Embedded String Loops as Internal Topological Boundaries in Quantum Spacetime

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Abstract

We explore a conceptual cosmological framework in which a closed, one-dimensional topological defect loop (a “string” in the broad sense) acts not merely as a line-like source of stress-energy, but as an internal topological boundary inside an already existing vacuum domain. The picture is inspired by a simple soap-film experiment: when a loop of string is embedded inside a soap film and the interior film is disrupted, the surrounding film pulls the loop into a nearly circular configuration. The length of the loop remains approximately fixed, but the area it encloses increases, and the soap film is reshaped without destroying the surrounding film surface. We ask what happens if an analogous mechanism exists in a quantum-spacetime or “vacuum-foam” background.

Rather than generating a new universe or bubble via tunneling in a scalar potential, an embedded loop in this scenario partitions an existing vacuum region into an exterior and an interior subregion. We treat the loop as a tensioned defect whose proper length is approximately conserved while its shape is driven toward configurations that minimize an effective energy functional. As this happens, the interior region grows, and we postulate that it becomes causally inaccessible from the exterior once the defect configuration stabilizes. The surrounding “foam” (a shorthand for small-scale fluctuations and defects superposed on a quasi-homogeneous background) is correspondingly warped.

This paper develops the idea at a conceptual and geometric level rather than as a full field-theoretic model. We review the relevant components from spacetime-foam heuristics, cosmic-string physics, and inflationary bubble cosmology; explain the soap-film analogy in detail; and propose a qualitative description of internal topological boundaries induced by embedded loops. We then discuss how such structures could warp the surrounding vacuum and, if formed before or during inflation, leave imprints on large-scale cosmological observables. We conclude by highlighting open questions and outlining directions for more mathematical and numerical work, including possible connections to dark matter phenomenology and internal structure in a multiverse of vacuum domains.

1. Introduction

Modern cosmology combines the smooth, large-scale description of spacetime given by general relativity with a variety of mechanisms that introduce structure at small and intermediate scales. Inflation stretches microscopic quantum fluctuations into macroscopic density perturbations that later seed the formation of galaxies. Symmetry breaking in high-energy theories creates topological defects such as domain walls, monopoles, and cosmic strings. In some scenarios, metastable vacuum regions nucleate “bubbles” of lower-energy vacuum, creating a patchwork or “multiverse” of “bubble universes” embedded in an inflating background. Alongside these mechanisms, quantum-gravity heuristics suggest that spacetime near the Planck scale may be highly irregular and dynamically fluctuating (a regime often called spacetime foam or vacuum foam).

Most of the work that combines these ideas has focused on either whole-domain processes (nucleation, expansion, and collision of bubbles) or on the local properties of defects, such as the conical geometry around a cosmic string or the field profile in a domain wall. Less attention has been given to the possibility that internal topological substructure might arise within a single vacuum domain, without the need to nucleate a new bubble or create a black hole. In other words, could there exist stable or metastable internal boundaries that carve out causally isolated subregions inside an otherwise ordinary vacuum region?

The conceptual starting point of this paper is a familiar and surprisingly rich soap-film experiment offers an instructive mechanical analogy for understanding how an embedded loop can reshape a surrounding medium without rupturing it. If a loop of string is placed inside the film spanning a wire frame or an external bubble, and the film inside the loop is disturbed or removed, the surrounding soap film pulls on the loop. Because the loop has a fixed length and is under tension, it relaxes toward a nearly circular configuration that encloses more area than the initial irregular shape. The external bubble or film does not rupture; instead, an internal circular boundary appears, with the soap film taking on a new pattern of curvature on either side of the loop.

In this work we treat that behavior as an analogy and ask how much of it can be carried over into a cosmological setting. Suppose that in a region of quantum spacetime (which we will loosely call vacuum foam) there exists a closed, one-dimensional defect loop.

Suppose further that the loop's proper length is approximately conserved over the epoch of interest, while interactions with the surrounding vacuum drive it toward an energetically preferred shape. In close analogy with the soap-film loop, this evolution could enlarge the spacetime region bounded by the loop, even though the loop's length remains roughly fixed.

