The Bubble Theory of the Universe: A Quantum Fluid Perspective on Cosmological Emergence

Haci, Sogukpinar.

Department of Physics, Faculty of Art and Sciences, and Department of Electric and Energy, Vocational School, University of Adiyaman, Adiyaman, 02040, TURKEY.

Corresponding author: hsogukpinar@adiyaman.edu.tr, orcid.org/0000-0002-9467-2005

Abstract

This work proposes a cosmological model in which our universe is conceptualized as a three-dimensional “bubble” formed within a higher-dimensional, quantum fluid-like primordial ocean medium. Integrating modern cosmological frameworks such as cosmic inflation, the holographic principle, brane cosmology, and fluid-gravity analogies, the model proposes that the universe emerged as a local explosion within a larger physical structure. The formation of the bubble could have been initiated by an external trigger related to the negative pressure of the medium surrounding the bubble, or by a phase transition or internal local explosion, explaining the observed accelerated expansion of the universe. The external medium could be the source of dark energy. The boundary of the bubble is treated as a reflective, information-encoding interface that interacts with electromagnetic and gravitational waves, potentially leaving observable cosmological signatures. The assumption that the ocean surrounding the bubble obeys different physical laws exhibits behavior consistent with scenarios in quantum gravity and multiverse theories. Testable predictions could include spectral distortions in the Cosmic Microwave Background (CMB), echoes in gravitational wave data, and topological patterns in the distributions of large-scale structures. This model brings together existing paradigms in cosmology while providing new insight into the nature, boundaries, and origin of our universe.

Keywords: Bubble Universe, Cosmological Bubble, Pre-universal Medium, Primordial Field, Cosmic Boundary

Introduction

The quest to understand the origins and structure of the universe has led physicists to propose increasingly bold theoretical models, many of which diverge from the classical big bang paradigm. Among these emerging frameworks is the concept that our universe is merely one of several dynamic "bubbles" embedded within a higher-dimensional medium, with its expansion potentially driven by interactions with this primordial substructure (Astronomy Explained 2025; Guendelman and Portnoy 2024; Vilenkin 2007). These bubble universe models challenge the traditional notion of a singular beginning, instead suggesting that the universe’s birth may be just one event in an eternally inflating multiverse—a continuous process rather than a unique occurrence (Quanta Magazine 2025; Guth 1981; Linde 1983). Within this view, numerous universes, potentially governed by different physical laws, could exist simultaneously in an expansive, multidimensional space.

Recent research, such as that conducted at Uppsala University, further develops this idea by positing that our observable universe resides on the boundary of a higher-dimensional bubble. In this scenario, matter may be understood as the endpoints of strings extending into an extra dimension, providing a novel framework for interpreting cosmic structure and expansion (Guendelman and Portnoy 2024; McInnes 2008). This model contributes to a more integrated understanding of cosmic inflation, string theory, and higher-dimensional geometry, offering insight into both large-scale cosmological evolution and quantum-scale gravitational phenomena.

Complementing this geometric model is the holographic principle, which theorizes that our three-dimensional reality may be a projection of information encoded on a two-dimensional boundary surface. This concept, deeply embedded in the foundations of quantum gravity and string theory, offers a potential unification of quantum mechanics and general relativity (Walter 2025; Mirbabayi 2022; Bousso 2002). It also provides a framework for interpreting observational data—such as anomalies in the cosmic microwave background (CMB)—as potential signatures of interactions with other bubble universes, thereby opening the door to empirical tests of multiverse theory (Quanta Magazine 2025; Susskind and Lindesay 2005; Maldacena 1999).

As these new perspectives reshape our understanding of spatial and dimensional boundaries, observational cosmology itself is undergoing a paradigm shift. Data from the Dark Energy Spectroscopic Instrument (DESI) indicate that dark energy, long thought to be constant, may in fact evolve over time (University of Queensland 2025; Roy 2025). This challenges the prevailing ΛCDM model, which assumes a constant dark energy density, and supports alternative proposals in which dark energy arises from vacuum fluctuations or curvature effects within bubble universes (Bousso 2002; Auci 2021; Verlinde 2011). Additionally, the recent identification of Hoʻoleilana—a colossal, billion light-year-wide galactic bubble associated with primordial baryon acoustic oscillations (BAOs)—poses further challenges to standard cosmological models, as it implies a faster expansion rate than ΛCDM predicts (University of Queensland 2025; Keisler et al. 2019).

Together, these ideas—bubble cosmology, holographic encoding, and dynamic dark energy—compose a richer and more intricate cosmological framework than previously imagined. By integrating these theories, scientists gain new avenues for probing the nature of spacetime and the universe's origins. This article examines how these theories interact, from the initial conditions of bubble universes (McInnes 2008) to the foundational structures of spacetime as outlined in string theory (Polchinski 1998), and explores how such a synthesis may resolve enduring cosmological mysteries.This work proposes a cosmological model in which the universe forms as a three-dimensional "bubble" in a higher-dimensional, quantum fluid-like primordial matter-like medium, such as a sea of quarks. The model combines concepts from cosmic inflation, the holographic principle, brane cosmology, and fluid-gravity analogies to propose that the accelerated expansion of the universe is driven by negative pressure or energy from the surrounding medium. It predicts observable cosmological signatures such as spectral distortions in the Cosmic Microwave Background (CMB), echoes in gravitational waves, and topological patterns in large-scale structures, providing new insights into the boundaries and origin of the universe.

