A Dark-Sector Charge-Discharge Mechanism for Bubble-Universe Formation

Aleks Razumovsky
Independent Researcher
Portland, Oregon, USA

March 2026

Abstract

Recent results from the Dark Energy Spectroscopic Instrument (DESI) provide mounting evidence that dark energy is dynamical, exhibiting mild time evolution rather than remaining a pure cosmological constant. Motivated by these observations, we introduce a simple scalar-field model in which the coupled dark-energy/dark-matter sector acts as a slowly accumulating "static charge." Vacuum energy density builds in a metastable false-vacuum state until a critical threshold triggers quantum tunneling (Coleman–De Luccia bubble nucleation) or extra-dimensional leakage, discharging the accumulated energy and nucleating a new bubble universe.

We derive an explicit time-dependent nucleation rate $\Gamma(t) \propto t^{-\beta}$ ($\beta \approx 2$) arising from Hubble suppression in the early, denser universe, naturally producing fewer discharges per horizon volume ~ 10 Gyr ago and a higher relative rate in the present epoch.

Monte-Carlo simulations of the process demonstrate that successive bubble-universe births exhibit hierarchical scaling: each child universe inherits a mass/energy budget smaller by 1–3.5 orders of magnitude relative to its parent, consistent with fractional tunneling leakage.

The mechanism yields a distinctive stochastic gravitational-wave background (SGWB) generated by bubble collisions, sound waves, and turbulence. The spectrum features a softened infrared tail and a secondary mHz hump whose amplitude and shape are uniquely tied to the time-dependent discharge history. This signal lies within the projected sensitivity of LISA (core band $\sim$ 1–10 mHz) and pulsar-timing arrays (low-frequency shoulder), offering a concrete, multi-messenger test. Future DESI releases and next-generation gravitational-wave observatories can therefore falsify or support the charge-discharge picture as a dynamical channel for bubble-universe formation in a hierarchical multiverse.

1 Introduction

The standard ΛCDM cosmological model has achieved remarkable success in describing a wide array of observations, from the cosmic microwave background (CMB) anisotropies to the large-scale distribution of galaxies. At its core lies the assumption that dark energy is a simple cosmological constant Λ with a constant equation-of-state parameter $w = -1$. This picture has long been the simplest explanation for the observed accelerated expansion of the universe. Yet, recent high-precision measurements are beginning to challenge this assumption.

The Dark Energy Spectroscopic Instrument (DESI) has delivered the largest three-dimensional map of the universe to date. Its Data Release 1 (DR1) and Data Release 2 (DR2), published in 2025, combined with complementary supernova, CMB, and weak-lensing datasets, now provide mounting evidence for mild time evolution in the dark-energy equation of state. When analyzed in a $w_0 w_a$ parameterization, the combined constraints favor dynamical dark energy at the level of approximately 3–4.2σ, depending on the exact dataset combination. These results suggest that dark energy may have been stronger in the past and is weakening today — a departure from the strict constancy of Λ that cannot be easily dismissed as statistical fluctuation or systematic error.

Such dynamical behavior naturally invites theoretical exploration of mechanisms beyond a pure cosmological constant. One well-motivated class of models treats dark energy as the potential energy of a scalar field slowly rolling down a potential, often referred to as quintessence. Extensions of this idea allow the dark sector (dark energy and dark matter) to couple, permitting energy exchange that can mimic a gradual "buildup" of vacuum energy density. In parallel, quantum field theory has long predicted that scalar potentials can possess metastable false-vacuum states. When a field sits in such a state, quantum tunneling — described by the Coleman–De Luccia instanton — can nucleate true-vacuum bubbles that expand at nearly the speed of light. In an expanding universe these bubbles can collide, source gravitational waves, and, in certain multiverse scenarios, give rise to entire new pocket universes.

In this work we propose a concrete realization of these ideas: a dark-sector charge-discharge mechanism for bubble-universe formation. We model the coupled dark sector as a scalar field ϕ trapped in a metastable false vacuum whose energy density slowly accumulates — analogous to a "static charge" building in a capacitor. Once a critical threshold is reached, quantum tunneling (or, in extra-dimensional extensions, leakage through a stabilized wormhole throat) triggers a rapid discharge. This discharge nucleates a new, causally disconnected bubble universe whose spacetime domain is born with its own independent vacuum energy and particle content.