The central conceptual leap is to then interpret the loop not only as a defect with localized stress-energy, but as a genuine topological boundary: a codimension-two defect (a one-dimensional object in a three-dimensional spatial hypersurface) that separates an interior spacetime region from an exterior, and that can, under suitable conditions, render the interior causally inaccessible to observers in the exterior. This is not a standard cosmic-string loop, nor is it a traditional bubble wall. The interior region is not a new universe nucleated from a false vacuum, and it is not a black hole interior produced by gravitational collapse. It is instead a domain carved out topologically by the loop itself.

The purpose of this paper is to articulate that scenario in a clear, structured way. We do not claim that such embedded topological boundaries exist in our cosmos, nor do we derive them from a specific quantum-gravity model. Rather, we aim to provide a concrete, physically motivated framework that other theorists can analyze, simulate, and either embed into detailed models or rule out. The focus is on conceptual clarity: what assumptions are needed, how the geometry should be understood, and what qualitative implications follow for the structure of vacuum foam and for cosmological observables.

2. Background and Context

Before developing the embedded-loop picture in detail, it is useful to review the standard components it draws upon. These include the heuristic notion of spacetime foam, the physics of topological defects such as cosmic strings, and the inflationary scenarios that give rise to bubble universes and vacuum domains. None of these topics is new, but the way we combine them is slightly unusual: instead of using defects to seed galaxies or bubbles to generate separate universes, we imagine defects as sculptors of internal boundaries within a single vacuum region.

2.1 Spacetime foam and vacuum microstructure

The idea that spacetime might have a nontrivial microstructure traces back to work by Wheeler, Hawking, and many others. At the Planck scale, quantum fluctuations of geometry and matter could be so violent that the classical picture of a smooth

Lorentzian manifold ceases to be useful. In qualitative terms, spacetime might resemble a froth of transient virtual black holes, wormholes, and rapidly fluctuating curvature. The phrase “spacetime foam” has been used both loosely and more technically to describe this regime.

Even without a complete theory of quantum gravity, semiclassical reasoning supports the idea that small-scale fluctuations of the stress-energy tensor can source large fluctuations in curvature over very short distances and times. From the perspective of an observer who only has access to scales much larger than the Planck length, these wild fluctuations would be averaged out, leaving an effective smooth metric plus small corrections. However, defects, boundaries, or other remnants of the microscopic dynamics could survive this coarse-graining and manifest as localized structures within an otherwise quasi-homogeneous background.

In this paper we will use “vacuum foam” or “quantum spacetime foam” in a deliberately modest way: as a shorthand for a background in which there is an underlying, perhaps discrete or highly fluctuating microstructure, but which on intermediate scales can be treated as an ordinary four-dimensional spacetime with additional localized defects. We will not attempt to model the detailed microscopic behavior of the foam. Instead, we treat it as an effective medium that can exert forces on defects, much as a soap film exerts forces on a string loop embedded in it.

2.2 Topological defects and cosmic strings

Topological defects arise naturally when a system undergoes a phase transition and different regions fall into different, topologically distinct ground states. In high-energy physics and cosmology, this is captured by the idea of spontaneous symmetry breaking: a field theory has a symmetric phase and a broken phase, and the manifold of vacuum states in the broken phase can have nontrivial topology. When the universe cools and fields roll into the broken phase in different patches, the resulting configuration can contain domain walls, strings, monopoles, or textures, depending on the homotopy of the vacuum manifold.

Cosmic strings are line-like defects associated with a nontrivial first homotopy group of the vacuum manifold. They carry tension, and at distances large compared to their core size, they can often be approximated as infinitely thin objects whose dynamics are governed by an action proportional to their worldsheet area. The simplest example is the Nambu-Goto string, which tends to minimize its length subject to the constraints imposed by the background geometry and any external forces. In flat space, closed loops of such a string oscillate and gradually lose energy, typically by emitting gravitational radiation, until they shrink away.

In more complex cosmological settings, however, the behavior of string loops can be richer. If a loop forms in an inflating background, expansion can stretch the surrounding space while the proper length of the loop changes more slowly. In certain models of topological inflation, the core of a defect itself can undergo inflation, effectively inflating a region around the defect. These scenarios do not precisely match the soap-film analogy, but they demonstrate that tensioned one-dimensional defects can play roles beyond simply acting as seeds for density perturbations or sources of gravitational waves.