Pre-Universe and the Emergence of the Cosmic Bubble

Before the birth of our universe, there was a primordial ocean encompassing all of existence: a pre-geometric realm or higher-dimensional substructure, similar to a vast "quark ocean." From this perspective, our universe emerged as a local fluctuation within this expanding medium, a local trigger or explosion, or like a bubble in a body of water due to an external trigger. This view is compatible with the concept of cosmic inflation, in which a small region undergoes rapid exponential expansion, and explains the emergence of our universe as the transformation and continuation of a much larger, pre-existing structure. In this framework, the universe can be understood as a three-dimensional "bubble" situated within a higher-dimensional liquid-like medium. This model is consistent with analog gravity theories that propose the universe emerged from a quantum fluid composed of a quark sea, whose spacetime structure remains uncertain. The formation of the bubble could have been triggered by an external perturbation, akin to a cosmic explosion, or as a result of a phase transition within the medium.

Moreover, the accelerated expansion of the universe, commonly associated with dark energy, can be explained by the negative pressure of this higher-dimensional environment. If this external medium possesses a negative pressure similar to a cosmological constant, the interplay between the internal dynamics of the universe (such as vacuum energy) and the external pressure could together drive the expansion. This concept presents the universe as a local formation developing within a much larger, overarching reality, offering a fresh perspective on cosmology and the origin of the universe.

The inflationary paradigm explains the universe's homogeneity and flatness through rapid exponential expansion driven by a scalar inflaton field. In the bubble universe extension, inflation corresponds to the growth of a 3+1-dimensional spacetime "brane" within a higher-dimensional bulk. This process is mathematically modeled via instanton solutions in string theory, where the bubble's nucleation rate depends on the bulk's curvature and energy density.

The accelerated expansion of the universe (attributed to dark energy) may arise from interactions between the bubble universe and the external medium. If the bulk possesses negative pressure ($P_{\text{bulk}}<0$) it exerts an outward force on the brane, mimicking a cosmological constant (Λ). This is formalized in braneworld models (e.g., Randall-Sundrum scenarios), where the Friedmann equations acquire corrections as:

$$\mathbf{H}^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_{\text{eff}}}{3} + \frac{8\pi G}{3}\frac{\sigma}{R_{max}}a^{-2} \tag{1}$$

Where, **H**, represents the Hubble parameter, which is the rate of expansion of the universe, G is Newton's gravitational constant, and **ρ** is the energy density of the universe (including matter, radiation, and dark energy). This term accounts for the contribution of all forms of energy density to the expansion. **k** is the curvature parameter, which describes the geometry of the universe. **k**=+1 for a closed universe (positive curvature), **k**=0 for a flat universe, and k=−1 for an open universe (negative curvature). The term -k/a^2 adjusts the expansion rate based on the curvature of the universe. Λ_{eff} is the cosmological constant due to external pressure, $\Lambda_{\text{eff}} = 8\pi G P_{ext}$, where P_{ext} is external pressure. In modern cosmology, **Λ** is associated with dark energy, contributing to the accelerated expansion of the universe. The final part added to the equation contains the term describing the expansion due to external pressure, and the energy-momentum contribution of the boundary is modeled by adding the surface tension term (σ) to the Einstein equations:

$$\sigma = \frac{P_{ext} R_{max}}{4} \tag{2}$$

Where, $R_{\max}$, Comoving radius of the bubble, P_{ext}, The pressure of the liquid surrounding the universe. a dimensionless quantity representing the relative size of the universe at a given time compared to the present (a=1 today). The negative pressure of the external environment accelerates the expansion.

Fig.1 Buble universe

Boundary Dynamics and Nature of a Bubble

The universe can be envisioned as a three-dimensional "bubble" embedded within a higher-dimensional fluid-like or quantum foam medium and presented in Fig.1. This conceptual framework draws from brane cosmology, analog gravity, and quantum field theory, proposing that our universe emerged from a localized fluctuation or phase transition in this primordial substrate. The expansion of the bubble is driven by the interplay between internal vacuum energy and the external negative pressure of the surrounding medium, analogous to dark energy in the standard cosmological model. By adding an additional term to the Friedmann equations, expressed in Eq.1, the expansion dynamics of a 3D bubble universe embedded in a higher dimensional bulk can be expressed as follows with the Modified Friedmann Equations with Bulk-Brane Interaction:

$$\mathbf{H}^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_{\text{eff}}}{3} + \frac{8\pi G}{3}\frac{\sigma}{a^2.R_{max}} + \frac{\epsilon}{a^4} \quad (3)$$

Where, ε: Projection of the bulk's Weyl tensor onto the brane (encodes bulk gravitational influence, behaves as "dark radiation"). In brane-world models, the universe is considered a 3+1-dimensional surface (the brane) embedded in a higher-dimensional space (the bulk). The gravitational field exists in the bulk and can influence the brane via its curvature. This term does not originate from matter on the brane, but from the gravitational field in the bulk—essentially, it's an imprint or shadow of higher-dimensional gravity seen from our 4D perspective. Bulk-brane interactions generate resonant gravitational wave spectra and it reflects the discreteness of the modes within the cosmological "bubble" and the boundary effects that lead to a quantized spectrum.

$$h(f) \propto \sum_{nlm} \frac{\delta(f - f_{nl})}{f_{nl}^{3/2}} \quad (4)$$

where, $f_{nl} = \frac{\alpha_{nl} c}{2\pi R_{max}}$,where α_{nl} is the quantized root of the spherical Bessel function, j_l (from the boundary condition). This is a typical result when dealing with a spherical cavity with discrete resonant frequencies. The relationship $f_{nl} = \frac{1}{R_{max}}$ suggests that the frequency scales inversely with the size of the bubble (or the comoving radius of the universe), consistent with the fact that higher frequencies correspond to shorter spatial scales or higher momentum modes.$f_{nl}^{3/2}$scaling is often seen in systems with specific boundary conditions (like standing waves in a finite geometry), which we correctly model as a holographic universe with boundary-induced effects.

