonian constraint becomes

$$\mathcal{H}_0 = \frac{16\pi G}{\sqrt{h}} \left(\pi_{ij}\pi^{ij} - \frac{1}{2}\pi^2 \right) + \frac{P_T^2}{2\sqrt{h} A(T)} + \cdots = 0.$$

Canonical quantization yields

$$\hat{\mathcal{H}}_0 \Psi[h_{ij}, T] = 0.$$

Theorem B.4 (ETIM Wheeler–DeWitt equation)**.** *The wavefunctional satisfies*

$$\left[-16\pi G \hbar^2 G_{ijkl} \frac{\delta^2}{\delta h_{ij} \delta h_{kl}} - \frac{\hbar^2}{2A(T)} \frac{\delta^2}{\delta T^2} + U[h_{ij}, T] \right] \Psi = 0,$$

where U contains curvature and potential terms.

B.7 Born–Oppenheimer decomposition and emergent time

Definition B.8 (BO decomposition)**.**

$$\Psi[h_{ij}, T] = \exp\left(\frac{i}{\hbar} S_0[h_{ij}, T]\right) \chi[h_{ij}, T].$$

Theorem B.5 (Emergent time)**.** *The semiclassical time parameter satisfies*

$$\frac{\partial}{\partial \tau} = \frac{1}{A(T)} \frac{\delta S_0}{\delta T} \frac{\delta}{\delta T}.$$

This provides the quantum origin of emergent time.

B.8 Scalar and tensor perturbations from the wavefunctional

Let

$$h_{ij} = a^2(\tau)(\delta_{ij} + \gamma_{ij}), \qquad T = T_0(\tau) + \delta T.$$

Theorem B.6 (Decoupling of scalar and tensor sectors)**.** *To quadratic order,*

$$\Psi = \Psi_{\text{scalar}}[\delta T]\, \Psi_{\text{tensor}}[\gamma_{ij}],$$

and the two sectors evolve independently.

Proof. See Section 11.1. □

This establishes the unified quantum gravitational origin of curvature perturbations and gravitational waves.

B.9 Temporal RT surfaces and holographic entropy

Definition B.9 (Temporal RT surface)**.** A codimension-2 surface γ_T extremizing

$$S_T = \frac{\text{Area}(\gamma_T)}{4G_N}$$

is the temporal Ryu–Takayanagi surface.

Theorem B.7 (Temporal entanglement monotonicity)**.** *If T increases monotonically,*

$$\frac{dS_T}{dT} > 0.$$

This provides the holographic interpretation of emergent time.

B.10 Summary

This appendix has presented the quantum and information-geometric foundations of ETIM, including the Fisher metric, interference geometry, measurement as localization, entanglement entropy, the Wheeler–DeWitt equation, the Born–Oppenheimer decomposition, scalar and tensor perturbations, and temporal holography. These results provide the continuous and quantum-theoretic basis for the physical phenomena analyzed in Sections 8–12 and complete the mathematical structure underlying emergent time.

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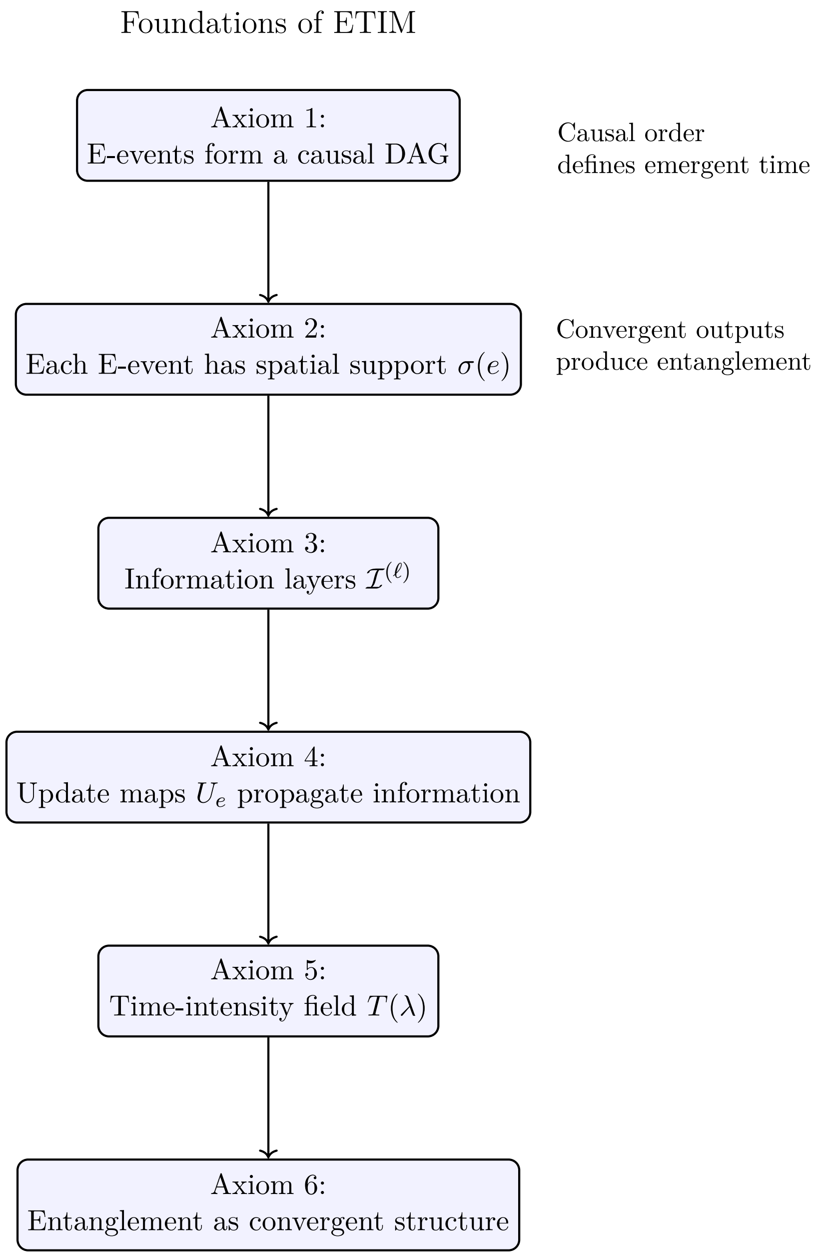