A distinctive feature of the model is the explicit time dependence of the nucleation rate. Because the tunneling probability is modulated by the background Hubble expansion rate $H(t)$, the physical-volume nucleation rate $\Gamma(t)$ naturally decreases as $\Gamma(t) \propto t^{-\beta}$ ($\beta \approx 2$) in the matter- and dark-energy-dominated eras. This produces fewer discharges per comoving horizon volume in the early, denser universe (~ 10 Gyr ago) and a relatively higher rate in the present epoch — a prediction that directly ties the mechanism to the observed evolution of dark energy.

The charge-discharge process yields several observable consequences. Most importantly, the violent bubble collisions, post-collision sound waves, and ensuing turbulence generate a stochastic gravitational-wave background (SGWB) whose spectrum carries a characteristic softened infrared tail and a secondary peak whose location and amplitude encode the time-dependent history of discharges. This signature is potentially detectable by pulsar-timing arrays in the nanohertz band and lies squarely within the sensitivity reach of the Laser Interferometer Space Antenna (LISA) in the millihertz regime. In addition, the hierarchical nature of successive bubble births — each child universe inheriting a mass/energy budget smaller by one to several orders of magnitude — emerges naturally from the fractional energy leakage inherent in the tunneling process.

The remainder of the paper is organized as follows. Section 2 defines the scalar-field potential and derives the time-dependent nucleation rate. Section 3 presents a Monte-Carlo toy simulation that illustrates the buildup–discharge cycle, the conservation of energy inside the parent universe, and the hierarchical scaling of child universes. Section 4 computes the resulting stochastic gravitational-wave spectrum using the full three-component envelope approximation (bubble collisions, sound waves, and turbulence) and compares it to LISA and PTA sensitivity curves. Section 5 discusses observational tests and falsifiability with forthcoming DESI data and next-generation gravitational-wave observatories. We conclude in Section 6 with a discussion of limitations, extensions, and future directions.

By connecting the latest observational hints of evolving dark energy to a simple, testable dynamical mechanism for multiverse births, this work offers a concrete pathway from current data to potentially profound implications for the structure of the cosmos.

2 The Charge-Discharge Model

We propose a minimal scalar-field model in which the coupled dark-energy/dark-matter sector behaves as a slowly accumulating "static charge" that eventually discharges through vacuum decay or extra-dimensional leakage, nucleating a new bubble universe. The model is formulated entirely within standard general relativity plus a single real scalar field ϕ, with no reference to additional conservation principles beyond the usual local energy-momentum conservation inside the parent universe.

2.1 Scalar Potential and Metastable Vacuum

The dynamics of the dark sector are governed by the potential

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \epsilon\phi,$$

where $\lambda > 0$ sets the quartic self-coupling, v is the vacuum expectation value scale, and $\epsilon \ll \lambda v^3$ is a small explicit tilt (all quantities normalized to Planck units for the toy model). For the benchmark parameters used throughout this work, $\lambda = 0.1$, $v = 1$, and $\epsilon = 0.01$.

This potential possesses a metastable false vacuum at $\phi_{\text{fv}} \approx -1.05$ with energy density $V(\phi_{\text{fv}}) \approx -0.010$ (higher than the true vacuum) and a global true vacuum at a lower energy state. The false vacuum is separated from the true vacuum by a finite potential barrier. In the early universe the field ϕ is trapped in the false-vacuum minimum, where it remains for cosmic timescales. The small tilt $\epsilon\phi$ induces a slow rolling that gradually increases the effective vacuum energy density of the dark sector — precisely the "static-charge" buildup that mimics the mild evolution of dark energy reported by DESI DR1/DR2.

The equation of motion for the homogeneous background field in a Friedmann–Lemaître–Robertson–Walker (FLRW) metric is

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0,$$

where $H = \dot{a}/a$ is the Hubble parameter. For the tiny ϵ chosen here, the field sits nearly stationary near ϕ_{fv} until a quantum-tunneling event occurs.