At the interface between our universe and this higher-dimensional environment lies a cosmological boundary—a transitional region that not only delineates the limits of the observable universe but may also serve as a physical membrane encoding the fundamental properties of spacetime. Within this boundary, familiar physical laws such as general relativity, quantum mechanics, and electromagnetism apply, while the boundary itself could manifest nontrivial dynamics that influence global cosmological behavior.

In line with the holographic principle, this boundary may act as a lower-dimensional information surface—a holographic screen on which the bulk information of our universe is encoded. This concept is supported by AdS/CFT duality in string theory, where a gravity-containing "bulk" space is mathematically equivalent to a conformal field theory on its boundary. Applied to our universe, this implies that the entire 3+1D cosmological evolution may be representable in terms of processes occurring on a 2+1D boundary. The 2+1D boundary encodes the universe's information via the holographic entropy formula:

$$S = \frac{A}{4G} = \frac{\pi R_{max}{}^2}{G} \quad (5)$$

Where, $A = 4\pi R_{max}{}^2$ is the boundary area.

Physically, the boundary may serve as a reflective or absorptive surface for certain types of radiation. For instance, electromagnetic and gravitational waves may undergo partial reflection or scattering at this interface, depending on the boundary's physical properties. This could be modeled using Dirichlet or Neumann boundary conditions applied to Maxwell's and Einstein's field equations. Such boundaries are well-known in mathematical physics for defining how wave functions behave at the limits of a domain and can lead to mode quantization in confined geometries (e.g., waveguides or resonant cavities). Applying Dirichlet conditions means that certain physical fields (say, scalar fields or electromagnetic potentials) must take specific values at the boundary of the universe. This could represent a confining behavior—as if the boundary "clamps" or anchors the field. A Dirichlet boundary condition fixes the value of a field at the boundary as:

$$E_{||} = 0; B_{\perp} = 0 \text{ (reflective boundary)} \tag{6}$$

The boundary might act like a mirror that holds the field to zero or to some equilibrium value. This can prevent the leakage of field energy or information into the higher-dimensional bulk. Could reflect a kind of information encoding on the boundary, aligning with the holographic principle, where the internal field configuration is fully determined by the boundary. A Neumann boundary condition fixes the derivative (or flux) of the field normal to the boundary as:

$$\partial_r E_{\perp} = 0, \partial_r B_{||} = 0 \text{ (transparent boundary)} \tag{7}$$

This would imply that there is no net flux of the field across the boundary—i.e., the field is "free" to vary inside the universe, but its normal derivative at the boundary is zero (or specified). The universe behaves like a resonant cavity, where standing waves are allowed to form, but energy does not escape through the boundary. This condition supports conservation laws and energy localization within the bubble. It aligns with the idea that the boundary is reflective (but not clamping), letting the field oscillate naturally inside However, if the universe were bounded in this way, we would expect discrete resonant modes in the cosmic microwave background (CMB) spectrum, contradicting the observed nearly perfect blackbody radiation. This discrepancy can be reconciled by proposing that the pre-inflationary universe underwent a homogenization phase, where boundary-induced reflections and symmetry-driven radiation fields smoothed initial fluctuations. The subsequent rapid inflationary expansion could have then stretched these homogenized regions beyond the observable horizon, effectively "hiding" any boundary-induced anisotropies from present-day observation. Electromagnetic and gravitational waves satisfy the Klein-Gordon equation in the bubble:

$$\nabla^2\Psi - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \left(\frac{mc}{\hbar}\right)^2 \Psi = 0 \tag{8}$$

In our case, since we're applying it to gravitational and electromagnetic fields, we're likely treating them as massless or effectively massless fields (m = 0), so the last term vanishes. This becomes the wave equation, appropriate for EM waves and gravitational waves in a curved or enclosed geometry like this bubble. With boundary conditions, in Spherical Coordinates solutions are quantized:

$$\Psi_{nlm}(r,\theta,t) = j_l\left(\frac{\alpha_{nl} r}{R_{max}}\right) Y_{lm}(\theta,\emptyset) e^{-iw_{nl}t} \quad (9)$$

Where, j_l: spherical Bessel functions – describe radial modes., Y_{lm} : spherical harmonics – describe angular dependence, α_{nl}: quantized roots (zeroes) of the Bessel function, dependent on boundary conditions (e.g., Dirichlet). $w_{nl} = \frac{\alpha_{nl} c}{R_{max}}$: frequency of each mode – discrete spectrum. Discrete modes are homogenized by inflation, leaving a nearly perfect blackbody spectrum. Residual anomalies (e.g., Cold Spot) may arise from incomplete homogenization. The external medium's negative pressure drives accelerated expansion:

$$w_{eff} = \frac{p_{ext}}{\rho_{ext}} = -1 + \frac{\sigma}{3R_{max}H^2} \text{ for } \sigma \ll R_{max}H^2 \text{ this reduces to } w_{eff} \approx -1 \quad (10)$$

Where, p_{ext}= pressure of the external (bulk) medium, ρ_{ext} effective energy density perceived by the brane/universe, σ surface tension or boundary energy of the bubble (can act like a pressure offset), R_{max} comoving radius of the universe, H Hubble parameter (expansion rate)The idea that external pressure (from a higher-dimensional bulk) drives accelerated expansion compatible with Braneworld models (e.g., Randall–Sundrum, DGP models), Holographic dark energy models, Fluid-gravity analogies, particularly where the interface/boundary contributes effective energy conditions.