Figure 1: **Foundations of the ETIM framework.** The six axioms of the Emergent Time from Information Mechanics (ETIM) are shown as a hierarchical informational flow. Axiom 1 introduces E-events as elements of a causal directed acyclic graph (DAG), establishing the structural basis for emergent time. Axiom 2 assigns each E-event a spatial support $\sigma(e)$, enabling localized informational interactions. Axiom 3 organizes information into layers $\mathcal{I}^{(\ell)}$, representing increasing levels of informational refinement. Axiom 4 defines update maps U_e that propagate information forward along the DAG, ensuring causal consistency. Axiom 5 introduces the time-intensity field $T(\lambda)$, which governs the density of E-events and determines when temporal order emerges, stabilizes, or collapses. Axiom 6 characterizes entanglement as convergent informational structure, arising when distinct spatial supports contribute to a shared informational output. The arrows indicate the logical and structural progression of the axioms, while the side notes highlight two key consequences: causal order induces emergent time, and convergent outputs generate entanglement.

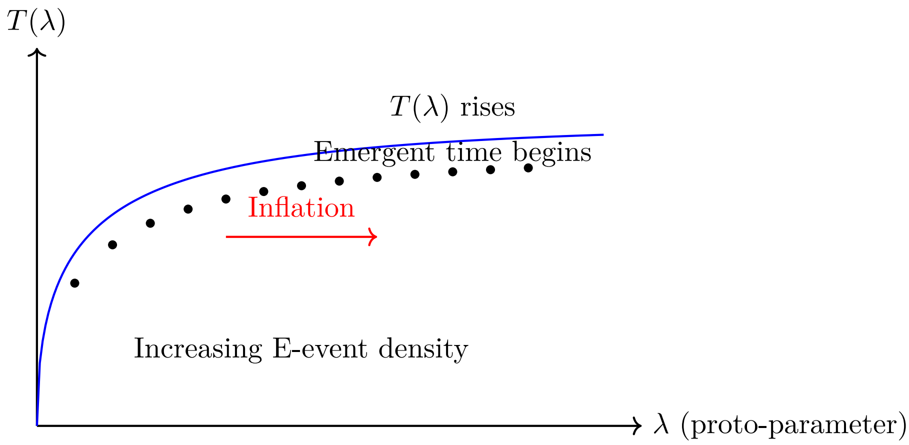

Figure 2: **Rise of the time-intensity field and the onset of inflation in ETIM.** The curve shows the growth of the time-intensity field $T(\lambda)$ as a function of the proto-parameter λ. When $T(\lambda)$ begins to rise from zero, E-events start to occur, marking the birth of emergent time. The black dots represent the density of E-events, which increases monotonically as T grows, in accordance with Lemma 3.5. This rapid increase in informational activity drives an accelerated expansion phase: the inflationary epoch. The red arrow highlights the region where the steep rise of $T(\lambda)$ produces a large effective Hubble parameter, demonstrating that inflation is a direct consequence of the emergence of time in the ETIM framework.

