Relational Coexistence Theory (TCR): Quantum and Cosmological Foundations

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Abstract

The "Teoria della Coesistenza Relazionale" (TCR, Relational Coexistence Theory) proposes an ontological framework in which spacetime R is not the primary level of reality, but rather the emergence of an original relational domain R'. The TCR thus simultaneously addresses fundamental issues of QM and GR, suggesting a connection between phenomena typically treated as separate, such as interference, entanglement, decoherence, cosmic expansion, and the arrow of time. The strength of the framework lies not in mathematical complexity, but in the parsimony of its ontological foundation: from R' multidisciplinary consequences spontaneously emerge, linking microscopic and cosmological phenomena.

The theory is presented as an open research program, with preliminary experimental predictions and room for further mathematical development, and it offers a unified reinterpretation of some well-known paradoxes of modern physics.

Keywords Emergent spacetime · Relational ontology · Arrow of time · Quantum decoherence · Entanglement · Cosmic expansion · Relational thermodynamics · Black holes · Quantum gravity · Dark energy · Dark matter · Quantum computing · Coherence time · Cosmological inhomogeneities · Unified theories

1 Introduction

In the current framework of physics, the description of the universe rests on two distinct theoretical pillars: general relativity (GR), which governs gravitation and the large-scale structure of spacetime [1, 2], and quantum mechanics (QM), which accounts for interactions at the microscopic level [3, 4, 5]. Both theories have been subjected to rigorous experimental tests, and their successes represent one of the highest achievements of modern science.

Nevertheless, contemporary theoretical physics is marked by a profound conceptual discontinuity: these two major triumphs of scientific knowledge operate in separate domains and fail to integrate into a unified framework. This fracture becomes evident in the inability to provide a coherent and widely accepted explanation of complex phenomena such as the origin of the universe, cosmic inflation [6, 7, 8, 9], the non-homogeneous distribution of expansion, or the very nature of quantum entanglement. Moreover, the conception of spacetime as a mere neutral "container" of events is challenged both by observations suggesting deeper structures and by unresolved issues such as the role of time in quantum processes. This situation results in a structural gap in the conceptual foundations of physics: the absence of a common ontological framework in which QM and GR can coexist without contradictions. Bridging this gap requires a perspective capable of operating at a primary level, offering a coherent framework that integrates phenomena currently treated in isolation.

Over the past decades, the unification of QM and GR into a consistent theoretical framework has become one of the central challenges of fundamental physics. This objective has given rise to research programs of remarkable mathematical and conceptual sophistication. Among the most notable attempts are:

- string theory, which describes particles as vibrations of one-dimensional entities in higher-dimensional spaces (Green, Schwarz, Witten, and others);
- loop quantum gravity, which discretizes the geometry of spacetime (Rovelli and Smolin [10, 11]);
- emergent gravity, which interprets curvature as a thermodynamic phenomenon (Jacobson [12], Padmanabhan [13], Verlinde [14]);
- various models of discrete or causal spacetime (Markopoulou [15], Seiberg [16]).

Recent theoretical developments have further strengthened this emergent-spacetime perspective. Padmanabhan's later work [17] and Verlinde's extended formulation of entropic gravity [18] have expanded the thermodynamic interpretation of curvature, while Van Raamsdonk [19] showed that spacetime connectivity can emerge directly from quantum entanglement. Together, these contributions indicate that the geometry of spacetime and the gravitational interaction may both arise from deeper relational or informational principles.

While offering valuable insights and formal developments, none of these approaches has yet achieved direct experimental validation or a shared interpretative consensus. This leaves the central question unresolved: what ontological framework can accommodate, without contradiction, the descriptions provided by QM and GR.

The TCR proposes a conceptual shift to overcome the structural limits that separate QM and GR. Instead of quantizing spacetime directly or postulating its emergence from indeterminate entities, the TCR distinguishes itself from previous unification attempts through four fundamental features:

- Internal coherence: it is grounded on a primary relational ontology in which space and time are not assumed *a priori*, but emerge as derivative descriptions of coexistences among entities. This approach removes conceptual and interpretative contradictions, offering a unified language for both quantum and gravitational phenomena.
- GR–QM compatibility: starting from fundamental relations rather than a predefined spacetime structure, the TCR naturally derives both GR metrics and the probabilistic formalism of QM, preserving their validity within their respective domains and providing a common ontological foundation.
- Predictive capacity: the formalization makes it possible to generate testable scenarios, such as local variations of cosmic expansion, persistent quantum correlations, and other physical phenomena.
- Current or potential experimental adherence: the model is designed to yield verifiable predictions, either indirectly, by confronting the formalism with existing cosmological and experimental data, or directly, through targeted experiments in quantum and astrophysical regimes, thus constituting an operationally feasible research program.

On these grounds, the TCR does not present itself as an antagonistic alternative to QM and GR, but rather as a unifying framework in which both find a natural place, without relinquishing their respective experimental achievements.

The TCR provides a unified framework in which apparently distinct phenomena are traced back to a single higher-level description grounded in primary relations. Within this perspective, cosmic inflation, large-scale inhomogeneities, and the current accelerated expansion of the universe emerge as manifestations of the same relational mechanism, thereby eliminating the need to introduce *ad hoc* postulated entities, such as dark energy, that lack direct observational confirmation. The theory also offers a new interpretation of entropy as an emergent property of coexistences, moving beyond purely statistical or geometric readings.

The approach is rooted in observational data, from which its theoretical structures are directly derived, and it leads to experimentally testable predictions both in the astrophysical domain and through experiments in fundamental physics. The implications of the TCR naturally extend to multidisciplinary fields, from the thermodynamics of information to observational cosmology, from quantum correlation physics to complex systems theory. This extension is not a conceptual imposition, but rather the logical continuation of a theoretical framework that seeks to describe reality as a coherent set of actualized and original relations.

The present work follows the IMRaD structure (Introduction, Methods, Results, and Discussion):

- Section 1 (Introduction): defines the central problem, the theoretical context, and the limitations of existing theories, motivating the need for a new ontological framework.
- Section 2 (Methods): presents the conceptual and formal structure of the TCR, introducing the primary relational ontology R', the function Ω, and the transformation Π, and specifies the criteria for derivation from observational data.
- Section 3 (Results): outlines the main unifications and reinterpretations provided by the TCR, including the connection between inflation, inhomogeneities, and cosmic acceleration, the proposed resolution of the black hole information problem, the new interpretation of entropy, and experimental predictions.

- Section 4 (Discussion): evaluates the theoretical and experimental significance of the results, explores the multidisciplinary implications of the proposed framework, lists supporting experiments for the theory, and proposes new ones for validation or falsification.

2 Method

2.1 Motivations and empirical context

The experimentally confirmed violations of Bell's inequalities [20], particularly through loophole-free tests, rule out the possibility of describing quantum phenomena by means of local hidden-variable theories. These results, first systematically observed by Aspect et al. [21] and subsequently confirmed in experiments conducted by Hensen et al. [22], Giustina et al. [23], and Zeilinger et al. [24], pose a profound challenge to the compatibility of realism and locality as classically conceived.

The most widespread interpretations follow two main directions: the anti-realist approach, such as that of Copenhagen, which relinquishes the description of a reality independent of the observer [25, 26]; and the realist but non-local approach, as in Bohmian mechanics, which introduces non-local causal mechanisms often difficult to reconcile with relativity [27, 28].

In our view, both positions are unsatisfactory: the first abandons an objective description of the physical world, while the second maintains realism but at the cost of introducing ontologically opaque structures. However, the results of Bell do not necessarily compel one to choose between realism and locality, but rather to question spacetime itself as the ontological foundation.

The proposal advanced here is to preserve realism while abandoning the assumption that physical relations must be mediated within spacetime. Instead, we introduce a relational ontology, in which the fundamental element is the coexistence among entities within an original pre-spatiotemporal structure, from which the physical reality accessible to us emerges as a derived phenomenon. By "coexistence" we mean here a real ontological connection between entities, not mediated by spacetime, but rooted in an original relational condition.

From this perspective, entanglement no longer appears as an anomaly to be explained in spatiotemporal terms, but rather as a relation of coexistence that precedes and transcends the geometry of the observable universe.

This perspective opens the way to a new paradigm, in which space, time, and causality emerge from a deeper relational structure, to be described in the following sections.

2.2 Ontological assumptions

If we accept that two entangled particles cannot communicate through mechanisms internal to our spacetime, and we do not find a more ontologically satisfactory solution within the current spatiotemporal framework[1], the most logical and at the same time most parsimonious conclusion is that they are connected in another reality, here denoted as R'.

I am aware that positing a new reality R' constitutes a strong ontological choice. However, this choice is consistent with the scientific method: one formulates a hypothesis, even a controversial one; verifies its coherence with experimental data; and finally explores its practical and philosophical implications. Many realities that are now widely accepted, such as the relativity of time, were once regarded as implausible hypotheses.

From this perspective, two entangled particles behave like two "shadows," that is, projections of the same entity in R' projected into R. Indeed, the two entities are indistinguishable and unidentifiable in their properties as long as they remain in this state, and they may be situated at arbitrarily large distances while preserving the characteristics of projections, namely, changing simultaneously.

When, on the other hand, quantum correlation ceases, the particles behave as two projections of distinct entities. This analogy leads to two fundamental assumptions:

1. Entities in our reality R are projections of original entities in R'. Consequently, R' is the ontologically primary domain, while R is the emergent domain in which observable physical properties manifest.
2. In R', entities may be at the same time perfectly united or completely separate, depending on their state of coexistence. To quantify this condition, we introduce the coexistence parameter Ω, defined as a measure of relational intensity in R'. Ω is a continuous and evolving parameter, with $\Omega = 1$ indicating that two entities in R' are, in fact, the same entity, and $\Omega = 0$ indicating a total absence of relation.

[1]Other known options, such as retrocausal interpretations or models based on non-spatial algebraic structures, have been considered but discarded, as they require more complex ontologies or are less consistent with experimental evidence. Their inclusion in this context would introduce concepts that are not developed in the present theory, increasing the risk of confusion without providing interpretative benefits.

These assumptions allow entanglement to be interpreted as the direct manifestation of coexistence in R', without requiring hypotheses of non-local interaction in spacetime. The physical laws in R thus emerge as effects of the relational structure and of the values of Ω specific to R', with space and time as parameters derived from the arrangement of such original relations.

If two entangled particles can be regarded as entities emerging from R' into our reality R, the logical next step is that all entities in our spacetime are nothing but emergences of entities from the original reality R'.

Here is a list of the only features of R' that we can deduce from experimental data:

1. R' is atemporal and aspatial, given the instantaneous emergence, at the quantum level, of changes in R'.
2. There exist entities in R', which we denote as $\mathbf{e}'$, to distinguish them from entities in R, denoted as $\mathbf{e}$.
3. The entities $\mathbf{e}'$ in R', inhabiting an atemporal and aspatial reality, cannot possess intrinsic state properties (such as mass, charge, or other physical attributes), but can only be described through their relations with other entities. This implies that R' is a purely relational reality.
4. Entities in R' possess a certain degree of coexistence with one another, ranging from $\Omega = 1$ (total fusion and indistinguishability) to $\Omega = 0$ (absence of any form of relation).