Another plausible interpretation is that the physical boundary of the bubble lies at scales far beyond our cosmic horizon, making any direct observational signature—such as repeating CMB patterns or directional anomalies—effectively undetectable with current instruments. Still, indirect hints, such as low-multipole anomalies in the CMB, cold spots, or statistical isotropy violations, could serve as potential signatures of large-scale boundary effects. Pre-inflationary fluctuations are smoothed by boundary reflections:

$$\langle \delta\rho \rangle \propto \int_o^{t_{infl}} \frac{\Gamma_{scatt}(t')}{a(t')} dt' \quad (11)$$

Where, $\Gamma_{scatt} \sim \frac{c}{R_{max}}$ scattering or interaction rate between waves (e.g. gravitational/electromagnetic), $\langle \delta\rho \rangle$ average density fluctuation amplitude due to boundary-induced interactions, $a(t')$ scale factor at time t',t_{infl} time at which inflation begins. Waves (like gravitational or electromagnetic) interact with the reflective bubble boundary, creating homogenization effects (i.e., smoothing out fluctuations).This is modeled by Γ_{scatt} , which represents how often these interactions happen. The factor $\frac{1}{a(t')}$ accounts for the dilution of these effects as the universe expands. It's similar to how energy densities or interaction rates scale in early-universe thermodynamics. The total contribution to the fluctuation smoothing accumulates before inflation begins, which fits your scenario where reflections from the boundary homogenize the universe early on. These homogenized regions are exponentially stretched by inflation. Thus, anisotropies from the boundary are "pushed" beyond the observable horizon, explaining why the CMB is so smooth despite having a boundary.

This cosmological bubble model, enhanced by the holographic encoding at its boundary, offers a compelling narrative that integrates modern developments in quantum gravity, string theory, and observational cosmology. It provides novel insight into fundamental questions about the origin, expansion, and global structure of the universe while remaining compatible with the standard cosmological framework (ΛCDM) when interpreted as a low-energy effective limit of a deeper theory.

Alternative Physical Laws Beyond the Cosmic Bubble

Inside the bubble, the laws of physics we know (general relativity, quantum mechanics, and electromagnetism) apply, providing a stable framework for the evolution of our observable universe. However, beyond the boundaries of this bubble, there may be a vast, unknown ocean-like environment that may operate under a completely different set of physical laws, or it may be something similar to our physics literature. Of course, we have to see the effects to know this. This external environment could potentially be a sea of quarks, a primordial fluid or structure that gives rise to the most basic constituents of matter, or it could be a sea of environments with completely different properties and interactions that our current understanding of physics cannot access. The basic idea is that the structure of this external environment suggests the possibility of a highly dynamic and more complex multiverse-like framework with properties that are completely different from the current laws we observe inside our bubble.The external medium is modeled as a relativistic fluid Euler equation in D-dimensions (D>4), with energy-momentum tensor:

$\partial_A T^{AB} = 0$(Conservation of energy and momentum)

This is the covariant conservation of energy-momentum in the higher-dimensional bulk. It ensures that energy and momentum are not created or destroyed but can flow within the bulk or across the bubble boundary. This equation governs the dynamics of the external ocean-like environment, and any interaction with the bubble (our universe) must respect this law. It's foundational in both general relativity and braneworld cosmologies. Bulk Stress-Energy Tensor can be written as:

$$T_{AB}^{(\text{bulk})} = (\rho_{bulk} + P_{bulk})U_A U_B + P_{bulk} G_{AB} + \Pi_{AB} \tag{12}$$

This is the perfect fluid form, extended to include anisotropic stresses via the Π_{AB} term. Where, ρ_{bulk} Energy density of the ocean-like external medium (e.g., quark sea or quantum foam).P_{bulk} Pressure in the bulk. In this model, this is negative, driving bubble expansion (similar to dark energy). U_A bulk fluid velocity — defines the rest frame of the external medium.G_{AB} Metric of the bulk spacetime (could be 5D or higher)., Π_{AB}Anisotropic stress It can represent fluctuations in the quantum foam, turbulence, or directional pressures in the bulk, which are entirely consistent with your ocean analogy and the idea of a nontrivial external environment). $P_{bulk} = {}^{w_{bulk}}/_{\rho_{bulk}}$, $w_{bulk} < -{}^{1}/_{3}$(for negative pressure) This is essential for driving accelerated expansion of the bubble.

This model, which is based on a brane-world cosmology scenario, suggests that this external medium is not merely a passive environment but an active participant in shaping the bubble universe's evolution. This could support scenarios where the forces and constants that govern the universe outside our bubble are distinct from those in our observable universe. Such variations could be a direct manifestation of higher-dimensional physics or quantum gravity effects that influence the boundary of the bubble and the space-time within. The bubble boundary (∂M) is a (D−1)-dimensional hypersurface where bulk and bubble physics interact. The extrinsic curvature $K_{\mu\nu}$ of the boundary relates bulk and bubble metrics.

$$K_{\mu\nu}^{+} - K_{\mu\nu}^{-} = -\kappa_D^2 \left(S_{\mu\nu} - \frac{1}{D-2} h_{\mu\nu} S \right) \tag{13}$$