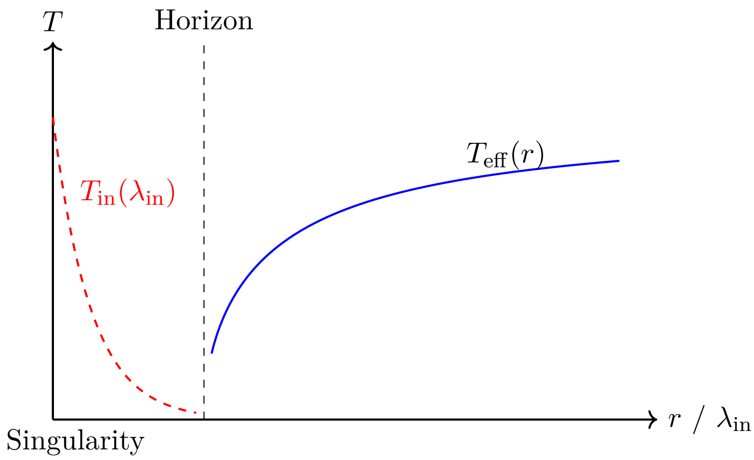

Figure 3: **Time-intensity profile across a Schwarzschild black hole in ETIM.** The blue curve shows the effective time intensity $T_{\text{eff}}(r)$ in the exterior region $r > 2M$, decreasing toward the horizon due to gravitational redshift. At the horizon (vertical dashed line), the effective time intensity approaches zero, reflecting the vanishing density of E-events for static observers. Inside the horizon, the red dashed curve represents the interior time intensity $T_{\text{in}}(\lambda_{\text{in}})$, which decays exponentially along infalling trajectories. As T_{in} collapses toward zero, the density of E-events vanishes and emergent time terminates, identifying the classical $r = 0$ singularity not as a geometric divergence but as a *temporal boundary.* This figure illustrates the ETIM interpretation of black hole interiors: the breakdown of spacetime corresponds to the collapse of temporal structure rather than curvature blow-up.

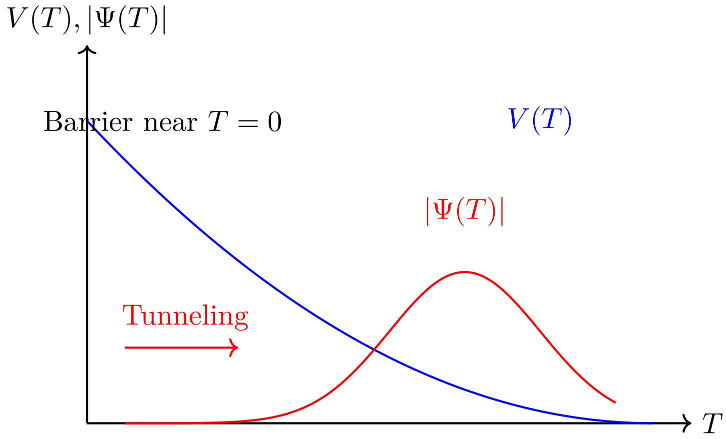

Figure 4: **Quantum origin of time in ETIM: potential barrier and wavefunctional tunneling.** The blue curve shows the effective potential $V(T)$ governing the quantum dynamics of the time-intensity variable T in the minisuperspace formulation of ETIM. Near $T = 0$, the potential forms a barrier, indicating that the pre-temporal state ($T = 0$) is classically forbidden. The red curve shows the wavefunctional amplitude $|\Psi(T)|$, which becomes peaked at finite T due to quantum tunneling through this barrier. The tunneling arrow illustrates the transition from the timeless regime ($T = 0$) to a state with nonzero time intensity, corresponding to the quantum creation of time. This figure visualizes the ETIM interpretation of the big bang as a tunneling event in the space of informational time intensity, rather than a geometric singularity.

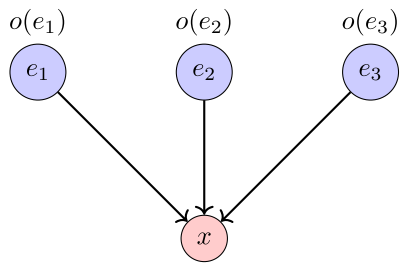

Figure 5: Convergent informational structure defining ETIM entanglement. Events e_1, e_2, e_3 have distinct spatial supports $o(e_i)$ but share a common output node x. This non-factorizable convergence of informational flows constitutes entanglement in the ETIM framework (Axiom 6). Unlike quantum entanglement in Hilbert space, which is defined by the non-separability of wavefunctions, ETIM entanglement is a structural property of the causal-informational architecture: multiple subsystems contribute to a single informational outcome that cannot be decomposed into independent parts. This convergent structure generates new E-events and therefore new temporal order, linking entanglement directly to the emergence of time.