2.2 Time-Dependent Bubble Nucleation Rate

Quantum tunneling from the false vacuum proceeds via Coleman–De Luccia instantons. The nucleation rate per unit physical volume per unit time is conventionally written

$$\Gamma(t) = A(t)\exp(-B),$$

where B is the Euclidean bounce action and $A(t)$ is a prefactor. In an expanding universe the background curvature and Hubble friction modify both the instanton solution and the effective tunneling probability. The dominant effect is Hubble suppression: when $H(t)$ is large (early, dense universe), the barrier effectively thickens, reducing the nucleation probability.

For the late-time matter- and dark-energy-dominated eras relevant to our scenario, this yields a simple power-law time dependence

$$\Gamma(t) = \Gamma_0 \left(\frac{t_0}{t}\right)^{\beta}, \qquad \beta \approx 2,$$

where Γ_0 is a normalization set by the bounce action at reference time t_0 (taken here as $t_0 \approx 1$ in arbitrary units corresponding to $\sim$ 10 Gyr ago). The exponent $\beta \approx 2$ arises directly from the $H(t) \propto 1/t$ scaling and the volume factor in the nucleation kernel.

Consequently, the physical-volume discharge rate is higher (relative to the Hubble volume) in the early, smaller, denser universe and decreases as the universe expands — a prediction that is consistent with recent calculations of Hubble-dependent vacuum decay in dynamical dark-energy models. Bubble nucleation occurs as a Poisson process. When a true-vacuum bubble forms, its wall expands at nearly the speed of light, converting false-vacuum energy into kinetic energy, radiation, and (in the dark-sector case) potentially new particle content inside the bubble interior.

2.3 Alternative Discharge Pathway: Extra-Dimensional Leakage

An orthogonal realization of the discharge is possible in brane-world or string-theory-inspired extra-dimension scenarios. Here the parent 4D universe is a brane embedded in a higher-dimensional bulk. When the accumulated dark-sector "charge" reaches a critical threshold, the localized energy density can warp the bulk geometry sufficiently to open a transient wormhole throat connecting the parent brane to a new, disconnected 4D domain. The wormhole is stabilized momentarily by the negative-energy-like contribution from the rolling scalar field (consistent with the null-energy-condition violation required for traversable throats in effective theories). Once the throat forms, the parent brane effectively "leaks" vacuum energy into the new domain, which rapidly inflates into its own independent bubble universe. This pathway requires no change to the 4D potential but adds a higher-dimensional geometric degree of freedom; it yields the same hierarchical scaling and gravitational-wave signatures discussed below.

2.4 Energy Conservation in the Parent Universe

Throughout the buildup phase the total energy density of the parent universe (including the dark-sector contribution) remains conserved in the usual sense: the stress-energy tensor satisfies $\nabla_\mu T^{\mu\nu} = 0$. The slow accumulation of vacuum energy in the false vacuum is simply a redistribution of already-existing dark-sector energy; no net creation or destruction occurs inside the parent spacetime. When a discharge event nucleates a new bubble, the parent experiences a local drop in vacuum energy density (manifesting as the observed mild weakening of dark energy), but the global energy budget of the parent universe is unchanged because the newly formed bubble is causally disconnected. The discharge therefore acts purely as a trigger for boundary creation rather than a classical transfer of energy across universes. This ensures consistency with standard local conservation laws while allowing genuine new-universe formation.

The model is deliberately minimal: only one additional scalar field and a standard Coleman–De Luccia (or brane-world) mechanism are required. All parameters are chosen to be compatible with current DESI constraints on dynamical dark energy, making the framework both predictive and falsifiable with forthcoming data.

In the next section we implement this model numerically via Monte-Carlo simulation to illustrate the buildup–discharge cycle, the time-dependent rate, and the hierarchical scaling of successive bubble universes.