This is a junction condition from general relativity in higher dimensions, often called the Israel–Darmois–Lanczos condition. This equation connects the geometry of the bubble boundary to the stress-energy on the boundary, bridging the bulk and the brane (bubble).Where$K_{\mu\nu}^{\mp}$ Extrinsic curvature of the boundary surface from either side (inside the bubble or from the bulk side).,κ_D, D-dimensional gravitational coupling constant: shows that gravity in the bulk affects the brane via boundary curvature., $S_{\mu\nu}$ Surface stress-energy tensor of the boundary — in this model, this could include brane tension (λ), surface pressure/energy (σ), and possible contributions from holographic information or quantum effects.$h_{\mu\nu}$ Induced metric on the boundary (from the bulk); defines how spacetime looks from the brane's perspective. S Trace of the boundary stress-energy tensor. The boundary between our universe and the external medium becomes crucial in understanding the large-scale structure of our cosmos. It acts as both a physical interface and a transitional zone where the properties of space-time might shift dramatically. Here, quantum gravitational effects, which are likely to be more pronounced at this interface, may not only influence the bubble's expansion but also the way in which information is encoded across dimensions. According to the holographic principle, this boundary may encode the information of our entire universe onto a lower-dimensional surface. This aligns with string theory and the AdS/CFT correspondence, which suggests that higher-dimensional gravity may manifest as a conformal field theory on the boundary of the bubble.

In the early universe, before inflation, quantum fluctuations at this boundary might have been prominent, leading to the homogenization of the cosmos through boundary-induced reflections or interactions. These fluctuations could have been smoothed out over time by rapid inflationary expansion, which stretched these regions beyond our observable horizon. Thus, any potential anisotropies or signs of the boundary conditions may no longer be detectable today, even though they were critical in shaping the cosmic structure.

However, if the bubble is in contact with a higher-dimensional bulk that contains differing physical laws, we would expect certain anomalies to potentially leak into our observable universe. The bulk's Weyl tensor C_{ABCD} projects onto the bubble as an effective energy density:

$$\rho_{Weyl} = \frac{\varepsilon}{a^4}, \varepsilon = \frac{l^4}{G_D} \rho_{bulk}^2 \tag{14}$$

This appears in the modified Friedmann equation (see eq.1). where, $\frac{\varepsilon}{a^4}$ is the "dark radiation" term: a non-standard, relativistic-like contribution from bulk gravity encoded in the Weyl tensor projected onto the brane (bubble universe).$\frac{l^4}{G_D} \rho_{bulk}^2$ shows how bulk energy density feeds into the brane. The square of ρ_{bulk} is typical in brane-world scenarios (e.g., RS models), showing nonlinear effects of bulk matter. a^{-4}Behaves like radiation, i.e., decays as the universe expands. But since it's from the bulk Weyl curvature, it's not tied to actual particles—just a geometric imprint of the bulk. These anomalies could manifest as small deviations in the Cosmic Microwave Background (CMB) or as cosmic ray anomalies that do not conform to the standard model. These "boundary effects" would likely remain hidden from our direct observation due to the inflationary expansion pushing them beyond our cosmic horizon, but indirect evidence could still be present. Bulk-induced fluctuations imprint on the CMB temperature anisotropy $\Delta T / T$:

$$\langle \left(\frac{\Delta T}{T}\right)^2 \rangle \sim \int \frac{d^3k}{(2\pi)^3} P_\Phi(k) |\Theta_l(k)|^2 \tag{15}$$

This is a standard structure in cosmological perturbation theory, representing how primordial fluctuations contribute to the angular power spectrum of the CMB. But here, we're interpreting the sources of these fluctuations in a bulk-reflective boundary context. Where, $P_\Phi(k)$, Power spectrum of bulk-sourced gravitational potentials, possibly originating from Weyl curvature perturbations, anisotropic stresses ($\Pi_{\_AB}$), or quantum foam dynamics in the bulk. $\Theta_l(k)$, Transfer function that includes effects of boundary reflections, scattering (as modeled earlier by Γ_scatt), and inflationary smoothing — this encodes how initial fluctuations project onto CMB multipoles. For example, some of the low-multipole anomalies or cold spots observed in the CMB could be subtle signatures of interactions or reflections at the boundary. These might not be direct evidence of a different physical regime at the boundary, but they could indicate the lingering effects of those boundary conditions from the pre-inflationary phase. For a bubble of radius $R \gg H^{-1}$, Low l anomalies happen at the quadrupole $(l = 2)$. CMB quadrupole anomaly expressed as:

$$C_2 \sim \frac{\varepsilon}{R^2 H^4} \tag{16}$$

Where, C_2 refers to the quadrupole moment of the CMB angular power spectrum. This eq. 16 elegantly links the bulk Weyl term with observable low-ℓ features in the cosmic microwave background (CMB). Furthermore, if quantum gravitational effects are prominent at the boundary, there could be a feedback loop between the bulk and the brane universe. The projection of bulk gravitational influences onto the brane may result in what is effectively dark radiation. This form of radiation could be detected as an imprint on the CMB, particularly in regions where the bulk's gravitational influence is stronger or more pronounced.

Lastly, the boundary could also serve as a kind of resonant cavity for waves (electromagnetic or gravitational). The way these waves behave at the boundary—whether they reflect, scatter, or remain confined within the bubble—could reveal more about the properties of the external medium. These boundary conditions could be modeled as Dirichlet or Neumann boundary conditions, determining the behavior of fields at the interface between the bubble and the bulk. These conditions could contribute to the energy localization within the bubble, ensuring that the universe behaves like a confined system with specific energy characteristics determined by the interaction at the boundary.

Observational Probes of the Bubble Universe Model

Various observational strategies can be applied to assess the validity of the bubble universe model. Inspection of boundary signatures on the Cosmic Microwave Background (CMB) can reveal subtle anisotropies, low-ℓ multipole anomalies, or reflection patterns potentially originating from the bubble boundary. These may manifest as statistical isotropy violations, hemispherical asymmetries, or suppressed power at large angular scales—features that deviate from standard ΛCDM predictions.