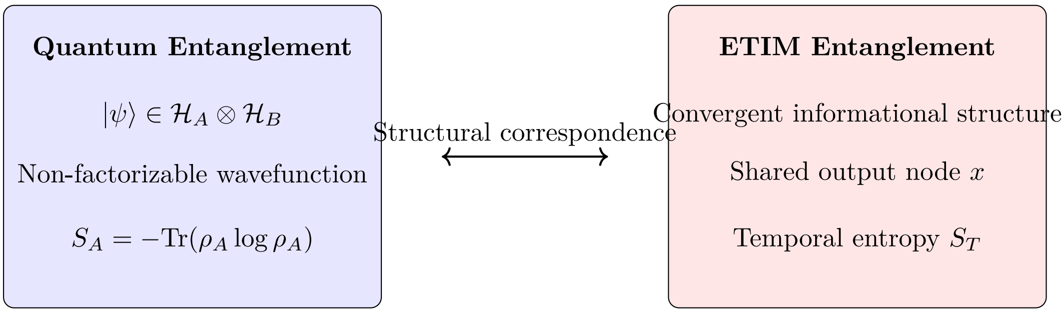

Figure 6: Comparison between standard quantum entanglement and ETIM entanglement. Left: In quantum mechanics, entanglement is defined by the non-factorizability of a state $|\psi\rangle \in \mathcal{H}_A \otimes mathcal H_B$, with entanglement entropy S_A quantifying correlations between subsystems. Right: In ETIM, entanglement is defined structurally as the convergence of informational flows from distinct subsystems into a shared output node. This structural entanglement does not rely on Hilbert-space tensor products but on the causal organization of E-events. The correspondence arrow indicates that quantum entanglement is recovered as a special case of ETIM entanglement when the informational structure is represented in a Hilbert space.

Figure 7: Mechanism by which entanglement generates emergent time in ETIM. Convergent informational structures (left) produce new E-events (center), which increase the time-intensity field T. As T grows, the rank function defining emergent time advances, establishing a temporal ordering of events. Thus, entanglement is not merely a correlation but the generator of temporal structure: the monotonic growth of entanglement leads to the monotonic growth of T, providing a microscopic origin for the arrow of time. This mechanism unifies quantum correlations, measurement, and temporal evolution within a single informational framework.

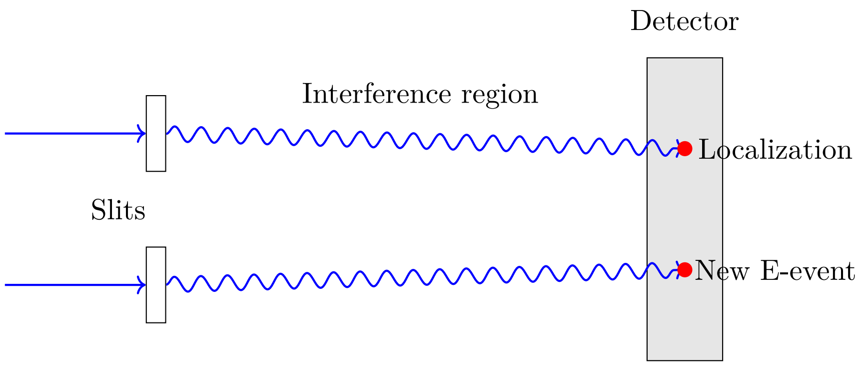

Figure 8: **Information-geometric interpretation of the double-slit experiment in ETIM.** The incoming informational flows (blue arrows) encounter two slits, which impose boundary conditions on the information manifold rather than representing physical paths. The flows bifurcate and propagate toward the detector, where their geometric overlap produces an interference region. In ETIM, this interference is not due to wave-like behavior but arises from the superposition of informational flows on the manifold. Upon reaching the detector, the extended informational distribution becomes localized, generating new E-events (red dots). This localization corresponds to measurement: the creation of definite temporal order through the production of new informational nodes. The figure illustrates how ETIM unifies interference and measurement as geometric processes within the same informational architecture.