The last ontological novelty we introduce is the function Π, which acts as a bridge between R' and R, enabling and quantizing the emergence in R of entities from R'. Experimental evidence indicates that the emergence of relations from R' to R is instantaneous in quantum phenomena, but that the evolution of relations in R follows the laws of spacetime.

The two elements Π and Ω will constitute the foundation for formulating testable predictions in the following chapters.

Both the parameter Ω and the function Π are new concepts introduced in this theory. In this section their ontological description is provided, while a first quantitative treatment will be presented here in simplified terms. As with all new theoretical structures, a long process—likely years—will be required before arriving at a rigorous mathematical formulation.

At this stage, we focus on the analysis of limiting cases:

- Case $\Omega = 1$: two entities in R' coincide completely, making them indistinguishable and inseparable; in R, this manifests as perfect correlations, independent of distance and experimental conditions, analogous to an "ideal" entanglement not subject to degradation.
- Case $\Omega = 0$: two entities in R' are totally independent, and in R they exhibit no correlation whatsoever, not even statistical.
- Transitions of Ω: intermediate variations of Ω generate partial correlations that could yield experimental signatures distinguishable from standard quantum models, especially in many-body systems or in weakly entangled states. From this perspective, gravity can also be integrated into the framework, representing an example of relatively low coexistence: the limiting case $\Omega \to 0$ can be described in R as a distance tending to infinity, consistent with the idea of a diffuse interaction such as gravitation[2].
- Discrete Π: if Π operates as a mapping into quantized events, the emergent phenomena in R display discrete jumps corresponding to changes in R'.
- Continuous Π: if Π operates as a fluid transformation, changes in R' are reflected in progressive and observable variations in R, since they operate within the temporal domain.

These limiting cases, though simplified, already allow for the formulation of novel and experimentally testable predictions, which will be outlined in the following sections.

As a final logical consideration, each entity $\mathbf{e}$ in R has a one-to-one correspondence with an entity $\mathbf{e}'$ in R'. Since the phenomenal reality R arises as a projection of R', which is purely relational, it follows that R too, in its original structure, is a relational space. Properties that we commonly interpret as "intrinsic," such as charge, may also emerge from deeper relational configurations. The theory proposed here assumes that every observable property in R ultimately derives from relations of coexistence in R', while acknowledging that a quantitative and predictive formulation of this derivation will require further developments.

This ontological framework provides an elegant way out of the paradoxes that have long plagued the interpretation of quantum phenomena. First, the paradox of action at a distance is dissolved: the observed correlations require no

[2]Formally, this idea can be expressed as $\lim_{\Omega \to 0} d_R(e_i, e_j) \to \infty$, where d_R is the distance in R between entities e_i and e_j.

mechanism of transmission within spacetime, since they are manifestations of a preexisting coexistence in R'. There is therefore no "action" between separated points, but an ontological unity projected into multiple points of R.

Second, the conflict between realism and locality, highlighted by Bell's theorem, loses its traditional meaning. Realism is preserved by assuming the objective existence of R', while "non-locality" is no longer an anomaly, since the fundamental relations are not subject to distance or propagation within spacetime during emergence in R.

Finally, this perspective neutralizes the apparent discontinuity between the microscopic and macroscopic worlds: the function Π ensures that the emergence of relations in R is instantaneous only in the transition from R' (as occurs in quantum phenomena), while their evolution within R remains constrained by relativistic laws and spatiotemporal causality.

In summary, what in traditional interpretations appears as a problem—instantaneous communication, non-local hidden variables, collapse of the wave function—becomes in this framework a natural effect of the original relational structure. The paradoxes find their ontological resolution in the existence of R'. The quantitative treatment of how R' accounts in detail for observed phenomena will be developed in the following sections.

2.3 Proposed framework

Having established in the ontological assumptions the existence of an original reality R' and the central role of entities $\mathbf{e}'$ and their relations, the next step is to construct a theoretical structure that translates these principles into an operational model. This step is not merely descriptive, but a methodological necessity: only by defining a coherent and structured framework is it possible to transform an ontological hypothesis into a theory capable of producing testable predictions.

In this context, the proposed model is articulated on three distinct yet interconnected conceptual levels:

1. Level 1 — Reality R': the ontologically primary domain, devoid of space and time, populated by entities $\mathbf{e}'$ whose only possible description is given by their mutual degree of coexistence Ω.
2. Level 2 — Function Π: the mapping that enables the emergence of entities and relations from R' to R. Π may operate in discrete mode (quantized events) or continuous mode (progressive transformations).
3. Level 3 — Reality R: the emergent domain in which entities $\mathbf{e}$, in one-to-one correspondence with entities $\mathbf{e}'$ in R', manifest endowed with physical properties and subject to spatiotemporal laws.

The parameter Ω quantifies relational intensity in R':

- $\Omega = 1$: total coexistence, indistinguishable entities in R' and perfect correlations in R, independent of distance or experimental conditions.
- $\Omega = 0$: absence of relation in R', no observable correlation in R.
- $0 < \Omega < 1$: partial correlations, potentially distinguishable from the predictions of standard quantum mechanics, particularly in complex systems or weakly entangled states.

The function Π governs the transition between the two domains:

- Discrete Π: emergence occurs through quantized jumps, generating abrupt variations in observed physical properties.
- Continuous Π: changes in R' are reflected in R gradually, with transitions observable as progressive variations in correlation.

The physical laws in R emerge as a consequence of the arrangement and evolution of relations in R'. Space and time are not fundamental constituents, but parameters derived from the original relational structure. This framework enables a unified reinterpretation of apparently disparate phenomena:

- Entanglement does not require instantaneous transmission of information in spacetime, but reflects a preexisting coexistence in R'.
- Bell's theorem does not imply a mysterious "non-locality," since the fundamental relations are not subject to distance.
- The collapse of the wave function is the manifestation in R of an instantaneous change in R' filtered through Π.
- The difference between microscopic and macroscopic phenomena reduces to a different dynamics of Π and a different degree of Ω.

The proposed framework paves the way for new categories of testable predictions:

1. Observation of "weakly" entangled states with intermediate correlations ($0 < \Omega < 1$) that deviate from standard predictions.
2. Identification of discrete or continuous transitions in Π through sudden or progressive variations of correlation in controlled systems.
3. Description of gravity as extremely low coexistence ($\Omega \to 0$), consistent with its weak and diffuse nature.

In conclusion, the proposed framework is not merely an interpretative hypothesis, but a theoretical structure that integrates quantum and macroscopic phenomena into a single scheme, preserving realism while overcoming the conceptual difficulties of traditional interpretations. The following sections will develop the quantitative formalization of Ω and Π and show how these can be employed to derive experimental predictions.

2.4 Comparison with existing paradigms

The proposed framework occupies an intermediate position between traditional interpretations of quantum mechanics and emerging ontological models, distinguishing itself both by its primary relational foundation and by the constitutive role of the function Π.

Compared to the Copenhagen interpretation [25, 26], the present formulation goes beyond the notion of a purely instrumental description of phenomena: here, the correlations observed in R derive from an ontologically primary reality R', rather than from a mere probabilistic formalism. The "collapse" is not an arbitrary process, but the manifestation in R of a relational change in R'.

When contrasted with hidden-variable interpretations (e.g., de Broglie–Bohm [29, 27]), the model does not postulate a deterministic evolution within spacetime, but a pre-spatiotemporal dynamics in which entities $\mathbf{e}'$ are described solely by their degree of coexistence Ω. Fundamental information is not transported through spacetime, but is intrinsic to the relations themselves.

Unlike many-worlds interpretations (Everett [30, 31]), the proposed framework does not require an ontological proliferation of branching universes. The uniqueness of R is ensured by the mapping Π, which selects and actualizes a coherent set of entities and relations from R'.

In comparison with emergent spacetime models (e.g., holographic approaches [32, 33] or causal set theories [34, 35]), the present approach is distinguished by the primary and non-derivative character of relations in R'. Space and time do not emerge from a network of causal events in R, but are parameters derived from preexisting coexistences in R'.

The holographic principle, as formulated by Bousso [36], also represents a significant precursor to emergent-spacetime approaches, emphasizing the informational and thermodynamic nature of gravitational degrees of freedom.

These proposals are conceptually connected to thermodynamic-gravity frameworks such as those of Jacobson [12] and Padmanabhan [13], and to Verlinde's entropic-gravity formulation [14, 18]. In contrast, the TCR postulates a deeper ontological layer R' in which relations themselves are primary, preceding both geometry and energy–entropy dualities.

Finally, in contrast with quantum gravity models, the proposed framework offers a reinterpretation of gravity as the universe's natural and constant tendency to increase coexistence among entities, rendering its weakness not as an anomaly but as a natural consequence of the original relational structure [10, 37].

In summary, the proposed model:

- preserves ontological realism, avoiding purely epistemic solutions;
- integrates microscopic and macroscopic phenomena within a single scheme;
- eliminates the need for unobservable assumptions such as multiple worlds or hidden fields within spacetime;
- provides a unified interpretative key amenable to targeted experimental verification.

3 Results

3.1 Mathematical formulation of the ontological assumptions

In Chapter 2, the ontological assumptions motivating the introduction of the original reality R', the coexistence parameter Ω, and the emergence function Π were outlined. These elements were presented as the logical and parsimonious consequence of a phenomenological analysis of quantum systems—particularly entanglement—and as a coherent alternative to traditional interpretations based solely on spatiotemporal structure.

In this section, we translate these assumptions into an essential mathematical formulation, with the goal of showing how the properties of R' and the relations among its entities can generate the observable correlations in R. The results presented here thus constitute the first step toward a quantitative modeling of the proposed framework, capable of directly connecting original relational quantities with experimental measurements in spacetime.

Let

$$R' = \{\, e'_1, e'_2, \dots \} \tag{1}$$

denote the *original reality*, composed of purely relational entities e'_i, lacking spatiotemporal coordinates and intrinsic physical properties, and let

$$R = \{\, e_1, e_2, \dots \} \tag{2}$$

denote the *emergent reality*, in which the entities e_i possess observable physical properties.

One-to-one correspondence We postulate the existence of a bijective mapping

$$\Pi : R' \longrightarrow R, \quad e_i = \Pi(e'_i), \qquad \Pi^{-1}(e_i) = e'_i \tag{3}$$

where Π is the *emergence function*, responsible for assigning physical properties to the entities of R'.