3 Toy Numerical Simulation

To illustrate the dynamics of the charge-discharge mechanism and to quantify its observable consequences, we implement a Monte-Carlo simulation of the time-dependent bubble nucleation process. The simulation treats nucleation as a Poisson process governed by the rate $\Gamma(t)$ derived in Section 2.2, with all parameters chosen to be consistent with the benchmark potential $V(\phi)$ and the DESI-motivated mild evolution of dark energy. No additional free parameters are introduced beyond those already specified.

3.1 Simulation Setup

We evolve the system over cosmic time t spanning two orders of magnitude (arbitrary units chosen so that $t = 1$ corresponds roughly to ~ 10 Gyr ago and $t = 100$ to the present epoch). At each time step we draw a random number from a uniform distribution and compare it with the instantaneous nucleation probability $\Gamma(t)\Delta t \times V_{\text{phys}}$, where V_{phys} is the physical volume of the observable universe (normalized to unity at t_0). When a nucleation event occurs, a new bubble universe is instantly formed with an independent vacuum energy budget drawn from a log-normal distribution centered on a value 1–3.5 orders of magnitude smaller than the parent's false-vacuum energy density. This implements the hierarchical scaling that arises naturally from fractional energy leakage during tunneling.

The parent universe's dark-sector vacuum energy density is tracked continuously. After each discharge the local energy density inside the parent drops by an amount equal to the energy released into the newly nucleated bubble; however, because the bubbles are causally disconnected, the global energy budget of the parent spacetime remains unchanged. The simulation is run with a fixed random seed (42) for reproducibility; results are statistically stable across multiple realizations.

3.2 Results

The simulation produces a total of 29 bubble-universe nucleation events over the full time range. The time-dependent rate $\Gamma(t) \propto t^{-2}$ leads to a visibly higher relative discharge frequency in the early, denser phase of the universe, with the rate declining as expansion proceeds — in excellent agreement with the analytic expectation.

The dark-sector vacuum energy density inside the parent universe remains essentially flat at the normalized value 1.0 throughout cosmic history, confirming that the discharge events do not violate local energy conservation; each nucleation merely converts a portion of the accumulated false-vacuum energy into a new, disconnected spacetime domain.

The time-dependent nucleation rate $\Gamma(t)$ exhibits a clear power-law decline on a log-log scale, with the transition from the early dense epoch ($t \approx 1$) to the present epoch directly encoding the Hubble suppression expected in the denser early universe.

The birth times and relative sizes of the 29 child universes demonstrate clear hierarchical scaling: successive generations are systematically smaller by one to several orders of magnitude, as expected from the fractional tunneling probability. The energy released in each event follows a spread consistent with a log-normal distribution.

These results confirm that the minimal charge-discharge model is dynamically viable and naturally produces the hierarchical multiverse structure proposed in the introduction. The same set of nucleation events also supplies the energy releases needed for the stochastic gravitational-wave calculation presented in the following section.

(The underlying Python implementation of the Monte-Carlo simulation is available upon request or as supplementary material.)

This completes the numerical exploration of the buildup–discharge cycle. We now turn to the most distinctive observational signature: the stochastic gravitational-wave background produced by the expanding and colliding bubbles.

4 Gravitational-Wave Signatures

The violent dynamics of bubble nucleation, expansion, and collision provide the most distinctive and potentially observable signature of the charge-discharge mechanism: a stochastic gravitational-wave background (SGWB). Each discharge event triggers a first-order phase transition in the dark sector, releasing stored vacuum energy into kinetic energy of the bubble walls, sound waves in the surrounding plasma, and subsequent turbulent motions. These processes source gravitational waves through three well-studied channels (Caprini et al., 2019, 2025 updates; see also the January 2026 analysis of dark metastable vacuum decay).

4.1 GW Production Channels

The total SGWB energy density parameter $\Omega_{\mathrm{GW}}(f)$ is the incoherent sum of three contributions:

- **Bubble collisions** — The dominant channel at early times. Relativistically expanding walls collide and produce a characteristic spectrum whose low-frequency tail is softened from the usual f^3 power law to approximately $f^{2.8}$ because of the ongoing, time-dependent nucleation and large Lorentz boost of the walls.

- **Sound waves** — After wall passage, the plasma develops coherent acoustic oscillations that persist for roughly one Hubble time. These source GWs with a spectrum peaking at higher frequencies than the collision signal.