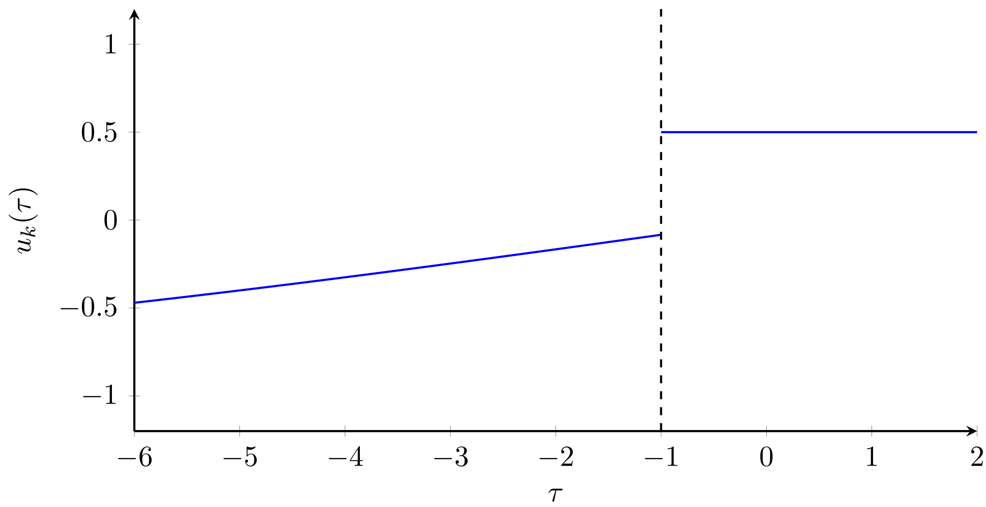

Figure 9: Schematic evolution of the canonical mode function $u_k(\tau)$ for fluctuations of the time intensity field in ETIM. For early times ($c_T k \gg aH$), the mode oscillates as in flat spacetime, reflecting the fact that local variations in the emergence of time propagate freely when their physical wavelength is much smaller than the emergent-time Hubble radius. As the universe expands and $c_T k$ becomes comparable to aH, the mode crosses the emergent-time horizon. Once in the super-horizon regime ($c_T k \ll aH$), the oscillations cease and the mode freezes to a constant value. This freeze-out corresponds to the local stabilization of emergent time: spatial variations in the density of E-events become imprinted as classical curvature perturbations on the spatial slices of the graded poset.

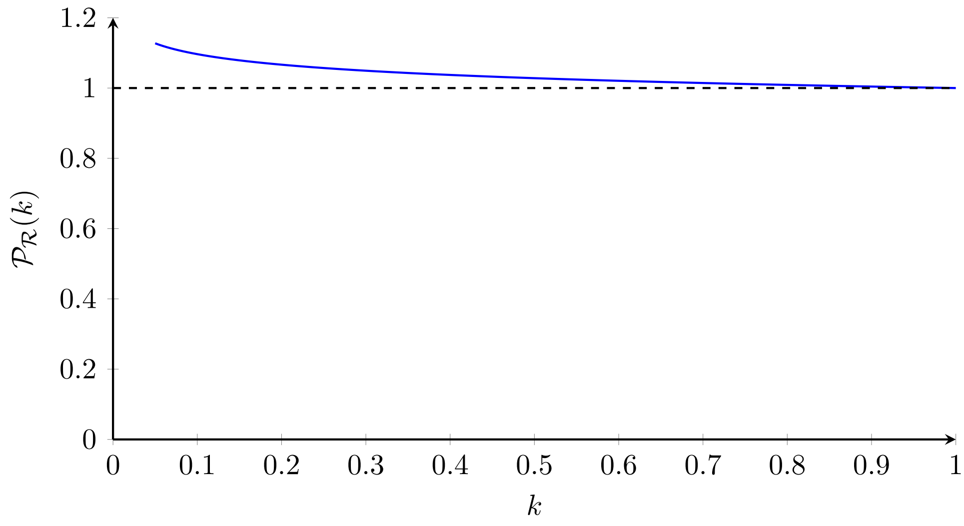

Figure 10: Schematic scalar power spectrum $\mathcal{P}_{\mathcal{R}}(k)$ generated by spatial fluctuations of the time intensity field in ETIM. Because the canonical variable u_k freezes at horizon crossing and $\mathcal{P}_{\mathcal{R}}(k) \propto H^2/(c_T^3 A)$, the resulting spectrum is nearly scale-invariant, with a slight tilt determined by the slow variation of $T(\tau)$ and the emergent-time Hubble parameter $H(\tau)$. Unlike standard inflation, where the tilt arises from the slow-roll parameters of a scalar field evolving within time, here the tilt reflects the rate at which time itself emerges. The dashed line shows the exactly scale-invariant case for comparison.