Coexistence parameter We define a function

$$\Omega : R' \times R' \longrightarrow [0,1] \tag{4}$$

that measures the degree of *relational coexistence* between two entities e'_i and e'_j in R', with the following properties:

$$\Omega(e'_i, e'_j) = \Omega(e'_j, e'_i) \quad \text{(symmetry)}, \tag{5}$$

$$\Omega(e'_i, e'_i) = 1 \quad \text{(identity)}, \tag{6}$$

$$\lim_{\Omega(e'_i, e'_j)\to 0} d_R(e_i, e_j) \to \infty \quad \text{(relational separation in } R\text{)}. \tag{7}$$

Observable correlations in R The projection of the correlations Ω of R' into reality R is given by:

$$R_{ij} = \Pi\Omega_{ij} \tag{8}$$

which, in extended form, can be written as:

$$\begin{array}{c|cccccc} & e_1 & e_2 & \cdots & e_{n-1} & e_n \\ \hline e_1 & e_{11} & e_{12} & \cdots & e_{1,n-1} & e_{1n} \\ e_2 & e_{21} & e_{22} & \cdots & e_{2,n-1} & e_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e_{n-1} & e_{n-1,1} & e_{n-1,2} & \cdots & e_{n-1,n-1} & e_{n-1,n} \\ e_n & e_{n1} & e_{n2} & \cdots & e_{n,n-1} & e_{nn} \end{array} = \Pi \begin{array}{c|cccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & [0,1] & \cdots & [0,1] & [0,1] \\ e'_2 & [0,1] & 1 & \cdots & [0,1] & [0,1] \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & [0,1] & [0,1] & \cdots & 1 & [0,1] \\ e'_n & [0,1] & [0,1] & \cdots & [0,1] & 1 \end{array} \tag{9}$$

Limiting regimes

$\Omega = 1$ $e'_i = e'_j$: entities are indistinguishable and inseparable in R'; in R they manifest as perfect correlations, independent of distance:

$$R(e_i, e_j) = \Pi \quad \text{independent of } d_R(e_i, e_j). \tag{10}$$

$\Omega = 0$ Absence of relation in R', no correlation in R:

$$R(e_i, e_j) = 0, \quad d_R(e_i, e_j) \to \infty. \tag{11}$$

$0 < \Omega < 1$ Partial correlations; for $\Omega \ll 1$ weak interactions such as gravity are obtained:

$$\Omega(e'_i, e'_j) \propto \frac{1}{d_R(e_i, e_j)} \quad \text{(decay hypothesis)}. \tag{12}$$

Nature of the function Π

- *Discrete* Π: the projection generates quantized states during the emergence of a relation in R, with jumps in observable properties.
- *Continuous* Π: the projection produces progressive and smooth transitions in R when relations evolve within the temporal domain.

3.1.1 Minimal correlation diagram

Figure 1 presents the empirical form of $\Omega(r)$, which is not fixed *a priori*, but, for illustrative purposes, an exponential decay is adopted in this section. The monotonic decay reflects the basic relational principle: the lower the ontological coexistence, the greater the separation in the spatiotemporal projection R.

This minimal form is of central importance, as it represents the baseline behavior upon which more complex physical contributions are superimposed.

3.1.2 Sensitivity of distance to variations in Ω

Figure 2 shows $\Omega(r)$ highlighting two regimes of physical relevance:

- **High-Ω regime** (filaments, galaxy clusters): in this region Ω is large and stable. Small variations in Ω correspond to negligible variations in the physical distance r. Local expansion of space is therefore strongly suppressed.
- **Low-Ω regime** (cosmic voids): here Ω is already small. Even minimal decreases in Ω correspond to large increases in r. This naturally leads to accelerated expansion in voids, without invoking a uniform "dark energy" field.

This property of the function $\Omega(r)$ is qualitatively consistent with astronomical observations showing differential expansion rates between underdense and overdense regions of the Universe.

3.1.3 Zones of influence of the fundamental interactions

In the TCR, the total coexistence function Ω_{tot} can be viewed as the *vector sum of the contributions of all fundamental interactions*, each dominating within a characteristic range of r. Figure 3 shows a conceptual decomposition into four domains:

1. Weak interaction – ultra-short range ($r \lesssim 0.2$)
2. Strong interaction – very short range ($0.2 \lesssim r \lesssim 1$)
3. Electromagnetic interaction – short-to-medium range ($1 \lesssim r \lesssim 3.5$)
4. Gravitational interaction – long range ($r \gtrsim 3.5$)

The value of Ω_{tot} at a given distance range results from the combination of these partial contributions. In high-density systems (e.g., atomic nuclei) the strong and electromagnetic terms dominate, keeping $\Omega_{\text{tot}} \approx 1$. On cosmological scales, the gravitational term provides the main residual contribution.

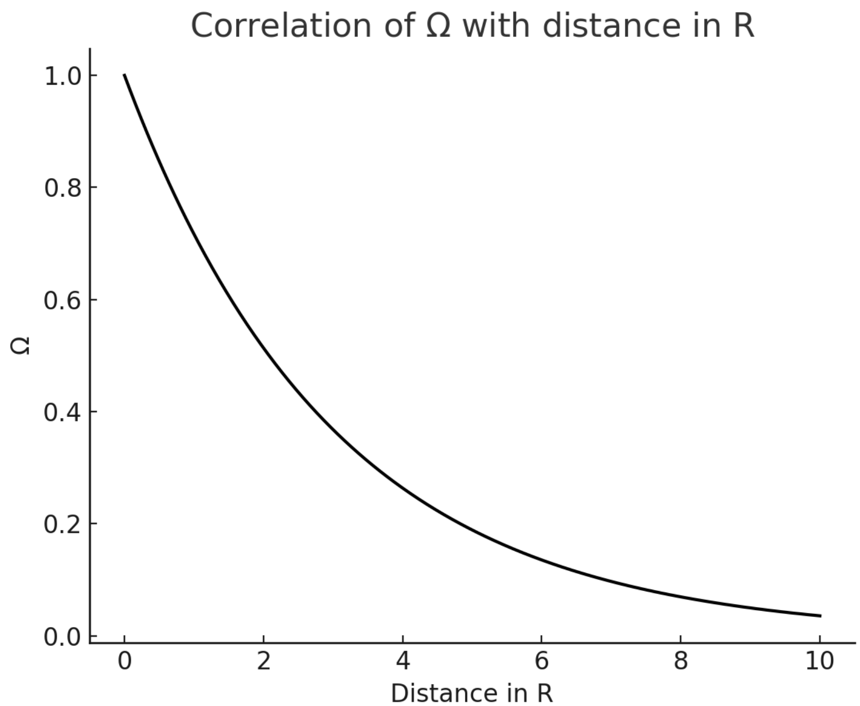

Figure 1: Minimal correlation between Ω and distance in R. The curve shows the monotonic decay of Ω with distance, without additional contributions.

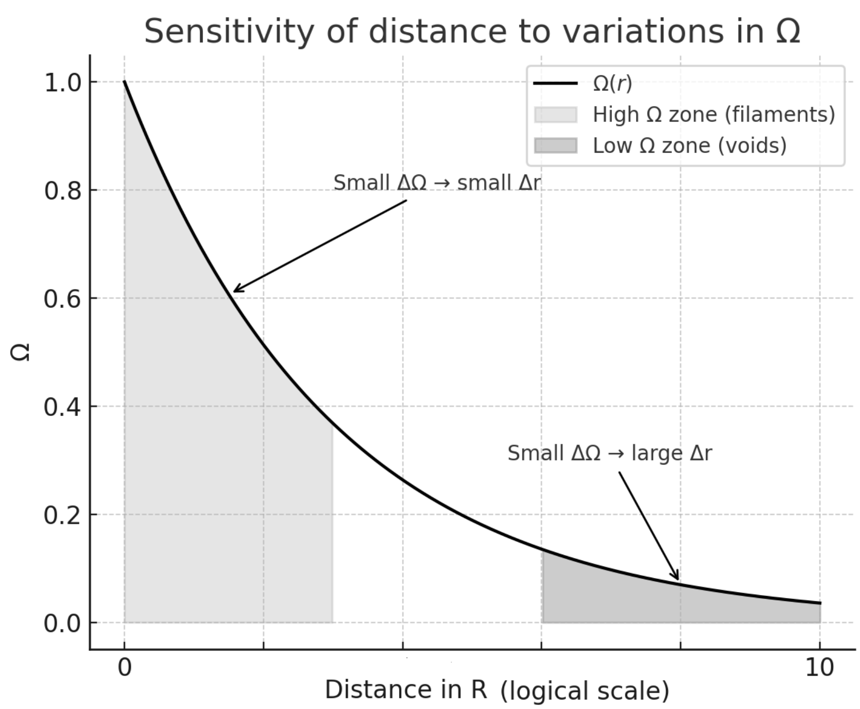

Figure 2: Sensitivity of the physical distance r to variations in Ω. The plot shows how, in low-coexistence regions, small variations in Ω produce large variations in r.

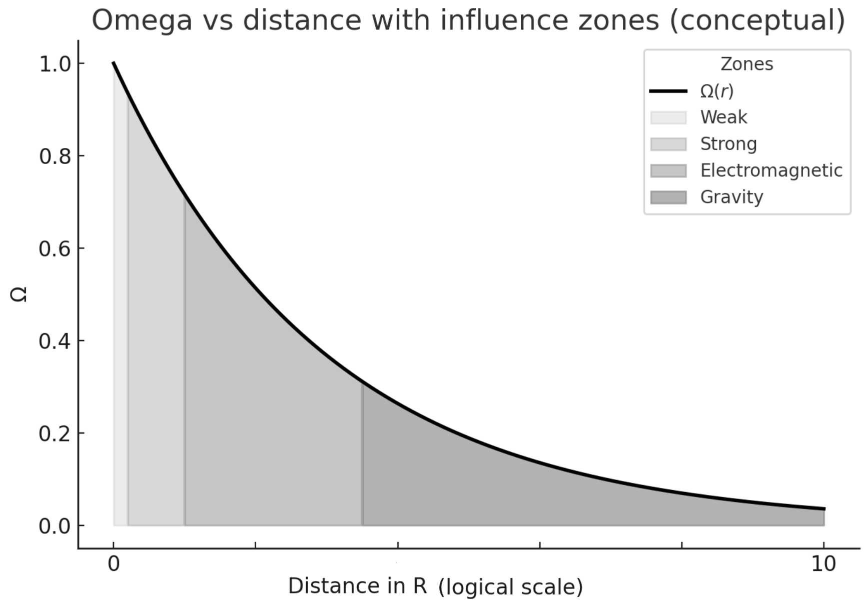

Figure 3: Conceptual zones of influence of the fundamental interactions on the function $\Omega(r)$.

3.2 Limiting case: the Big Bang

3.2.1 Model in R'

In the standard model, the Big Bang [38, 39] is interpreted as the origin of space and time. In the TCR, however, spacetime does not constitute an ontological foundation, but rather a phenomenon derived from the actualization of relations among original entities in R'.