In the embedded-loop picture we pursue here, we borrow only a subset of these ideas. We assume the existence of closed, tensioned loops whose length is approximately conserved on the timescales of interest. We assume that the surrounding vacuum foam can exert pressure-like or surface-tension-like forces on the loop, driving it toward energetically preferred shapes. But we are not committed to any specific underlying field theory. The loop could be a cosmic string in the usual sense, or it could be some more exotic topological or geometric defect left over from a quantum-gravity phase. The key property is that it behaves, mechanically, like a closed tensioned string immersed in a medium.

2.3 Inflationary Bubbles and Vacuum Domains

A second theoretical input is the inflationary picture of vacuum domains generated during transitions between different vacuum states. In many models of inflation, a scalar field slowly rolls along a nearly flat potential, while in some regions the field becomes trapped in a metastable false vacuum. Quantum tunneling or classical evolution can trigger transitions to lower-energy vacua, producing expanding “bubbles” of true vacuum within the false-vacuum background.

In scenarios of eternal inflation, such transitions continue indefinitely, generating a mosaic of vacuum domains with differing energies and cosmological properties. The physics of bubble nucleation, expansion, and collision has been studied extensively: bubble walls behave like thin, tensioned membranes, the bubble interiors evolve like open FRW universes, and bubble collisions may imprint signals on the cosmic microwave background or in large-scale structure.

In most of this work, attention is focused on the appearance, evolution, and interactions of whole vacuum domains. Much less explored is the structure of the underlying vacuum medium itself (the fluctuating spacetime foam out of which such domains form) and whether that foam could support localized defects or boundaries that do not correspond to new bubbles or tunneling events.

For the purposes of this paper, we adopt a simplified viewpoint. We imagine that the universe contains large-scale vacuum domains (loosely analogous to “bubbles” or pockets in eternal inflation) embedded within a deeper, fluctuating quantum-foam background. These domains may contain remnants of earlier phases or localized topological defects, but importantly, the defect loop considered here is not a bubble-wall phenomenon at all. Instead, it is described as a codimension-two structure embedded directly in the vacuum foam itself, whose evolution reshapes the internal geometry of its surrounding region without nucleating a new vacuum state.

3. The Soap-Film Defect Analogy

The central mechanical intuition behind the embedded-loop scenario comes from a simple and visually striking demonstration with soap films. Although soap films and cosmological vacuum domains are obviously very different systems, the experiment captures three key features we would like to reproduce in a spacetime context: the conservation of loop length, the expansion of the enclosed region, and the reshaping of the surrounding medium without rupturing the outer boundary.

Consider a thin soap film stretched across a rigid wire frame. The film minimizes its surface area subject to the boundary conditions imposed by the frame and by any internal constraints. Now imagine placing a closed loop of string inside the film, so that the film spans both the outer frame and the interior loop. If the loop is initially irregular, the film will exert forces on it, but as long as the film remains intact on both sides, the loop may simply sit at some equilibrium position.

The interesting behavior appears when the film inside the loop is disrupted. One way to do this is to touch the interior film with a drop of soap solution that changes the local surface tension. In many versions of the demonstration, the interior film breaks, leaving the loop bounding a “hole” in the film. The external soap film, which now spans only the region outside the loop, pulls uniformly on the loop from all directions. Because the loop has a fixed length and some tension of its own, the energetically favored configuration is a nearly circular loop that encloses a larger area than the initial irregular shape.

Several features are noteworthy. First, the outer film and the outer frame remain intact: the soap bubble or surface is not destroyed, and no new bubble is created. All that has changed is the internal structure. Second, the loop has not grown longer; instead, it has reconfigured itself to enclose more area. Third, the region inside the loop is qualitatively different from the region outside it. In the experiment it is literally a hole in the film, but one can equally well imagine replacing the interior film with a different phase or with air at a different pressure. The loop then becomes a boundary between two distinct internal regions.

This is the behavior we would like to mimic in a cosmological setting. Replace the soap film with an effective description of vacuum foam or quantum spacetime. Replace the string loop with a tensioned topological defect. Replace the interior hole with a spacetime region whose physical or causal properties differ from the exterior. The question is then: under what assumptions about the defect, the vacuum, and their interactions can an embedded loop in spacetime behave like the string in the soap-film experiment, acting as an internal boundary that reshapes the surrounding medium?