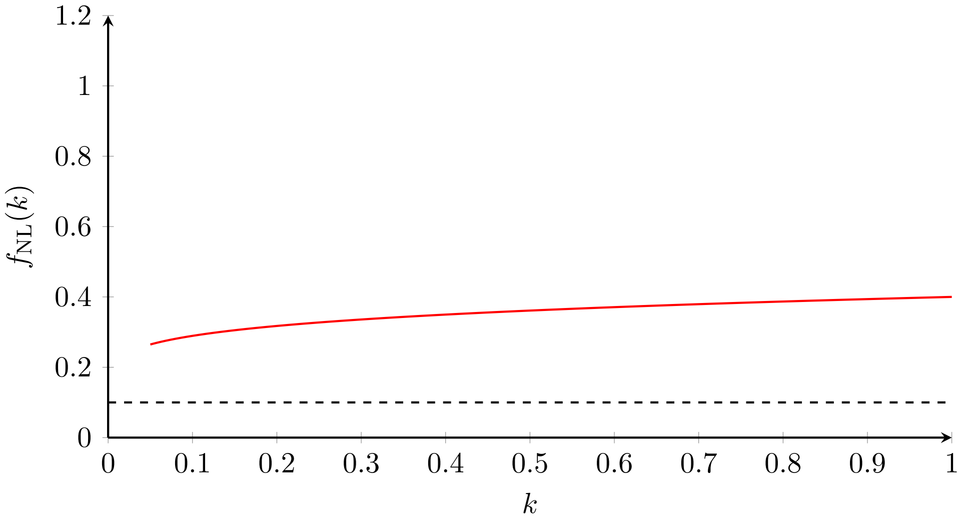

Figure 11: Scale dependence of the bispectrum amplitude $f_{\mathrm{NL}}(k)$ in ETIM. Non-Gaussianity arises from nonlinearities in the emergence of time, encoded in the cubic interactions of the time intensity field. The mild scale dependence shown here reflects the fact that the strength of nonlinear emergent-time interactions varies slowly with τ, and that the propagation speed c_T enhances higher-order correlations when $c_T < 1$. In contrast to standard inflation, where non-Gaussianity is typically small unless the scalar field has non-canonical kinetic terms, ETIM predicts non-Gaussianity as a direct consequence of the informational structure of emergent time. The dashed line indicates the minimal value corresponding to purely Gaussian fluctuations.

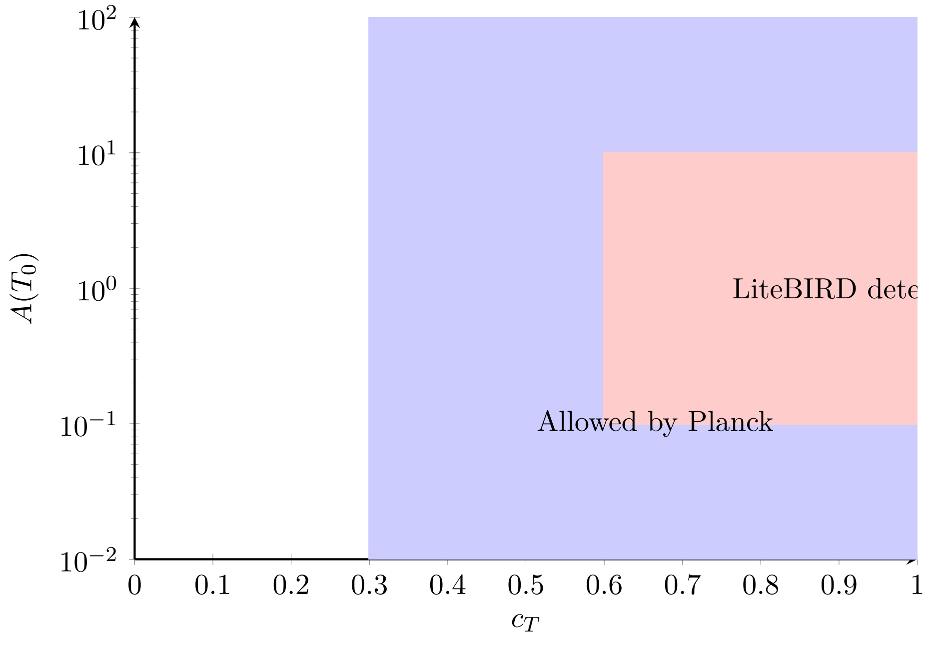

Figure 12: Parameter space of the emergent-time cosmology in the $(c_T, A(T_0))$ plane. The blue region indicates the range of parameters consistent with current Planck and BICEP/Keck constraints on the scalar amplitude, scalar tilt, and tensor-to-scalar ratio. The red region shows the subset of this space that produces a tensor amplitude detectable by LiteBIRD. The horizontal direction c_T controls the propagation speed of fluctuations in the emergence of time, while the vertical direction $A(T_0)$ encodes the effective kinetic weight of the time-intensity field. Together, these parameters determine the amplitude and scale dependence of primordial curvature perturbations generated by spatial variations in the density of E-events.