To understand the relationship between the model and cosmic expansion, the dynamics between expansion rates and boundary-induced energy exchange mechanisms must be thoroughly investigated. This includes studying how the external medium's negative pressure or surface tension effects modify the effective equation of state w_{eff} and whether these modifications can account for the observed dark energy-like behavior. Precision measurements of the Hubble parameter across redshifts (e.g., via BAO, Type Ia supernovae, and gravitational lensing) can help test these effects.

In the context of high-energy astrophysics, observations of ultra-high-energy cosmic rays, black hole evaporation near Planck-scale regimes, or gamma-ray bursts may reveal deviations from standard physical laws. These anomalies could be indirect evidence of non-standard interactions occurring at or near the bubble boundary, especially if quantum gravitational corrections or boundary-induced violations of Lorentz invariance are present.

Gravitational wave observatories (such as LISA, DECIGO, or advanced ground-based interferometers) offer another crucial window. The detection of resonant modes or discrete frequency spectra in the stochastic gravitational wave background may signal boundary reflections, as predicted by the quantized mode structure arising from boundary conditions (e.g., Dirichlet or Neumann types). Matching such spectral features with theoretical mode distributions (e.g., from spherical Bessel roots) could serve as a powerful diagnostic of the bubble's geometry and boundary physics.

Large-scale structure surveys can be employed to detect topology-dependent features in the matter power spectrum. If the universe is topologically finite—as suggested by the bubble model—discontinuities, cutoffs, or modulations in galaxy correlations may arise on scales comparable to the bubble's maximum comoving radius Rmax. Future surveys (e.g., Euclid, LSST, DESI) will enable precision mapping of such structures.

In order to assess the model's compatibility with cosmic inflation, the bubble can be interpreted as a rapidly expanding structure resulting from a phase transition in the external environment. In this framework, pre-inflationary boundary reflections may provide a mechanism for the observed homogeneity, while inflation stretches these effects beyond the horizon. Primordial gravitational wave measurements and polarization modes in the CMB (B-modes) could provide further clues.

Finally, the model offers a bridge between cosmology and quantum gravity. By defining the external environment as a regime where quantum gravitational or string-theoretic effects dominate, and treating the bubble universe as a semi-classical emergent structure, observational tests might include searches for Planck-scale relics, nonlocal correlations, or holographic noise in interferometric detectors.

Collectively, these observational tests can provide vital constraints to assess the physical consistency of the bubble universe model, inform its parameter space, and offer new insights into the deep structure and origin of spacetime itself. A short list of possible critical experimental findings and their scientific contexts can be listed as follows:

1.Cosmic Microwave Background (CMB) Signatures

Anomalous Polarization Patterns: Use next-generation CMB experiments (e.g., CMB-S4, LiteBIRD) to search for:Concentric Temperature Rings: Circular anomalies in the CMB polarization (E/B-modes) caused by collisions between our bubble and neighboring universes. Suppressed Large-Scale Power: Low-ℓ multipole alignments ($\ell=2-5$) or hemispherical asymmetries, potentially linked to boundary-induced reflections.

Spectral Distortions: Deviations from the blackbody spectrum (e.g.,μ- or y-distortions) due to energy injection at the boundary during pre-inflationary phases.

Statistical Isotropy Tests: Apply multipole vector analysis or bipolar spherical harmonics to quantify directional anomalies in the CMB, which could reflect residual boundary topology.

This model predicts boundary-induced imprints in the CMB. This includes low-ℓ anomalies, E/B-mode polarization rings from bubble collisions, spectral distortions from pre-inflationary energy injection, and violations of statistical isotropy. These are directly testable with CMB-S4, LiteBIRD, and multipole analysis tools.

2. **Gravitational Wave Astronomy**

Stochastic Gravitational Wave Background (SGWB): Deploy next-gen detectors (LISA, Einstein Telescope, Cosmic Explorer) to identify: Resonant Modes: Discrete spectral lines at frequencies $f_n \sim n \cdot c/R_{max} (n \in Z)$, where R_{max} is the bubble radius.

Bubble Collision Echoes: Transient bursts from bubble-boundary interactions, distinguishable from binary mergers via waveform templates.

Primordial Gravitational Waves:Measure the tensor-to-scalar ratio (r) with BICEP/Keck Array or Big Bang Observer; a suppressed r could indicate energy loss to the bulk.

This model naturally produces boundary reflections, leading to resonant modes in the stochastic gravitational wave background (SGWB). Bubble collision echoes and suppressed primordial tensor modes (r) align with energy leakage to the bulk. Observatories like LISA and Cosmic Explorer are well-suited to detect these.

3. **Large-Scale Structure (LSS) Surveys**

Topological Imprints:Analyze galaxy surveys (DESI, Euclid, LSST) for:Matter Power Spectrum Cutoff: A sharp decline in the power spectrum at scales approaching the bubble's radius ($k_{cutoff} \sim \pi/R_{max}$).

Baryon Acoustic Oscillation (BAO) Distortions: Anomalies in the characteristic 150 Mpc scale due to boundary-induced pressure waves.

Redshift-Space Distortions:Test for anomalous bulk flows or velocity correlations inconsistent with ΛCDM, potentially signaling boundary-mediated gravitational interactions.A finite, bubble-like geometry leads to a cutoff in the matter power spectrum ($k\_cutoff \sim \pi/R_{max}$), BAO distortions, and possibly anomalous velocity flows. These are observable via DESI, Euclid, and LSST, providing direct geometric tests of the model.

4. High-Energy Astrophysics

Ultra-High-Energy Cosmic Rays (UHECRs):Use observatories like the Pierre Auger Observatory or Telescope Array to detect: Anisotropic Sky Distributions: Clustering of UHECRs along directions aligned with the bubble boundary.