Before the Big Bang, in the original state R', all entities were mutually coexistent in potential, that is, each was connected to all the others according to the following scheme:

$$\Omega_{ij} = \begin{array}{c|ccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & 1 & \cdots & 1 & 1 \\ e'_2 & 1 & 1 & \cdots & 1 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & 1 & 1 & \cdots & 1 & 1 \\ e'_n & 1 & 1 & \cdots & 1 & 1 \end{array} \tag{13}$$

Conditions of maximal coexistence

- Each entity $e'_i \in R'$ is maximally related to every other e'_j, including itself.
- The coexistence function satisfies: $\Omega(e'_i, e'_j) = 1 \quad \forall\, i, j \in \{1, \ldots, n\}$.
- The resulting configuration corresponds to a fully filled, symmetric, and homogeneous matrix (fully connected).

This condition of perfect symmetry can be described as an "external instant," characterized by the absence of variation. In such a regime, time in R did not exist, as it was unnecessary, and likewise space was undefined: all entities were fused in total coexistence, rendering the actualization of R itself superfluous.

Emergence of R We may conclude that the actualized reality R in which we live is an emergent phenomenon of the breaking of the initial perfect symmetry in R'.

R arises from the variation of perfect coexistence among entities in R'.

Comparative ontology In other terms:

- The existence of R (the actualized reality) is contingent.
- The existence of R' (the original reality) is necessary, eternal, and self-sufficient.

At this stage it becomes necessary to introduce the parameter τ, conceived as the functional equivalent of time within R'. It does not represent a physical quantity, but rather a logical-mathematical construct that allows one to describe and model the order of variations of the coexistence function Ω in R'. In this sense, τ should be understood solely as a formal representational tool, devoid of its own ontology.

Summary

- Time in R derives from the variation of Ω along τ.
- Space in R derives from the separation of entities not perfectly coexistent in R'.
- Actualization in R is necessary only in the presence of imperfect coexistence.

3.2.2 Relational temperature

We may define relational temperature as the sum of the oscillations (in amplitude and frequency) of the coexistences Ω between an entity e' and all entities connected to it in R':

$$T_{\text{rel}} \propto \sum_i A_{e'_i} \cdot f_{e'_i} \tag{14}$$

where:

- $A_{e'_i}$ is the amplitude of the oscillation of coexistence $\Omega_{e'_i}$,
- $f_{e'_i}$ is the frequency of the same oscillation,
- the sum extends to all entities e'_i connected to e' in R'.

3.2.3 Initial temperature of the universe

On the basis of the previously introduced definition of relational temperature, and assuming the existence of a correlation between the temperature T_{rel} in R' and the temperature T in R, one may deduce that, at the initial instant and for an extremely brief interval, the temperature of the universe was $T = 0$, subsequently increasing rapidly and massively during the inflationary phase [40, 41].

3.2.4 Cosmic inflation

Cosmic inflation [6, 8, 9, 40, 7] can be interpreted as a sudden decrease of coexistence in R' and, simultaneously, as the emergence of R as the actualized domain.

$$\Omega_{ij} = \begin{array}{c|ccccc} & e'_1 & e'_2 & \cdots & e'_{n-1} & e'_n \\ \hline e'_1 & 1 & 0.555 & \cdots & 0.556 & 0.557 \\ e'_2 & 0.555 & 1 & \cdots & 0.556 & 0.556 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ e'_{n-1} & 0.556 & 0.556 & \cdots & 1 & 0.555 \\ e'_n & 0.557 & 0.556 & \cdots & 0.555 & 1 \end{array} \tag{15}$$

This decrease led to the emergence of space and time in R, where entities began to separate, and it dramatically increased both the generated temperature and space. But if the variation of coexistence $\Omega_{e'_i}$ manifested as the emergent effect of the discrete creation of space and time in R, we may deduce that every variation of Ω in R' discretely creates or destroys space and time. As Ω decreases, space and time are created, whereas as it increases, they are destroyed. Through a sequence of logical steps, we have thus clarified both the reasons for the expansion of space and time and the mechanisms by which it occurs. In the next paragraph, the theoretical and practical implications of this phenomenon will be discussed.

3.3 Relational entropy

Starting from an initial state of maximal order in R', the universe transitioned, through inflation, toward a chaotic configuration. This transition naturally allows the introduction of the notion of relational entropy.

In the TCR, we define *relational entropy* S_{rel} as the global measure of the dispersion of entities due to the cumulative loss of coexistence in R'. Formally, it is expressed as the negative sum of coexistence variations. Relational entropy can be defined in two equivalent forms, depending on whether finite or infinitesimal variations of coexistence are described.

Discrete form. When coexistence variations are treated as finite quantities:

$$S_{\text{rel}}(\tau) \;=\; -\sum_{i<j} \Delta\Omega_{ij}(\tau) \tag{16}$$

Continuous form. In the differential limit, the definition becomes:

$$\frac{dS_{\text{rel}}}{d\tau} \;=\; -\sum_{i<j} \frac{d\Omega_{ij}(\tau)}{d\tau} \tag{17}$$

In this way, S_{rel} globally measures the loss of coexistence, while its derivative with respect to τ represents the growth rate of relational entropy.

This entropy is not merely a measure of relational disorder, but represents the intrinsic tendency of original reality to lose coherence among its configurations.

This progressive loss of relational coexistence is identified as the primary cause of several fundamental phenomena, which will be described in 4.1.

3.4 Fundamental forces as anti-entropic entities

Within the TCR framework, the fundamental forces of the universe assume a new and unifying role: they represent modalities through which the cosmos attempts to counteract the natural entropic drift inherent in the relational evolution of entities. In particular, if entropy is defined as the negative sum of coexistence variations in R', then every force that acts to stabilize, reinforce, or maintain coexistences may be interpreted as an *anti-entropic entity*, in continuity with insights already discussed in the literature [42, 43], but developed here within a coherent relational framework.

Gravity, in this context, is no longer viewed as mere curvature of spacetime, but as the force that, at every point in the cosmos, tends to increase relational coherence among entities, opposing the structural degradation that leads to fragmentation of bonds. Likewise, the strong nuclear force acts within the atomic nucleus to hold together particles that, due to charge and quantum dynamics, would tend to separate: it maintains a very high degree of relational coexistence. The electromagnetic force, which governs molecular structures, and the weak force, which regulates particle transformations, can also be reinterpreted as mechanisms of relational stabilization within specific phenomenological domains.

This reinterpretation resonates with prior attempts to link gravity to thermodynamic quantities, notably Jacobson's derivation of Einstein's equations from Clausius relations [12], Padmanabhan's thermodynamic view of horizons [13], and Verlinde's formulation of gravity as an entropic force [14, 18]. Within the TCR, these results acquire a direct ontological grounding: entropy and gravitation emerge from the same relational dynamics in R'.

In this sense, all fundamental interactions act as *ontological counterforces* to relational entropy, generating structures, local coherences, persistences, and symmetries—phenomena that would otherwise be incompatible with a universal tendency toward the dissolution of relations. However, these anti-entropic forces do not prevail across most of the universe: the coherence they produce always remains local. The ordered structure of the universe—stars, planets, molecules, life—is therefore not an anomaly to be explained, but the local effect of a dynamic balance between increasing entropy and forces seeking to restore lost coexistence.

3.5 Relational entropy, decoherence time, and the flow of time

In the TCR, quantum decoherence is interpreted as a local consequence of the increase of relational entropy [44]. Consider an actualized entity e in the domain R, associated with its original counterpart e' in R'. The coexistence function $\Omega_{e'_i}(\tau)$ is defined as the degree of coherence between e and each of the entities e'_i connected to it in R', at relational time τ.

The *relational coherence* of e at a given instant is given by:

$$C_{\text{rel}}^{(e)}(t) = \sum_i \Omega_{ei}(\tau) \tag{18}$$

This quantity measures the level of integration of e within its relational environment. If all coexistences are perfect ($\Omega_{e'_i} = 1$), C_{rel} attains its maximum value and the system is fully coherent. Conversely, if the coexistences collapse, C_{rel} tends to zero, indicating system decoherence.

When *relational entropy*(16) assumes positive and significant values, this implies a progressive reduction of coexistences, with a corresponding loss of coherence. There exists a critical threshold, C_{crit}, below which the system can no longer sustain coherent superpositions. In such a case, that is when $C_{\text{rel}}(t) < C_{\text{crit}}$, *effective decoherence* occurs: the wave function can no longer remain extended, and reality actualizes one of the possible outcomes through the function Π.

From this perspective, decoherence is not a sudden event, nor does it depend on an external observer, but rather emerges as a progressive and intrinsically relational process. The so-called "quantum measurement" is merely the manifestation of the crossing of a relational threshold: an ontological collapse due to the local loss of coexistence. The phenomenon of decoherence therefore appears as a particular case of the overall evolution of relational entropy in the cosmos.

Within the TCR framework, the flow of time is directly linked to the growth rate of relational entropy. Environmental noise represents the observable manifestation of this growth: the more noise a system experiences, the faster new relations are actualized in R, and the faster relational entropy increases. Cooling and isolating a quantum system can thus be understood as an attempt to reduce the derivative of relational entropy, thereby slowing the passage of time.

Formally, this relation can be expressed as:

$$t_{\text{int}} \;\propto\; \frac{dS_{\text{rel}}}{d\tau} \;\propto\; \frac{1}{\tau_{\text{dec}}} \tag{19}$$

where t_{int} denotes the internal time of the system, S_{rel} the relational entropy, and τ_{dec} the characteristic decoherence time.

This formulation implies that shorter decoherence times correspond to a faster flow of time, while longer decoherence times correspond to a slower flow. In the limit $\tau_{\text{dec}} \to \infty$, time halts, and for $\tau_{\text{dec}} < 0$, the arrow of time reverses.

For $\tau_{\text{dec}} < 0$, the system naturally undergoes the opposite transition: from a corpuscular state in R back to a wave-like superposition in R', in contrast to ordinary decoherence in our everyday experience, where the spontaneous and natural process is the transition from wave to corpuscle.

3.6 Postulates

Postulate 1 – Existence of a relational domain R' There exists an original ontological domain R', composed of original entities e'_i, devoid of spatial localization and temporal dynamics, which exist in relation to one another through a symmetric coexistence function:

$$\Omega : R' \times R' \to [0, 1] \tag{20}$$

where $\Omega(e'_i, e'_j)$ represents the degree of coexistence between two original entities.

Postulate 2 – Perfect coexistence as an eternal stationary state If for all entities $e'_i, e'_j \in R'$ one has $\Omega(e'_i, e'_j) = 1$ and Ω is constant along the internal relational parameter τ, then such a configuration is atemporal, aspatial, and non-actualizable. The actual reality R does not exist under these conditions.

Postulate 3 – Perfect coexistence and absolute zero Perfect coexistence ($\Omega = 1$ for all pairs of entities $e'_i, e'_j \in R'$) is realized exclusively at zero relational temperature ($T_{\text{rel}} = 0$). In this condition:

$$\forall i, j \quad \Omega(e'_i, e'_j) = 1 \iff T_{\text{rel}} = 0 \iff T = 0 \tag{21}$$

Postulate 4 – Temperature as a relational effect The temperature of an actualized entity $e \in R$ is derived from the relational temperature (14) of its original counterpart $e' \in R'$.