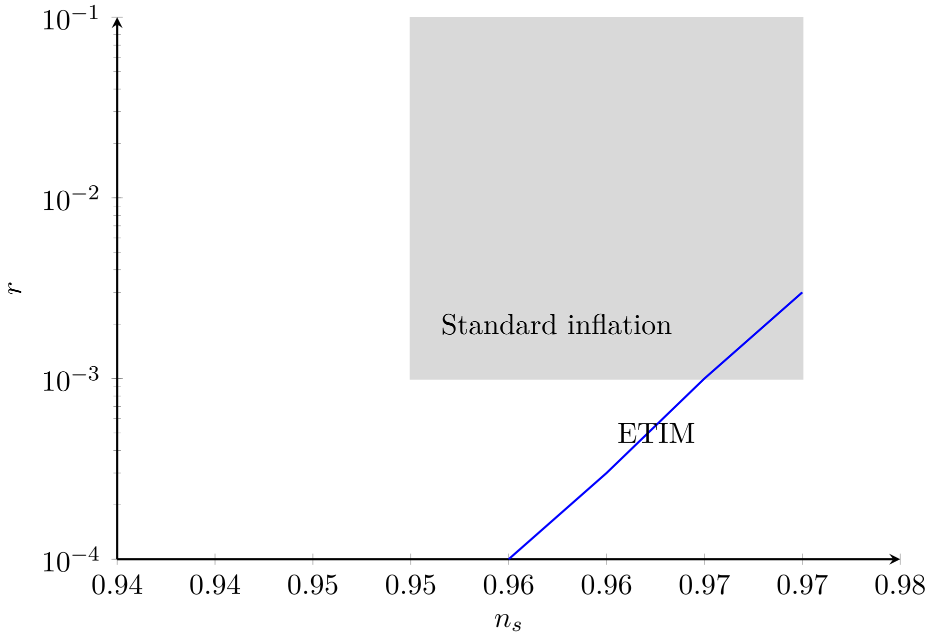

Figure 13: Predictions of emergent-time cosmology in the (n_s, r) plane. The gray band represents the region allowed by current Planck constraints on the scalar tilt n_s and the upper bound on the tensor-to-scalar ratio r. The blue curve shows the ETIM prediction obtained from the dynamics of the time-intensity field, which differs qualitatively from standard slow-roll inflation (shown in gray). In ETIM, the scalar and tensor sectors are not tied by the usual consistency relation $r = -8n_T$; instead, r depends on the emergent-time parameters c_T, $A(T_0)$, and N_T. This produces a characteristic trajectory in the (n_s, r) plane that can be distinguished by next-generation CMB experiments.

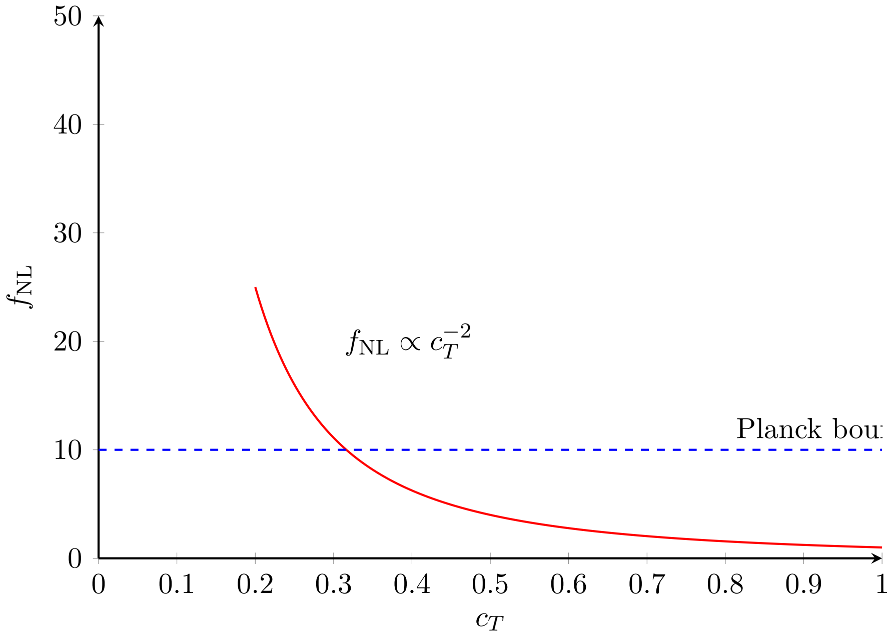

Figure 14: Non-Gaussianity as a function of the emergent-time propagation speed c_T. The red curve shows the characteristic ETIM prediction $f_{\mathrm{NL}} \propto c_T^{-2}$, which arises from nonlinearities in the emergence of time and the cubic interactions of the time-intensity field. The dashed blue line indicates the current Planck bound on local-type non-Gaussianity. Because f_{NL} grows rapidly as c_T decreases, ETIM predicts a strong correlation between the speed of emergent-time fluctuations and the amplitude of primordial non-Gaussianity. This provides a sharp observational signature that can be tested by CMB-S4 and future large-scale structure surveys.