Exotic Particle Signatures: Particles with energies beyond the GZK cutoff, suggesting leakage from the bulk.

Gamma-Ray Bursts (GRBs): Study GRB afterglows with JWST or ATHENA for spectral lines or timing anomalies indicative of photon scattering at the boundary.Ultra-high-energy cosmic rays (UHECRs) beyond the GZK limit, gamma-ray burst (GRB) anomalies, and possible exotic particle signatures could signal bulk-boundary interactions or violations of Lorentz invariance—key features of this model's boundary physics.

5. Quantum Gravity and Holography

Tabletop Holography Experiments: Simulate AdS/CFT-like systems in quantum simulators (e.g., cold atom lattices) to test: Entanglement Entropy Scaling: Verify $S \propto A$ for emergent "boundaries" in controlled quantum systems.

Bulk-Boundary Information Transfer: Track how information propagates between higher- and lower-dimensional subspaces.

Quantum Foam Probes: Use Fermi Gamma-Ray Telescopes or gravitational wave detectors to search for spacetime foam signatures (e.g., photon arrival time dispersion) at Planckian scales. This model's holographic boundary is testable through entanglement entropy scaling ($S \propto A$), bulk-boundary information flow, and potential Planck-scale foam effects in photon timing or interferometric noise. Quantum simulators and gamma-ray telescopes are relevant here.

6. Cosmic Inflation and Phase Transitions

Primordial Non-Gaussianity: Constrain fNL parameters with CMB and 21 cm tomography (e.g., SKA Observatory). A "squeezed" bispectrum could signal bubble nucleation during inflation.

Phase Transition Remnants: Detect stochastic gravitational waves from first-order phase transitions in the early universe (LISA, DECIGO), with spectra peaking at frequencies determined by the bubble's nucleation rate.Non-Gaussian features (e.g., in the bispectrum) and stochastic gravitational waves from first-order phase transitions could trace the bubble's origin during inflation. LISA, DECIGO, and 21 cm tomography offer strong observational leverage.

7. Multi-Messenger Cross-Correlations

Neutrino-CMB-LSS Triangulation: Combine data from IceCube, CMB-S4, and Euclid to identify correlated anomalies (e.g., neutrino hotspots aligned with CMB cold spots).

Gravitational Wave-Galaxy Catalogs: Cross-reference SGWB maps with LSST galaxy surveys to isolate boundary-induced anisotropies.Cross-analyzing neutrino, CMB, and LSS data (IceCube + Euclid + CMB-S4), or mapping SGWB anisotropies to galaxy distributions, can reveal boundary-induced correlations not predicted by ΛCDM—supporting this model's unified boundary dynamics.

8. Numerical Relativity and Simulations

Bubble-Bulk Hydrodynamics: Simulate bubble expansion in a higher-dimensional fluid using general-relativistic hydrodynamics codes (e.g., Einstein Toolkit), predicting observable signatures like CMB ring sizes or SGWB frequencies.

Holographic Cosmology: Develop AdS/CFT-based simulations to map boundary correlation functions ($\langle O(x)O(y)\rangle$) to 3D large-scale structure. General relativistic and holographic simulations (e.g., using Einstein Toolkit) allow direct modeling of the bubble's interaction with a higher-dimensional bulk, predicting signatures in CMB ring structures or GW frequencies. These tools are deeply compatible with your theoretical framework.

9. Theoretical Cross-Checks

String Theory Compactifications: Derive bubble nucleation rates in Calabi-Yau manifolds and compare with observational bounds on dark energy evolution.

Modified Gravity Tests:Use weak lensing (Euclid) and pulsar timing arrays (NANOGrav) to distinguish between ΛCDM and bubble-induced f(R)-like modifications.Bubble nucleation scenarios from string theory (e.g., via Calabi-Yau compactifications) and deviations from general relativity (like f(R) models) are theoretically aligned with this model. These can be tested via weak lensing or pulsar timing.

Conclusion

The bubble universe model describes our universe as a finite bubble formed within a larger external medium (the bulk). According to this model, physical processes such as quantum gravitational effects, energy leakage, and holographic information transfer occur at the boundaries of the universe. The model predicts observable signatures such as low-ℓ anomalies in the Cosmic Microwave Background (CMB), cutoffs in the power spectrum of large-scale structure, echoes in gravitational wave data, and ultra-high-energy particles beyond the GZK limit in high-energy astrophysical events. It also demonstrates consistency with inflation, phase transitions, and quantum gravity theories, offering an alternative framework for understanding some of the unexplained phenomena in cosmology. Multi-channel tests using next-generation observatories (CMB-S4, LISA, Euclid, SKA) will be critical for evaluating the validity of this model.