Postulate 5 – Relational entropy and the emergence of time In R', relational entropy S_{rel} (16) is defined as the negative sum of coexistence differences among all entities $\mathbf{e}'$. It determines the arrow of time as the privileged direction of decreasing coexistence.

The flow of time is directly linked to the growth rate of $S_{\rm rel}$: the internal time of a system is proportional to $\frac{dS_{\rm rel}}{d\tau}$ and inversely proportional to the decoherence time $\tau_{\rm dec}$,

$$t_{\rm int} \;\propto\; \frac{dS_{\rm rel}}{d\tau} \;\propto\; \frac{1}{\tau_{\rm dec}}. \tag{22}$$

Shorter decoherence times correspond to a faster flow of time, while longer decoherence times correspond to a slower one. In the limit $\tau_{\rm dec} \to \infty$, time halts, whereas for $\tau_{\rm dec} < 0$ the arrow of time reverses. In this inverted regime, the natural spontaneous transition is from corpuscular states in R back to wave-like superpositions in R', in contrast to ordinary decoherence in our everyday experience, where the natural process is the transition from wave to corpuscle.

Postulate 6 – Creation of spacetime Every modification of relational entropy produces space and time in R. Spacetime is not a pre-existing continuous background, but an emergent effect of changes in coexistence within R'.

$$\frac{dV_R}{d\tau} \propto \frac{dS_{rel}}{d\tau}, \quad \frac{dt}{d\tau} \propto \frac{dS_{rel}}{d\tau}. \tag{23}$$

- If $\frac{dS_{rel}}{d\tau} > 0$: new units of space and time are generated, producing expansion. In this regime the arrow of time is positive, and temporal flow unfolds in the same direction as in common experience, providing the phenomenological basis of ordinary temporality.
- If $\frac{dS_{rel}}{d\tau} = 0$: the creation of new units halts, and the already actualized spacetime remains constant. In this condition the arrow of time is suspended and temporal flow ceases, corresponding to a state of halted temporality.
- If $\frac{dS_{rel}}{d\tau} < 0$: previously actualized units are progressively subtracted, leading to a contraction of space and time that disappears in the limit $\Omega \to 1$. In this regime the arrow of time reverses, and temporal flow acquires an inverted orientation with respect to ordinary experience.

At the present stage, it is not established whether space and time are discrete or continuous. The formula represents an effective description.

4 Discussion

In this chapter we examine the physical and conceptual implications of the results obtained in the previous sections, with particular attention to the central role of relational entropy in the dynamics of the universe and in the emergent phenomena of R. The aim is to show how the TCR provides a unifying interpretative key for processes that, in standard physics, are treated separately and described by independent laws: the growth of entropy, the arrow of time, quantum decoherence, and cosmological expansion. This perspective is not only of conceptual value, but also paves the way for the construction of coherent and predictive mathematical models.

This approach makes it possible to trace apparently heterogeneous phenomena back to a single principle.

4.1 Relational entropy and physical implications

In the TCR, relational entropy (16) is not defined in terms of spatial disorder or microstatistical multiplicity, as in the classical formulations of Boltzmann [45] or Gibbs [46], but rather as a measure of the relational indifferentiation among the original entities e' in R'.

This concept extends the thermodynamic interpretation of gravity introduced by Bekenstein [47] and Hawking [48], later unified by Jacobson [12] and Padmanabhan [13], where spacetime geometry obeys an equation of state. The TCR generalizes this principle beyond geometric thermodynamics, interpreting entropy growth as a manifestation of the loss of coexistence among entities in R'.

Arrow of time In the TCR, time emerges from the tendency of coexistences in R' to degrade. The temporal arrow is therefore defined by the direction in which $S_{\rm rel}$ increases.

Quantum decoherence Decoherence is reinterpreted as an entropic process: the loss of phase coherence in a quantum system corresponds to the reduction of specificity in certain Ω_{ij}. This entails an increase of $S_{\rm rel}$, analogous to the increase of the von Neumann entropy [49] of the reduced density matrix in the standard formalism. In the TCR, therefore, decoherence and entropy are manifestations of the same phenomenon.

Cosmic expansion The expansion of the universe is viewed as the projection in R of the average relational thinning in R'. Since the loss of constraints is globally the most probable process, cosmological expansion does not cease as long as

$$\frac{dS_{\rm rel}}{d\tau} > 0. \tag{24}$$

This distinguishes it from the standard interpretation, in which expansion depends on the balance between gravity and dark energy: in the TCR, by contrast, it is a structural phenomenon tied to the arrow of time, which requires neither dark energy, nor dark matter, nor an inflationary field.

Gravity as an anti-entropic force In the TCR, gravity is the emergent effect proportional to gradients of Ω in R'. It acts as an anti-entropic force, seeking to increase coexistence and reduce $S_{\rm rel}$. In extreme conditions, such as in black holes, gravity may prevail locally, driving the system to maximal coexistence. However, on cosmological scales, the anti-entropic contribution of gravity is insufficient to counterbalance the processes of global indifferentiation, and thus cannot halt universal expansion.

Unification of phenomena From the TCR perspective, quantum decoherence, entropy growth, the arrow of time, and cosmic expansion are different manifestations of the same fundamental process: the progressive loss of relational specificity in R'. This unification provides a common ontological basis for phenomena that, in standard physics, are treated separately and under distinct laws.

4.2 Superconductivity and relational entropy

In the TCR, superconductivity represents a state of maximal relational stability. The entities within the superconductor (such as Cooper pairs [50, 51]) maintain constant coexistences in the original domain R'. Formally, the variation of relational entropy is equal to zero when considered over a discrete time interval:

$$\frac{\Delta\Omega_{e'_i}(\tau)}{\Delta\tau} = 0 \quad \text{for every } e'_i, \tag{25}$$

Moreover, the coexistence oscillations are also constant: $A_{e'_i} = \text{const}$, $f_{e'_i} = \text{const}$, from which it follows that the relational temperature (14) is constant.

However, $\Omega_{e'_i} \neq 1$ (not all entities coexist at the same point) and $\Omega_{e'_i} \neq 0$ (there is no total isolation): the system is in a state of stable, extended relational coherence, within the interval between 0 and 1.

This condition has profound implications: since there is no variation of coexistence, relational entropy does not increase. The superconductor is thus a state of stationary relational entropy and constant relational temperature. This explains the absence of dissipation in the ideal limiting case of constant relational entropy.

From the perspective of quantum decoherence, superconductors are ideal environments because they suppress the relational fluctuations that would otherwise lead to collapse. In quantum computers, the use of superconducting materials ensures that coexistences between superposed states remain high and stable, reducing coherence loss and prolonging qubit lifetime.

In the language of the TCR, the superconductor realizes one of the limiting cases of physics: a system in which relations do not degrade. Phenomenological models (such as BCS theory [52] or Ginzburg–Landau theory [53]) can be understood as effective descriptions of this relational equilibrium.

Finally, within the TCR perspective, superconductors can be interpreted as *relational insulators*, in which the entities involved establish constant coexistences that block all thermal dissipation and prevent the dispersion of coexistence, thus isolating the system from entropic interactions with the environment.

4.3 Black holes, time, and information conservation in the TCR

Within the TCR framework, black holes do not represent an illogical singularity or a terminal point of physics, but rather the domain in which the relational dynamics of the universe manifest themselves in their most extreme form. Gravity, defined in TCR as an anti-entropic force that tends to increase coexistence among entities, operates in gravitational collapse up to the point where the variation of relational entropy vanishes:

$$\frac{dS_{\text{rel}}}{d\tau} = 0. \tag{26}$$

At this moment, the creation of new units of space and time in R ceases. The space and time already actualized persist, but without further increments. The arrow of time, defined by the increase of S_{rel}, is therefore nullified.

Beyond this critical point, if the system remains closed and gravity continues to prevail, relational entropy may begin to decrease:

$$\frac{dS_{\text{rel}}}{d\tau} < 0. \tag{27}$$

In this regime, not only are no new units of spacetime created, but those already actualized are progressively subtracted until they vanish in the limit $\Omega \to 1$, where all entities return to a state of perfect coexistence. This scenario amounts to an inversion of the arrow of time, conceived as the progressive reconstruction of the original relational order.

From this perspective, gravity is no longer a force subordinated to entropy, but a principle that can locally assert itself. In black holes, entropy can be temporarily suppressed: the coexistence among entities within the system asymptotically tends to 1, re-establishing a condition analogous to that of the primordial universe. These points of maximal cohesion appear as domains of absolute order, in which the pre–Big Bang relational logic finds a local manifestation.

This framework also provides a natural resolution of the black hole information paradox. In the TCR, entities actualized in R maintain a constant one-to-one relation with their counterparts in R', even if their actualization is suspended. No information is therefore lost: the collapsed entities remain potentially coexistent in R' and may re-emerge in R in new configurations, for example through a mechanism analogous to Hawking radiation [48], reinterpreted as the gradual loss of relational coexistence between the black hole and the entities that constitute it.

In summary, the black hole is not the end of the universe, but a point of relational inversion: entropy may begin to decrease, time may reverse, and a local configuration of original relational coherence may be restored.

From this viewpoint, supermassive black holes are not structures formed after the Big Bang, but primordial regions of the projection of R' onto R in which gravity prevailed over entropy. They would thus constitute persistent traces of the original coexistence, already present in the earliest phases of the universe.

4.4 Cosmological implications of the TCR and the TCR-Cosmo model: expansion, entropy, and the structure of the universe

The TCR proposes an ontological revision of cosmological dynamics, in which the geometry of spacetime and the evolution of the universe emerge from variations in the network of coexistences among original entities in R'. From this perspective, cosmic expansion is not merely a stretching of spatiotemporal metrics, but rather a macroscopic manifestation of the increase of relational entropy, that is, the progressive loss of coherence in the structure of relations.

This relational-cosmological view shares conceptual affinities with the timeless or relational approaches of Barbour [54], Rovelli [55, 10], and Smolin [11]. Further relational formulations, such as Markopoulou's internal logic of relational space [56], extend these ideas to non-geometric frameworks in which the structure of reality is entirely constituted by interrelations. in which the fundamental structure of reality is constituted by inter-relations rather than by an external spacetime background. The TCR extends these ideas by providing explicit ontological mechanisms, through Ω and Π, capable of generating quantitative cosmological predictions.

Within this ontology, local density acts as a fundamental variable to explain observational phenomena such as accelerated expansion. In particular, the TCR predicts that regions of the universe characterized by low density, the so-called cosmic voids, exhibit a higher expansion rate than denser regions. This occurs because, in the absence of strong relations among entities (i.e., high-Ω coexistences), the entropic tendency toward separation acts more efficiently and undisturbed. Conversely, in galaxies and black holes, where gravity and nuclear forces maintain high relational coherence, expansion is more limited or counterbalanced.