At the same time, it is important to respect the limits of the analogy. Soap films live in an ordinary three-dimensional space with a preferred time parameter; their dynamics are governed by classical fluid and surface-tension physics; and the interior “hole” is not a region of spacetime in its own right. In cosmology, by contrast, the vacuum is not literally a thin film, and the interior of a loop is a full spacetime region with its own causal structure. We must therefore be careful not to read too much into the analogy. The soap-film experiment is valuable because it gives us an intuitive picture of how a fixed-length loop can enlarge the region it bounds and how an internal boundary can arise without creating a new outer surface. But the cosmological implementation must be expressed in the language of spacetime geometry and causal relations rather than fluids and surfaces.

4. Conceptual Model of Embedded Topological Boundaries

With the components and analogy in hand, we can now sketch the embedded-loop scenario more systematically. The setting is a four-dimensional spacetime that is, on large scales, well approximated by a homogeneous and isotropic cosmology, for example, a region of an inflationary or post-inflationary universe. On smaller scales, we assume that there exist localized topological defects and other remnants of the underlying quantum foam, but that the metric can still be treated as a smooth field for the purposes of defining geodesics and causal structure.

Within this spacetime, select a spacelike hypersurface, a “moment of time” in some convenient slicing. On that hypersurface, consider a closed, one-dimensional loop. Physically, the loop corresponds to the intersection of a defect worldsheet with the hypersurface. Topologically, it is a circle embedded in the three-dimensional spatial slice. For the purposes of this model, we assume that the loop bounds a two-dimensional region in the slice, so that it truly functions as a closed boundary rather than as a knotted or self-intersecting curve with more complicated topology.

We now posit several key properties, inspired by the soap-film analogy and by the behavior of tensioned defects in field theory:

(1) The loop carries tension and has an associated energy proportional to its length. To first approximation, one can treat it as an object that resists stretching but can bend and move in response to forces from the surrounding vacuum.

(2) The proper length of the loop is approximately conserved over the timescales of interest. This means that the loop can change shape – becoming more circular, for example – without significantly changing its total length.

(3) The surrounding vacuum foam exerts effective forces on the loop that drive it toward energetically preferred configurations. In the simplest picture, these are analogous to uniform surface-tension forces in a soap film, which pull the loop toward shapes that maximize the enclosed area for a fixed perimeter.

(4) The spacetime region bounded by the loop can be treated as a distinct domain. Before the loop relaxes, this region may be small and irregular. As the loop evolves under the influence of the vacuum, the region grows. At some point, the geometry and fields inside the bounded region may become sufficiently decoupled from the exterior that the interior behaves effectively as its own "pocket" of spacetime.

The crucial conceptual step is to then interpret the loop as a genuine topological boundary between two spacetime regions. On one side lies the exterior: the part of the original vacuum domain in which observers like us reside. On the other side lies an interior region whose causal accessibility may be restricted. In ordinary general relativity, boundaries of this kind are associated with horizons or with singular structures such as cosmic strings and domain walls. Here we imagine something in between: a boundary created by a defect whose worldsheet marks the edge of a spacetime region that is topologically present but causally isolated.

To make sense of this idea, one can think in terms of causal curves. A causal curve is a path through spacetime that could, in principle, be followed by a light signal or a massive particle. In standard cosmological models, any two points within a connected region of spacetime are either causally related or not, depending on the expansion history, but the region itself is assumed to be part of a single manifold. In the embedded-loop picture, by contrast, we postulate that once the loop has stabilized into an appropriate configuration, no future-directed causal curve beginning in the exterior can cross the loop and enter the interior region. The interior exists, but from the point of view of the exterior, it is forever out of reach.

This postulate is not derived here from a microscopic calculation; instead, it is introduced as a defining property of the scenario. The idea is that whatever physics governs the defect and the vacuum foam enforces boundary conditions on fields and geodesics at the loop, such that the interior cannot be probed from outside. In a more complete theory, this might emerge from quantum-gravitational effects, from nontrivial topology of the underlying spacetime, or from some form of “surgery” on the manifold that identifies or removes regions in a way that preserves the consistency of the field equations. In this first conceptual treatment, we simply treat the causal inaccessibility of the interior as a working hypothesis and explore its implications.

5. Foam Warping and Large-Scale Effects

If embedded loops of the kind just described can form in a vacuum-foam background, they will not only carve out internal regions; they will also deform the surrounding spacetime. The soap-film analogy again provides helpful intuition. When the loop inside the film relaxes from an irregular shape to a more symmetric one, the curvature of the film adjusts accordingly. The local forces and tensions balance differently, and the film’s shape away from the loop is slightly altered. In spacetime, something similar can happen: the presence and evolution of a defect loop can change how nearby geodesics converge or diverge, and thus how the surrounding foam is “warped” on larger scales.