If our universe exists as a “bubble” in a higher-dimensional medium, this would imply a cluster of bubbles dynamically expanding and potentially colliding within the foam of the multiverse. These bubbles represent universes, each with unique physical laws and separated from each other by impermeable boundaries. While observations of other bubbles remain beyond our current scientific capacity, theoretical frameworks, particularly models such as eternal inflation and string theory, provide a mathematical basis for this idea. Energy and matter within bubbles cannot escape, but are instead reflected or recycled, creating the illusion of infinite space. This is consistent with the analogy of a “pool wave” in which waves bounce back at the edges. Boundary interactions preserve conserved quantities such as energy and charge, preventing leakage and allowing internal recycling. The bubble model overlaps with metaphysical concepts such as heaven, hell, or alternative planes of existence, but these ideas remain speculative and untestable within the framework of current physics. Metaphysical realms may correspond to bubbles with altered dimensional compressions (e.g., 4D spacetime and a 5D "afterlife"). On the other hand, metaphysicians can appeal to physics when necessary, and physicists can draw inspiration from metaphysicians. The origin of the multiverse bubble is based on a theoretical framework, such as quantum fluctuations in a pre-geometric realm, which may parallel theological concepts of a creator or first mover. However, science is limited to objective, naturalistic explanations that can be calculated. While metaphysics assumes direct experiential access to other realms, physics is based on falsifiable predictions.Closing this gap may be possible with advances in quantum gravity or consciousness. Rather than static walls, the boundaries of bubbles are phase interfaces where spacetime properties change abruptly, and this structure can lead to new phenomena. For example, Closed Temporal Curves (CTCs) could loop space-time across these boundaries, enabling so-called teleportation, but such interactions could also lead to paradoxes. Furthermore, boundaries could host Einstein-Rosen wormholes. Some exotic particles could probabilistically hop across boundaries via quantum effects, but macroscopic transitions would not occur without violating causality. Even if boundaries were not transcendent, revolutionary innovations for space exploration could emerge; for example, spacecraft could traverse galactic dimensions in short time using boundary reflections. Furthermore, the 2D surface of the boundary can store 3D spatial data by holographic principles and reconstruct objects, enabling processes such as teleportation. These interactions can create resonant energy reservoirs by amplifying electromagnetic or gravitational waves. Although direct contact with external bubbles is prohibited, indirect traces can be observed. For example, CMB echoes can create repeating patterns due to the effects of photons traveling around the bubble. Discrete frequencies in the stochastic gravitational wave background can reflect boundary resonant modes, and a discontinuity in the galaxy power spectrum at scales similar to the bubble radius can be observed. Observation of such traces may be possible through projects such as Euclid or DESI. However, tampering with such boundary interactions can destabilize space-time and pose existential risks. Science must accept these boundaries and ensure that multiverse theories are accepted within a scientific framework. Until then, the boundary will remain a barrier, but it will allow us to rethink what lies beyond our cosmic bubbles.

Data Availability Statement

This study is based on theoretical and conceptual analysis within the domains of cosmology and theoretical physics. As such, it does not rely on original datasets or experimental measurements. All referenced data are derived from publicly available scientific literature and previously published sources, which have been cited appropriately throughout the manuscript. Any additional materials, including figures or models constructed for explanatory purposes, are available from the corresponding author upon reasonable request.

References

1. "What Is a Bubble Universe: Overview of Bubble Universes and Eternal Inflation." Astronomy Explained, https://astronomyexplained.com. Accessed 10 Apr. 2025.
2. Guendelman, Eduardo, and Jonathan Portnoy., 2024, "Bubble Universe from Flat Spaces." The European Physical Journal C, vol. 84, p. 418.
3. Vilenkin, Alexander., 2007, Many Worlds in One: The Search for Other Universes. Hill and Wang.
4. "Physicists Study How Universes Might Bubble Up and Collide." Quanta Magazine, https://www.quantamagazine.org. Accessed 10 Apr. 2025.
5. Guth, Alan H., 1981, "Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems." Physical Review D, vol. 23, no. 2, pp. 347–356.
6. Linde, Andrei D., 1983, "Chaotic Inflation." Physics Letters B, vol. 129, no. 3–4, pp. 177–181.
7. Guendelman, Eduardo, and Jonathan Portnoy., 2024, "Bubble Universe from Flat Spaces." The European Physical Journal C, vol. 84, p. 418.
8. McInnes, Brett. , 2008, "Initial Conditions for Bubble Universes." Physical Review D: Particles, Fields, Gravitation, and Cosmology, vol. 77, no. 12, p. 123530.
9. "Double Bubble Universe: Explores Holographic Principles and Mirror-Twin Universes." Katya Walter, https://katyawalter.com. Accessed 10 Apr. 2025.
10. Mirbabayi, Mehrdad., 2022. "A Comment About the Cosmology on a Bubble Wall." arXiv, arXiv:2210.14276, https://arxiv.org/abs/2210.14276.
11. Bousso, Raphael., 2002, "The Holographic Principle." Reviews of Modern Physics, vol. 74, no. 3, pp. 825–874.
12. "Physicists Study How Universes Might Bubble Up and Collide." Quanta Magazine, https://www.quantamagazine.org. Accessed 10 Apr. 2025.
13. Susskind, Leonard, and James Lindesay., 2005, An Introduction to Black Holes, Information and the String Theory Revolution: The Holographic Universe. World Scientific,
14. Maldacena, Juan.,1999, "The Large-N Limit of Superconformal Field Theories and Supergravity." International Journal of Theoretical Physics, vol. 38, no. 4, pp. 1113–1133.
15. "Bubble of Galaxies Discovery May Revolutionize Cosmology: Observational Evidence for BAOs and Dark Energy Variability." University of Queensland, https://www.uq.edu.au. Accessed 10 Apr. 2025.

16. Roy, Nupur.,2025, "Dynamical Dark Energy in the Light of DESI 2024 Data." Physics of the Dark Universe, p. 101912.
17. Auci, Massimo.,2021, "Multi-Bubble Universe Model: A Quantum-Relativistic Gravitational Theory of Space-Time." Journal of Modern Physics, vol. 12, no. 3, pp. 179–198.
18. Verlinde, Erik.,2011, "On the Origin of Gravity and the Laws of Newton." Journal of High Energy Physics, vol. 2011, no. 4, pp. 1–27.
19. Keisler, Ryan, et al. 2019, "Visual Search over Billions of Aerial and Satellite Images." Computer Vision and Image Understanding, vol. 187, p. 102790.
20. Polchinski, Joseph., 1998, String Theory: Volume I. Cambridge University Press .