This interpretation carries with it a verifiable prediction: for equal material content, larger cosmic voids should expand more rapidly.

A second crucial aspect concerns the very origin of the universe. The TCR interprets the Big Bang not as a geometric singular point in spacetime, but as a global breaking of relational symmetry in R', from which the actualized reality R emerges. The initial instant is thus identifiable with the moment when the original coherence of perfect coexistences in R' begins to degrade, initiating the entropic process that generates observable time, space, and matter.

In this dynamic, time assumes a derived and relational role: its direction and intensity depend on the entropy gradient among coexistences. However, the presence of gravity—defined in the TCR as an anti-entropic force—locally limits the rate at which entropy grows, thereby slowing time. This mechanism accounts, in an ontologically coherent manner, for the slowing of time near large masses as predicted by general relativity, offering a unifying interpretative key linking thermodynamics, geometry, and relational ontology.

The current distribution of cosmic structures thus reflects the thermodynamic history of coexistences. Galaxies, stars, and planets represent islands of coherence, configurations resistant to entropy, emerging within the overall flow of relational disintegration.

Finally, the theory suggests an alternative reading of dark energy: the accelerated expansion of the universe may not require a new form of energy, but may derive directly from the relational structure of R', that is, it occurs where entropy tends to increase more rapidly due to low density.

From these conceptual foundations, the TCR-Cosmo model was developed [57], which represents the first quantitative implementation of the TCR in the cosmological domain. As far as we are aware, it is distinguished by four main features:

- it is the first cosmological model grounded in a pre-spatiotemporal physics capable of achieving a competitive fit with observational data from supernovae, BAO, and cosmic chronometers;
- it is the first model derived from a unifying theory, the TCR, which bridges quantum mechanics and general relativity, to provide a quantitative agreement with precision cosmological data;
- it is the first model that does not invoke either dark energy or dark matter, showing that observational data can be explained without resorting to hypothetical components lacking direct empirical evidence.

4.5 Quantum mechanics and the double-slit experiment

In the TCR, quantum mechanics does not represent the ultimate structure of physical reality, but rather the emergence in R of coherent configurations already present in R'. The original entities $e' \in R'$ possess neither intrinsic properties nor trajectories, but are defined solely by their degree of coexistence $\Omega(e'_i, e'_j)$. From this perspective, what appears in QM as the wave function ψ is the projection in R of the complete relational map in R', while the actualization function Π governs the transition between the two domains.

This means that R' is not a metaphysical construct, but a domain experimentally accessible through its manifestations. Interference experiments [58], entanglement [59, 60, 61, 62], and decoherence [63, 64] already display phenomena that find a natural explanation when interpreted as projections of coexistences in R'.

The double-slit experiment [65] is paradigmatic. Before measurement, the electron does not simultaneously travel along two trajectories in spacetime, but propagates in R' as a diffuse distribution of coexistences Ω. The interference observed in R is the phenomenal projection of this pre-actualization propagation. When measurement occurs, the relational temperature $T_{\rm rel}$ rises above a critical threshold, and the function Π actualizes a specific configuration: the electron manifests as a localized entity $e = \Pi(e')$. The so-called "collapse" of the wave function is therefore not a mysterious phenomenon, but the natural consequence of the $R' \to R$ transition.

A relevant aspect is the initial moment of the electron's emission. When it is emitted by the source, the actualized entity e detaches from strong local bonds (for example, the constraint with the emitting atom). In R', this corresponds to a diffuse redistribution of the coexistences of e', that is, to a local decrease of relational entropy for the electron: the system loses specific constraints and acquires coexistences with many other entities. The subsequent measurement represents the inverse process: diffuse coexistences collapse into a restricted set of specific bonds with the detector, producing a net increase of relational entropy for the electron. The entire process of emission, propagation, and measurement can thus be read as an entropic dynamic in R', projected into R as probabilistic evolution and collapse.

A fundamental corollary of this framework concerns the wave–particle dichotomy. Within the TCR ontology, the *particle state* corresponds to an entity in R characterized by high relational entropy and strongly localized bonds. Conversely, the *wave state* corresponds to the same entity when, having lost its specific bonds in R, it propagates in R' as a potential relation distributed over many possible coexistences. The transition from R to R' therefore requires a local reduction of entropy, whereas the reverse process ($R' \to R$) — the actualization of one relational path into a concrete event — is a spontaneous phenomenon of entropy increase. From this perspective, the traditional dichotomy between wave and particle is reinterpreted in thermodynamic terms: *wave and particle are not two irreducible aspects, but two thermodynamically distinct states of the same entity.*

A further implication of the TCR concerns the traditional dichotomy between observer and observed. Within the relational framework, such a distinction loses ontological meaning: the act of measurement is a *symmetric co-actualization*. The function Π does not act unilaterally on the quantum system, but actualizes a bilateral relation in which both the quantum entity e' and the entities constituting the apparatus participate as nodes of the same network in R'. Measurement does not introduce ontological asymmetries, but simply represents the emergence in R of a relational configuration already coherent in R'.

In this way, the TCR overcomes the limits of traditional interpretations. Compared to Copenhagen [25, 26], it avoids the arbitrariness of an observer-dependent collapse. Unlike epistemic or participatory interpretations such as QBism [66], the TCR maintains ontological realism by grounding quantum phenomena in a pre-spatiotemporal relational domain. Compared to Bohm [29, 27], it does not postulate hidden variables in spacetime, but a single relational parameter Ω. Compared to many-worlds [30, 31], it does not require an ontological proliferation of universes, since the uniqueness of R is ensured by the function Π. Finally, compared to retrocausal interpretations [67], the TCR offers a more parsimonious explanation: what appears as influence from the future is simply the projection in R of a coherent configuration already existing in R'.

In summary, the TCR proposes that what we observe in QM is not a paradox, but the experimental manifestation of a primary relational reality. R' is therefore as real as R: the difference is that in R' reality is distributed in coexistences, whereas in R it actualizes in events and properties.

Within the TCR framework, the ability of an entity to exhibit behaviors typically associated with R' (such as interference and superposition) depends on the degree of separation it can maintain from the coexistences already actualized in R. For elementary particles or small systems, such separation can be achieved relatively easily, since the bonds in R are limited. As the size and internal complexity of an entity increase, however, the number of internal bonds already actualized in R also increases, and these cannot currently be eliminated.

It follows that a complete separation from R becomes increasingly difficult: the entity remains bound by a growing network of already actualized relations, which hinder its propagation in R'. This property defines what we call *relational mass*, understood as a measure of the amount of coexistences already actualized in R that tie the entity to the classical domain.

Recent experimental advances have demonstrated the quantum interference of increasingly large entities, ranging from fullerenes [68] to organic molecules with masses exceeding 10,000 amu [69] and macromolecules beyond 25 kDa [70]. These results show empirically how the growth of relational mass makes it progressively harder to isolate complex entities from R and thus to preserve their coherent propagation in R'.

> In principle, if the internal bonds actualized in R could be temporarily suppressed, there would be no fundamental limit of scale for propagation in R'. Even macroscopic entities could then exhibit quantum behaviors usually restricted to microscopic systems.

A crucial aspect of the TCR concerns the connection between decoherence and time. The decoherence time, in fact, represents the operational measure of the arrow of time: shorter times correspond to a rapid transition from the wave-like state in R' to the corpuscular state in R, whereas longer times indicate a slower dynamics of the time arrow. In the limit of an infinite decoherence time, time itself comes to a halt, and for negative decoherence times the possibility would arise of a spontaneous inverse transition, from the corpuscular state in R back to a superposed wave state in R'. This wave-like phase, characterized by a diffuse distribution of coexistences, constitutes the necessary condition for approaching perfect coherence ($\Omega \approx 1$).

This interpretation also makes it possible to connect quantum dynamics with thermodynamic and gravitational phenomena. Temperature, by increasing environmental noise, accelerates the loss of coherence and reduces the decoherence time, thus speeding up the growth of relational entropy and intensifying the arrow of time. Conversely, gravity acts as an anti-entropic force: it reinforces coexistences and tends to extend decoherence times, providing an ontological basis for the gravitational time dilation predicted by general relativity. It is hypothesized that under conditions of strong gravity, the tendency towards the wave-like phase favors a re-coherence of the system, with a progressive approach to states of coexistence close to $\Omega = 1$.

4.6 Rethinking the nature of time

One of the broader implications of the TCR concerns the concept of time itself. By treating time as an emergent property rather than as a continuous external parameter, the TCR provides a vantage point from which its nature can be better understood and redefined.

Within this framework, time corresponds to the entropic tendency of entities to separate from one another. The forward arrow of time thus reflects the progressive disintegration of coexistences, whereas the inverted arrow of time would correspond to the opposite process: entities would naturally tend to unite.

This inversion carries striking consequences. In our everyday experience, living systems expend energy to keep entities bound together against their natural tendency to disperse. In an inverted temporal regime, the opposite would hold: energy would be required to separate entities that would otherwise spontaneously cohere. Such a perspective is profoundly different from the traditional view of time as a homogeneous and continuously flowing background. It instead situates time as a relational and thermodynamic phenomenon, whose direction and intensity are determined by the dynamics of coexistences.

4.7 Inflation as generalized decoherence (hypothetical interpretation)

A further speculative implication of the TCR concerns the early inflationary epoch of the universe. Within this framework, it may be hypothesized that what is conventionally described as cosmic inflation could correspond to a generalized decoherence process. At the initial instant, all entities were in a state of perfect superposition in R', corresponding to maximal coherence ($\Omega = 1$). The onset of inflation could then be reinterpreted as the rapid loss of this global coherence, where diffuse coexistences collapsed into a multiplicity of localized configurations in R.

Such an interpretation would imply that the extraordinary rapidity of the inflationary phase is not due to the dynamics of a hypothetical scalar inflaton field, but rather to the entropic dynamics of relational decoherence on a cosmic scale.

4.8 Experiments supporting the TCR

In this section we gather a set of experiments and observations which, although developed in different theoretical contexts, provide direct or indirect support for the fundamental principles of the TCR. The evidence is organized into three main areas: quantum mechanics, quantum thermodynamics, and observational cosmology. For each case, we summarize the setup, the essential results, and the relevance for the TCR.

4.8.1 Quantum Mechanics

Coherence and entanglement in bosonic systems at near-zero temperature. In bosonic Josephson junctions (Bose–Hubbard model), macroscopic coherent and entangled states are observed, which tend toward Schrödinger-cat configurations as temperature decreases [71]. *Relevance for the TCR:* represents a manifestation of nearly perfect relational coexistence ($\Omega \approx 1$) under stable conditions ($\Delta\Omega = 0$).

Evolution of coherence in null thermal environments. Theoretical models and experimental verifications show that decoherence can be halted in environments with $T \to 0$ [72]. *Relevance for the TCR:* confirms that a stationary relational environment maintains high coexistence Ω and thus the temporal coherence of systems.