In a precise treatment one would write down the stress-energy tensor associated with the defect and solve the Einstein equations for the metric in its presence. In the case of ordinary cosmic strings, this leads to conical geometries and characteristic lensing signals. In the embedded-boundary scenario we are considering, the picture is more complicated, because the loop is associated not only with local stress-energy but also with the very existence of an interior region with restricted causal access. Nevertheless, we can qualitatively describe the effects on the foam.

First, the defect loop defines a preferred location and scale within the vacuum domain. Even if the background is statistically homogeneous, the presence of the loop breaks that homogeneity in its vicinity. Curvature and expansion near the loop may differ slightly from their values far away. Second, as the loop reconfigures from an irregular, small-boundary shape to a larger, more symmetric one, it can sweep curvature perturbations outward, much as the changing tension balance in a soap film redistributes curvature over the surface.

Now consider the timing of these processes relative to cosmic inflation. If loops of this kind form before or during an inflationary phase, their influence on curvature could be stretched to superhorizon scales. A small, localized distortion near the loop at early times could be inflated into a pattern that spans an entire observable universe at later times. From the point of view of observers inside a particular bubble or vacuum domain, this might manifest as large-scale anisotropies, preferred directions, or subtle departures from perfect isotropy in the cosmic microwave background or in the distribution of large-scale structure.

Alternatively, if the loops form after inflation but still very early in cosmic history, their effects would be confined to smaller scales but could still be significant. They might act as seeds for structure formation, generate characteristic gravitational-wave backgrounds, or contribute to phenomena we currently attribute to dark matter or dark energy. In all of these cases, the exact observational signatures would depend sensitively on the abundance, distribution, and evolution of the embedded loops. Since this paper does not specify a microscopic model, we do not attempt to make quantitative predictions. Instead, we emphasize that the embedded-boundary scenario raises a different class of questions: how might the vacuum foam itself acquire internal structure shaped by topological boundaries rather than by bubble dynamics or field-theoretic phase transitions?

6. Comparisons to Existing Scenarios

It is useful to situate the embedded-loop picture relative to other speculative structures that have been proposed in cosmology and quantum gravity. At first glance the idea of an inaccessible interior region bounded by a defect loop might resemble baby universes budding off from a parent universe, or wormholes connecting distant regions, or even miniature black holes. However, the similarities are limited, and the differences help clarify what is distinctive about the present scenario.

Baby universes and related constructions typically involve processes in which a region of spacetime pinches off from the parent manifold, perhaps through quantum tunneling. Observers in the parent universe may no longer have access to the interior of the baby universe, but the baby universe itself evolves with its own internal time. In many treatments, the pinch-off is associated with extremely high curvatures or with non-classical configurations that are not easily described by smooth metrics. By contrast, the embedded-loop scenario does not require a region to detach from the parent manifold. Instead, the interior region remains topologically part of the same global spacetime, but is separated from the exterior by the defect-boundary in a way that restricts causal access.

Wormholes and Einstein–Rosen bridges also involve nontrivial topology, but they usually connect distinct regions of spacetime rather than excising an interior domain. Traversable wormholes, where they can be made consistent, allow causal curves to pass from one mouth to the other. Non-traversable wormholes may have some superficial resemblance to an inaccessible region, but again the geometry and the physical interpretation differ from that of a defect-bounded interior. In the present picture there is no second mouth elsewhere in the universe; there is simply a bounded region separated from its surroundings by a topological boundary.

Black holes provide a closer analogy, since they, too, contain regions that cannot send signals to the exterior. The boundary of a black hole, the event horizon, is defined in terms of causal structure: it separates events that can influence future null infinity from those that cannot. One can imagine an extreme limit of the embedded-loop scenario in which the defect and the interior region conspire to produce something akin to a tiny black hole. However, the intent of the model is to remain in a regime where curvatures need not be Planckian and where the interior region is not necessarily associated with a singularity or with standard black-hole thermodynamics. The embedded boundary is meant to be more geometric and topological than dynamical and collapse-driven.