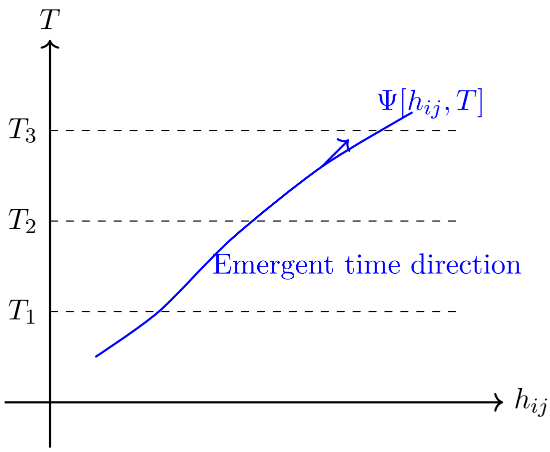

Figure 15: Superspace representation of the ETIM wave functional $\Psi[h_{ij}, T]$. The horizontal axis denotes the infinite-dimensional configuration space of spatial metrics h_{ij}, while the vertical axis represents the time-intensity field T, which parametrizes the emergence of temporal order. The blue curve shows a semiclassical trajectory in superspace obtained from the Hamilton–Jacobi equation. As T increases, the wave functional flows monotonically along this trajectory, reflecting the fact that the density of E-events grows and the system approaches a classical spacetime regime. The dashed horizontal lines represent constant-T slices, which correspond to hypersurfaces of equal emergent time. The arrow indicates the direction of increasing T, which defines the emergent arrow of time in the semiclassical limit.

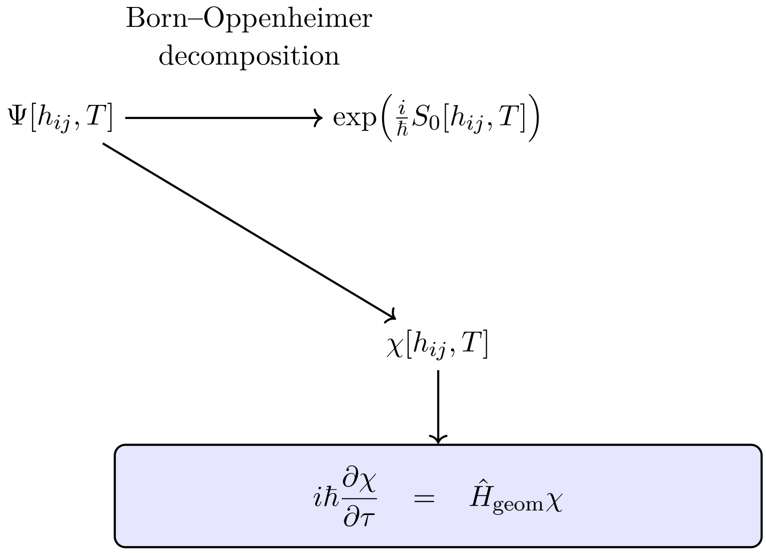

Figure 16: Born–Oppenheimer decomposition of the ETIM wave functional. The full quantum state $\Psi[h_{ij}, T]$ is factorized into a rapidly varying WKB phase $\exp(iS_0/\hbar)$ and a slowly varying prefactor $\chi[h_{ij}, T]$. The WKB phase encodes the semiclassical dynamics of the time-intensity field and determines the emergent time parameter τ through $\partial/\partial\tau \propto (\delta S_0/\delta T)\, \delta/\delta T$. The prefactor χ satisfies a Schrödinger equation for quantum geometry, with τ acting as an internal clock. This figure illustrates how the Born–Oppenheimer hierarchy converts the timeless Wheeler–DeWitt equation into a time-dependent Schrödinger equation, thereby explaining how classical time emerges from the joint quantum state of geometry and the time-intensity field.

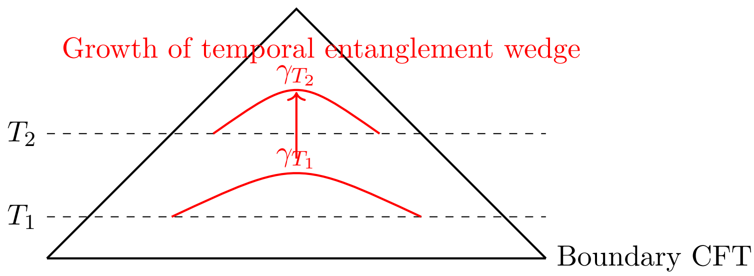

Figure 17: Temporal entanglement wedge associated with the emergence of time in ETIM. The horizontal axis represents the boundary theory, while the triangular region represents the bulk spacetime reconstructed from boundary data. The red curves γ_{T_1} and γ_{T_2} are temporal Ryu–Takayanagi (RT) surfaces corresponding to two different values of the time-intensity field, $T_1 < T_2$. As T increases, the RT surface moves deeper into the bulk and its area grows, reflecting the monotonic increase of temporal entanglement entropy S_T. This growth encodes the arrow of time: emergent time corresponds to the expansion of the entanglement wedge and the accumulation of informational correlations between geometry and the time-intensity field. Near the temporal boundary $T \to 0$, the wedge collapses, indicating the absence of classical temporal structure.