Energetic entanglement at zero temperature. In multi-fermion systems, measured energy fluctuations are proportional to the degree of entanglement [73]. *Relevance for the TCR:* establishes a direct link among energy, relational temperature, and the coexistence function Ω.

Non-local entanglement in superconducting beam splitters. Experiments in S–N–S devices have produced entanglement between spatially separated regions [74]. *Relevance for the TCR:* confirms the possibility of stable relational coexistences ($\Omega > 0$) between spatially distant entities, consistent with the Π mapping from R' to R.

Synthesis: quantum mechanical experiments show that the stability of coexistence (high Ω and minimal variations) preserves entanglement and coherence, while collapse occurs when the loss of coexistence exceeds a critical threshold.

4.8.2 Quantum Thermodynamics

Reversal of heat flow through quantum correlations. NMR experiments have demonstrated heat transfer from colder to hotter systems due to quantum correlations [75]. *Relevance for the TCR:* shows that relational coexistences can locally reduce entropy, reversing the direction of thermal flow.

Quantum engines enhanced by coherence. Quantum engines based on NV centers in diamond have exceeded classical efficiency limits [76]. *Relevance for the TCR:* energy efficiency becomes a direct indicator of the persistence of stable relational coexistences.

Quantum friction and controlled decoherence. A purely quantum component of dissipation, distinct from classical heat, has been identified [77]. *Relevance for the TCR:* this "quantum friction" can be interpreted as an indirect measure of variation in coexistence $\Delta\Omega$.

Reversibility of entanglement with quantum batteries. Quantum battery systems have demonstrated partial reversibility of entanglement [78]. *Relevance for the TCR:* constitutes active control of relational temperature, suggesting that Ω can be manipulated.

Synthesis: quantum thermodynamics confirms that energy efficiency, the direction of thermal flow, and the reversibility of entanglement are emergent effects of the degree of coexistence Ω, consistent with the relational definition of entropy.

4.8.3 Observational Cosmology

Primordial supermassive black holes. The JWST has identified a black hole of $3.8 \times 10^7 M_\odot$ only 500 Myr after the Big Bang [79]. *Relevance for the TCR:* in the TCR, black holes represent primordial fragments where gravity locally prevailed over entropy, preserving nearly perfect coexistence ($\Omega \to 1$).

Anisotropic expansion and bulk flow. Observations have detected large-scale anomalous, directional matter flows [80]. *Relevance for the TCR:* indicates that cosmic expansion depends on local variations of coexistence Ω in R', rather than on a homogeneous field.

Local cosmic void. Catalogs of supervoids and analyses of the Hubble tension suggest the presence of a local gigaparsec-scale void [81][82]. *Relevance for the TCR:* confirms that expansion is inhomogeneous and structurally dependent on the loss of relational coexistence, consistent with the TCR–Cosmo model.

Synthesis: cosmological observations show that voids and black holes behave as boundary regions where relational entropy follows different dynamics: accelerated in voids (low Ω), suppressed in black holes ($\Omega \to 1$).

4.8.4 General conclusion of the section

The experiments and observations reviewed demonstrate that apparently disjoint phenomena—quantum entanglement, quantum engines, cosmological flows, primordial black holes—can be interpreted in a unified way within the TCR framework:

- Direct support comes from measurements of decoherence, entanglement, and quantum efficiency (Ω as a measurable physical quantity);
- Indirect support comes from cosmological observations showing inhomogeneities and structures consistent with the ontological role of Ω and with the function Π.

4.9 Proposed experimental test of the TCR through quantum decoherence in superconducting cavities

We propose an experimental test of the TCR based on the measurement of quantum decoherence times under different shielding regimes. According to the TCR, superconducting confinement not only suppresses coupling with external noise sources, as predicted by standard quantum theory, but also reduces the local generation of new space and time and provides relational isolation for the confined system. These effects combine, leading to coherence times longer than those explainable solely by environmental noise suppression.

4.9.1 Experimental design

The proposed setup consists of:

- **Test systems:** identical qubits (NV centers, trapped atoms, or superconducting qubits).
- **Two environments:**
  1. Cavity A: Conventional electromagnetic shielding (copper, mu-metal, cryogenic isolation).
  2. Cavity B: Complete shielding with superconducting shells: entirely surrounding the quantum processor with superconducting coils or closed chambers, creating a condition of relational isolation. Extension of superconducting materials: not limiting superconductivity to the qubits alone, but extending it to control components, wiring, and cryogenic housings, thereby reducing relational coupling with the external environment.
- **Measurement protocol:** coherence time T_2 obtained via Ramsey interferometry or spin echo, repeated over multiple cycles to reduce statistical error.
- **Controls:** matched temperature (difference $< 1\%$), identical internal materials, randomized measurement sequences.

4.9.2 Quantitative estimate of the decoherence time increase in a time box

Starting from the standard expression for the decoherence time of an open quantum system [83, 84, 85, 86, 87],

$$\tau_{\rm dec}^{\rm std} \sim \frac{\hbar^2}{\Lambda\, k_{\rm B} T}, \tag{28}$$

where Λ represents the effective coupling to the environmental degrees of freedom, the *Theory of Relational Coexistence* (TCR) introduces a correction term that accounts for the residual *relational entropy flux* within the system:

$$\tau_{\rm dec}^{\rm rel} = \frac{\tau_{\rm dec}^{\rm std}}{\gamma_{\rm rel}}, \qquad \gamma_{\rm rel} \propto \frac{\dot{S}_{\rm rel}}{\dot{S}_{\rm rel,0}}, \tag{29}$$

where $\dot{S}_{\rm rel} = dS_{\rm rel}/d\tau$ represents the local rate of relational entropy growth. In the TCR framework, this term quantifies the emergent flow of time itself, in analogy to thermodynamic entropy production in standard non-equilibrium physics [88, 89, 90].

The TCR links decoherence to the relational arrow of time through

$$\tau_{\rm dec} \propto \left(\frac{dS_{\rm rel}}{d\tau}\right)^{-1}, \tag{30}$$

so that any local suppression of $dS_{\rm rel}/d\tau$ — as produced by a fully superconducting cavity or *time box* [91, 92, 93] — leads to a proportional increase in the coherence lifetime.

4.9.3 Separation between standard and TCR contributions

The experimentally measurable ratio of decoherence times between a conventional configuration (A) and a time-boxed configuration (B) can be factorized as:

$$\frac{\tau_{\rm dec}^{B}}{\tau_{\rm dec}^{A}} = \underbrace{\frac{\Lambda_A}{\Lambda_B}}_{\text{standard, engineering term}} \times \underbrace{\frac{1}{\gamma_{\rm rel}}}_{\text{TCR excess}} . \tag{31}$$

The first term accounts for conventional electromagnetic coupling reductions (Purcell effect suppression [94, 95], dielectric and radiative losses [96, 97]), while the second term captures the intrinsic TCR slowdown of the local temporal flow due to a lower relational entropy gradient.

4.9.4 Parametric model for $\gamma_{\rm rel}$

In the absence of a microscopic mapping between $\dot{S}_{\rm rel}$ and material properties, a phenomenological parametrization consistent with the TCR assumptions can be written as:

$$\gamma_{\rm rel} \simeq a_0(1-c)^\alpha + a_1(1-s)^\beta + a_2 \tan\delta_{\rm eff} + a_3 \frac{R_{s,\rm eff}(\omega, T)}{Z_0}, \tag{32}$$

where:

- $c \in [0,1]$ is the fraction of total surfaces and volumes covered by superconducting material,
- $s \in [0,1]$ quantifies the topological completeness of the cavity closure (absence of open EM channels),
- $\tan\delta_{\rm eff}$ is the effective dielectric loss tangent of internal materials [98, 99],
- $R_{s,\rm eff}$ is the residual surface resistance of the superconducting shielding at the operating frequency ω [100],
- and $Z_0 \simeq 377\ \Omega$ is the vacuum impedance.

Following the physical reasoning of the TCR, the dominant contributions are the topological and superconducting completeness terms, as both directly control the degree of relational isolation. A conservative but realistic choice is

$$\alpha = \beta = 2, \quad a_0 = a_1 = 0.25, \quad a_2 = 5\times10^{-2}, \quad a_3 = 10^{-1}.$$

To avoid the unphysical limit $\gamma_{\rm rel} \to 0$, we introduce a floor value $\gamma_{\rm min}$ representing the unavoidable residual relational entropy flow due to the non-superconducting matter inside the box:

$$\gamma_{\rm rel} = \max\left[\,0.25(1-c)^2 + 0.25(1-s)^2,\ \gamma_{\rm min}\,\right], \qquad \gamma_{\rm min} \in [0.5, 0.7]. \tag{33}$$

This range reflects the minimal relational entropy flux expected for systems containing normal metal interfaces and dielectrics, even at millikelvin temperatures.

4.9.5 Numerical estimates

Using Eq. (33), three representative configurations are:

Moderate isolation (B1): $c = 0.90$, $s = 0.85$, $\gamma_{\rm min} = 0.7 \Rightarrow \gamma_{\rm rel} = 0.7$, giving a TCR gain of

$$\tau^B_{\rm dec}/\tau^A_{\rm dec} \approx 1/0.7 \approx 1.43.$$

This corresponds to an additional $\sim 43\%$ increase in decoherence time, beyond standard electromagnetic suppression.

Advanced isolation (B2): $c = 0.95$, $s = 0.90$, $\gamma_{\rm min} = 0.5 \Rightarrow \gamma_{\rm rel} = 0.5$, yielding

$$\tau^B_{\rm dec}/\tau^A_{\rm dec} \approx 2.0,$$

that is, a doubling of the coherence time due solely to relational effects.

Idealized limit: If $\dot{S}_{\rm rel} \to 0$, the TCR predicts $\tau_{\rm dec} \to \infty$, corresponding to a stationary relational state. This bound is physically unattainable but defines a theoretical limit analogous to the zero-entropy production limit of reversible thermodynamics [88].

4.9.6 Experimental discriminants

To empirically isolate the TCR contribution from standard environmental improvements, one can:

1. Measure $\tau_{\rm dec}$ (via Ramsey or Echo) in configurations A and B at identical temperature and materials.
2. Determine Λ_A/Λ_B from Purcell and dielectric characterization [95, 97].
3. Compute the residual term in Eq. (31) to infer $\gamma_{\rm rel}$.
4. Verify that the same $\gamma_{\rm rel}$ rescales both T_1 and T_2: this universality is the TCR signature.

4.9.7 Final estimate

Combining Eqs. (31) and (33), the expected relational enhancement is:

$$\frac{\tau_{\rm dec}^B}{\tau_{\rm dec}^A} = \frac{\Lambda_A}{\Lambda_B} \cdot \frac{1}{\gamma_{\rm rel}}, \qquad \gamma_{\rm rel} \in [0.5, 0.7]. \tag{34}$$

For a well-designed superconducting time box ($c > 0.9$, $s > 0.85$), the TCR predicts a **relational excess of** 30**–**100% in coherence times beyond what is accounted for by conventional open-system physics. This defines a falsifiable quantitative benchmark for experimental validation.