Finally, one can compare the scenario to more conventional cosmic-string loops and topological inflation. In those models, the focus is usually on how defects act as localized sources of curvature or as sites where inflation can begin. The defects themselves are not typically treated as boundaries of inaccessible regions. Our picture inverts that emphasis: the loop's primary role is to demarcate an interior domain, with its stress-energy and gravitational effects playing a supporting role. This shift in perspective is what makes the scenario new, even though it draws on familiar building blocks.

7. Limitations and Directions for Future Work

Because this paper is intentionally conceptual, it leaves many questions open. Some of these are technical questions about how to embed the scenario in a consistent field-theoretic or quantum-gravity framework. Others are phenomenological questions about how such embedded boundaries, if they exist, would influence observable cosmology. Here we briefly outline some of the most important avenues for future work.

On the theoretical side, the most pressing need is for a more precise mathematical characterization of the defect-boundary and its interior. In a fully relativistic treatment one should specify the stress-energy tensor associated with the defect, the junction conditions at the boundary, and the behavior of geodesics and fields near the loop. Tools from the theory of thin shells, distributional curvature, and non-smooth geometry may be helpful. One might, for example, construct a toy model in which the interior region is represented by a patch of spacetime with different curvature or vacuum energy, glued to the exterior along a codimension-two surface representing the defect. The goal would be to show, explicitly, that the resulting geometry is consistent and that the interior can indeed be causally disconnected while the exterior remains regular.

A second theoretical challenge is to identify plausible mechanisms for the formation and evolution of such loops in the early universe. Are they produced during phase transitions, like ordinary cosmic strings? Do they arise as remnants of quantum foamy processes that survive coarse-graining? Under what conditions would their length be approximately conserved, and what kinds of interactions with the vacuum would drive them toward the analog of the circular, area-maximizing configuration seen in soap films? Numerical simulations of defect networks in expanding backgrounds, supplemented by simple effective models of vacuum-defect interactions, could shed light on these issues.

On the phenomenological side, it would be valuable to explore the range of possible observational signatures. If only a few embedded loops form within our observable region, they might produce isolated anomalies: unusual gravitational lensing events, patches of the sky with slightly different statistical properties, or localized departures from isotropy in the cosmic microwave background. If many loops form, their collective effect might resemble an additional contribution to dark matter or dark energy, or it might change the statistics of large-scale structure in characteristic ways. Even if no such signatures are observed, the absence of evidence can be turned into constraints on the abundance and properties of embedded loops, placing limits on the underlying high-energy physics.

Finally, there are conceptual questions about the role of such internal boundaries in broader discussions of information, entropy, and holography. If an interior region is causally inaccessible, does it nevertheless contribute to the entropy budget of the universe? Is there a sense in which information about the interior is stored on the boundary, analogous to the way black-hole entropy is associated with horizon area in some approaches? Could networks of embedded loops provide a new way of thinking about the partitioning of information in a quantum spacetime? These questions require tools from quantum information theory and quantum gravity, and are beyond the scope of this first paper, but they illustrate the conceptual richness of the basic idea.

8. Conclusion

We have proposed and explored a conceptual model in which embedded string-like loops act as internal topological boundaries within a vacuum-foam cosmological background. Inspired by the behavior of a string loop in a soap film, the scenario imagines a closed, tensioned defect whose length is approximately conserved while its shape adjusts under the influence of the surrounding vacuum. As the loop relaxes, it can enlarge the spacetime region it bounds, carving out an interior domain that, under suitable conditions, becomes causally inaccessible from the exterior. The surrounding foam is warped in the process, potentially leaving imprints that could be stretched to large scales by inflation.

Unlike more familiar constructions involving bubble nucleation, wormholes, or black holes, the embedded-loop picture emphasizes internal boundaries that are topological and geometric rather than dynamical products of collapse or tunneling. The interior region is not necessarily a separate universe, nor need it be associated with singularities or horizons in the usual sense. Instead, it is a subregion of spacetime shaped and isolated by the presence of a defect. This shift in viewpoint opens up new conceptual possibilities for how vacuum domains might be structured and how topological defects might influence cosmological evolution.

The framework developed here is only a first step. Much remains to be done to turn the idea into a fully worked-out theory or to rule it out as inconsistent or phenomenologically implausible. Nonetheless, by articulating the assumptions, geometry, and qualitative consequences of embedded internal boundaries, we hope to provide a concrete target for future analytical, numerical, and observational work. Whether or not nature actually realizes such structures, thinking about them can sharpen our understanding of the interplay between topology, defects, and cosmology in a quantum spacetime.

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