4.10 Conclusions

4.10.1 First tangible results: the TCR-Cosmo model

A crucial point concerns the transition from conceptual ontology to quantitative implementation. From the relational framework of the TCR, the cosmological model *TCR-Cosmo* has been developed [57]. This represents the first operational realization of a pre-spatiotemporal theory capable of confronting cosmological data.

Specifically, TCR-Cosmo has been tested against low-redshift observations (SN, BAO, CC), showing that:

- it provides a competitive fit to precision data without the need for dark matter or dark energy;
- it improves the description of BAO at low redshift compared to ΛCDM;
- it demonstrates that a unifying and relational ontology can generate falsifiable quantitative predictions.

These results should be regarded as the first tangible confirmation that the relational ontology of the TCR is not confined to conceptual reformulation, but can yield effective models consistent with observational cosmology. Although still limited in scope (particularly at high redshift), the TCR-Cosmo framework opens the path toward systematic numerical and observational investigations, establishing a direct bridge between foundational ontology and empirical validation.

4.10.2 Limitations of the TCR

Despite its conceptual coherence and explanatory capacity across diverse phenomena, the TCR currently presents several significant limitations that define its scope and indicate future directions for development.

- **Incomplete mathematical formalism.** The theory has so far been formulated primarily at the ontological and conceptual level. Although the concepts of coexistence Ω, actualization Π, and relational entropy $S_{\rm rel}$ provide a unifying language, a fully developed mathematical formalism is still lacking—one that would enable systematic derivations and detailed predictive calculations.
- **Experimental predictions still preliminary.** No laboratory experiments have yet been carried out with the explicit purpose of validating or falsifying the TCR.
- **Epistemological acceptance.** The adoption of a primary ontological domain R' represents a radical conceptual shift. This may encounter resistance, particularly within a community accustomed to highly sophisticated formal models that are nonetheless often devoid of experimental verification. The challenge will be to translate the relational ontology into mathematical and predictive tools that are acceptable within contemporary physics practice.

In summary, the TCR remains a proposal in its early stages, with strong conceptual and predictive points, but also with evident limitations that require further development. Recognizing such limitations does not weaken the theory; rather, it situates it as an open research program, amenable to theoretical, mathematical, and experimental refinement.

4.10.3 Implications for the scientific community

In recent decades, fundamental physics has often responded to observed anomalies by adding new hypothetical entities or further layers of formal complexity: dark energy, dark matter, inflatons, extra dimensions. This incremental approach, though effective in adapting the standard cosmological model to the available data, resembles a multiplication of *ad hoc* elements introduced to preserve an underlying paradigm.

The TCR, by contrast, follows a different path. The simplification it proposes does not stem from voluntaristic choice, but arises naturally from the assumption of a primary relational ontology R'. From this perspective, multidisciplinary consequences emerge spontaneously: interference, entanglement and quantum decoherence, entropic dynamics, cosmological structure, and gravity find a unified description without the need for additional hypotheses. By shifting perspective, the entirety of physics is transformed in a natural way, rendering coherent phenomena that are otherwise treated as separate.

Taken together, these elements constitute a sufficient basis to encourage the establishment of research groups dedicated to systematically analyzing, both theoretically and experimentally, the consequences of the TCR. The invitation to the scientific community is therefore to consider this theory not as an isolated speculation, but as a parsimonious alternative already supported by concrete observational hints, worthy of parallel analyses and extensive comparisons with existing data.

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Appendix A — Glossary and Fundamental Notations

Name	Symbol	Description
Actualized reality	R	The actualized reality, in which entities manifest spatiotemporal properties and obey observable physical laws.
Original reality	R'	The original reality or relational domain, where the original entities e' reside. It is not describable in spatiotemporal terms but only in relational terms. From it, R emerges.
Actualized entity	e	An entity actualized in R, endowed with spatiotemporal coordinates and measurable physical properties.
Original entity	e'	An entity in R', defined solely by its coexistences with other entities. Each e in R corresponds bijectively to its e' counterpart.
Actualization function	Π	The function that transforms entities and coexistences from R' into corresponding entities and relations in R.
Relational coexistence	Ω_{ij}	The function of relational coexistence between the original entities e'_i and e'_j. It takes values $0 \leq \Omega_{ij} \leq 1$.
Relational time	τ	A mathematical construct that models variations of coexistence Ω in R'. It is not a physical time but a parameter used to describe relational evolution in R'.
Decoherence time	$\tau_{\rm dec}$	The characteristic time of quantum decoherence in R, inversely proportional to the growth rate of relational entropy. It defines the effective flow of time in actualized systems and must be distinguished from τ, which is only a mathematical parameter in R'.
Relational temperature	$T_{\rm rel}$	Proportional to the sum of oscillations (in frequency and amplitude) of the coexistences Ω_{ij}. At $T_{\rm rel} = 0$, absolute entanglement occurs.
Relational entropy	$S_{\rm rel}$	Defined as: $S_{\rm rel}(\tau) = -\sum_{i<j} \Delta\Omega_{ij}(\tau)$. It increases when coexistences lose specificity. It is the cause of the breaking of the original symmetry, cosmic expansion, the arrow of time, and quantum decoherence.
Total relational coherence	$C_{\rm rel}^{(e)}$	The sum of the coexistences $\Omega_{e'_i}(\tau)$ of an entity e in R with all other entities to which it is connected in R'. Measures the degree of relational integration of e within its environment.
Relational reduction factor	γ_{rel}	Represents the combined reduction due both to lower entropic variation and to reduced creation of relational time. Takes values $\gamma_{rel} < 1$.
Spatiotemporal distance	d_R	Distance between two actualized entities in R, measured according to the spatiotemporal metrics of the actualized reality.
Arrow of time	—	Emergent direction defined by the variation of relational entropy $S_{\rm rel}$: if $\frac{dS_{\rm rel}}{d\tau} > 0$, new units of spacetime are created and time advances; if $\frac{dS_{\rm rel}}{d\tau} = 0$, creation halts but already actualized units persist; if $\frac{dS_{\rm rel}}{d\tau} < 0$, space and time are progressively subtracted until they dissolve in the limit $\Omega \to 1$.
Quantum decoherence	—	Loss of relational specificity ($\Delta\Omega_{ij} < 0$), equivalent to entropy increase in the standard description.
Cosmic expansion	—	Manifestation in R of the progressive relational degradation in R'. A structural and irreversible phenomenon.
Gravity	—	Emergent effect of Ω_{ij} gradients. Interpreted in the TCR as an anti-entropic force that can locally restore maximum coexistence (e.g., black holes).
Principle of Relational Indifferentiation	—	Postulate according to which, on average, coexistences in R' tend to lose specificity $\frac{d\Omega_{ij}}{d\tau} < 0$, causing $S_{\rm rel}$ to increase.
Entanglement	—	Limiting case of perfect coexistence ($\Omega_{ij} = 1$), which manifests in R as an ideal quantum correlation.
Black holes	—	Systems in which gravity locally prevails over entropy. Inside, the creation of new units of space and time initially halts ($dS_{\rm rel}/d\tau = 0$). If relational entropy becomes negative ($dS_{\rm rel}/d\tau < 0$), space and time are progressively subtracted, until disappearing in the limit $\Omega \to 1$, which restores the original relational coherence.

Appendix B — Physical Paradoxes Reinterpreted in the TCR

Many of the paradoxes that afflict theoretical physics arise from the assumption that spacetime R constitutes the entire ontological reality. Within the TCR, however, R represents only the actualized reality, projected from the relational domain R' through the transformation Π.

In R', the entities e' and their coexistences Ω constitute the fundamental level, where information and unitarity are always preserved. Paradoxes emerge only in R because actualization obscures part of the underlying relational structure, generating apparent contradictions. What in R appears as "information loss," "non-locality," or "singularity" is in fact a perspectival effect: a limited projection of coherent and continuous dynamics in R'.

In this appendix we list some of the principal paradoxes reinterpreted by the TCR, showing how each of them finds a natural explanation when referred back to the relational dimension.

1. Black hole information paradox

In R, Hawking radiation appears thermal and devoid of information, leading to an apparent violation of unitarity. In R', information is preserved in the coexistences Ω, while the radiation is the entropic projection in R. **Conclusion:** unitarity is not violated, and the paradox dissolves.

2. Entanglement and non-locality

In R, entanglement seems to imply instantaneous transmission of information. In R', it corresponds to perfect coexistence ($\Omega = 1$ at zero relational temperature): there is no transmission, but simultaneous actualization of already existing relations. **Conclusion:** no real non-locality.

3. Wave function collapse

In R, quantum measurement appears as a sudden and inexplicable collapse of the state. In R', the quantum state is a network of original coexistences; measurement is the actualization through Π of a coexistence in R. **Conclusion:** collapse is a projection process, not a mysterious phenomenon.

4. Vacuum fluctuations

In R, the quantum vacuum produces particle pairs from nothing. In R', the vacuum is a relational field rich in latent coexistences; pairs emerge from relational oscillations, not from nothing. **Conclusion:** there is no creation *ex nihilo*.

5. Arrow of time

In R, the direction of time remains unexplained. In R', it emerges from the decrease of coexistences and the increase of relational entropy. **Conclusion:** the arrow of time is a natural effect of relational dynamics.

6. Cosmic inflation

In R, the primordial rapid expansion is explained through *ad hoc* hypotheses [101, 102]. In R', inflation is interpreted as a diffuse breaking of the original relational symmetry, driven by entropy. **Conclusion:** no additional entities are required.

7. Singularities in black holes

In R, the central singularity is physically inconceivable. In R', it corresponds to the restoration of relational coherence ($\Omega \to 1$), where time ceases to flow. **Conclusion:** not a mathematical absurdity, but a return to the relational origin.

8. Infinite temperature of the Big Bang

In R, the standard model implies an initial singularity at infinite temperature, a concept physically devoid of meaning. In R', instead, "infinite temperature" corresponds to the perfect coherence of coexistences ($\Omega = 1$) prior to the original symmetry breaking. The emergence of time and space in R transforms this state into an apparent thermal divergence. **Conclusion:** there is no real infinite temperature, but rather a transition from relational unity to thermal actualization.

Appendix C — Final Notes

Statement of Originality

The TCR was introduced by Pietro Curatola, beginning with the preprint deposited in 2025 and subsequent publications in preparation. It is founded on a relational ontology defined in terms of original coexistences (R'), actualizations (R), and the functions Π and Ω.

Attribution and Usage

The content of the TCR is published in open form, in order to promote scientific discussion and collaborative development. Anyone wishing to extend, discuss, or apply the TCR is free to do so, provided that:

- the original denomination TCR is preserved;
- the preprint and original sources by Pietro Curatola are cited;
- the fundamental symbols and definitions (e.g., R', R, Π, Ω) are not altered without a clear indication of the proposed variation.