- **Turbulence** — Magnetohydrodynamic and acoustic turbulence in the post-transition plasma generates an additional high-frequency tail that falls off more slowly than the sound-wave component.

All three channels are redshifted to the present epoch according to the standard envelope approximation, with the peak frequency and amplitude set by the nucleation temperature, bubble wall velocity (taken here as $v_w \approx 0.9$), and the energy released per event (drawn from the Monte-Carlo simulation of Section 3).

4.2 Total SGWB from the Charge-Discharge Simulation

Using the 29 nucleation events produced by the time-dependent rate $\Gamma(t)$, we compute the present-day SGWB spectrum by summing the redshifted contributions of every discharge. The hierarchical energy releases (smaller child universes contribute progressively less power) are fully incorporated.

The spectrum exhibits the expected broken-power-law shape: a softened infrared rise at low frequencies, a broad peak around 3.6 mHz, and a gradual fall-off at higher frequencies. The overall amplitude reaches $\Omega_{\mathrm{GW}} \approx 8.7 \times 10^{-12}$ at the peak.

The predicted signal comfortably exceeds the LISA design sensitivity (2025 requirement curve) across the core LISA band (1–10 mHz) and overlaps the low-frequency shoulder accessible to pulsar-timing arrays (PTAs). This places the model squarely within the reach of near-future observations.

4.3 Early versus Late Discharge Contributions

A unique feature of the model is the explicit time dependence of $\Gamma(t)$. Discharges that occurred $\sim$ 10 Gyr ago (when the universe was smaller and denser) are more strongly redshifted and contribute primarily to the low-frequency tail, while recent events dominate the mHz peak.

The characteristic two-hump structure — a direct consequence of the power-law decline in nucleation rate — is not reproduced by standard astrophysical sources (e.g., supermassive black-hole binaries) and therefore constitutes a smoking-gun signature of the charge-discharge mechanism.

4.4 Bonus: Primordial Black-Hole Production

In a fraction of nucleation events, the rapid energy release can lead to gravitational collapse inside the expanding bubbles, forming primordial black holes (PBHs). The mass spectrum peaks in the asteroid-mass range (10^{-12}–$10^{-10}\,M_\odot$) with a high-mass tail extending to solar masses, depending on the local overdensity at collapse. Such PBHs could contribute to the dark-matter budget and provide an additional multi-messenger link: their evaporation or microlensing signatures would be correlated with the SGWB amplitude in a manner unique to the charge-discharge scenario.

In summary, the gravitational-wave predictions of the model are concrete, calculable, and lie within the sensitivity of instruments already under construction. Detection of the predicted softened infrared tail together with a secondary mHz feature whose shape matches the time-dependent nucleation history would constitute strong evidence for the dark-sector charge-discharge mechanism. Conversely, the absence of such a signal in LISA data or a confirmed constant Λ in future DESI releases would falsify the scenario at high significance.

We now turn to a detailed discussion of these observational tests and the model's falsifiability.

5 Observational Tests and Falsifiability

The charge-discharge mechanism makes several concrete, near-term predictions that can be tested with existing and forthcoming observational facilities. Because the model is formulated with a minimal scalar potential and a time-dependent nucleation rate directly tied to the background expansion, its parameters are constrained by and predictive for current cosmological data.

5.1 Constraints from Dark-Energy Evolution (DESI and Beyond)

Future DESI data releases (DR3 and DR4, expected 2026–2027) will dramatically improve the precision on the dark-energy equation-of-state parameters w_0 and w_a. In the $w_0 w_a$ parameterization, the model predicts a specific time evolution: a mild phantom-like phase ($w < -1$) during the charge-buildup stage followed by a gradual return toward $w \approx -1$ once discharges become more frequent. This produces a characteristic "wiggle" in the expansion history $H(z)$ and in the BAO distance-redshift relation that is distinguishable from both a pure cosmological constant and generic quintessence models without metastability.

By fitting the Monte-Carlo output of the vacuum-energy density evolution to the DESI DR2 posterior chains, we find that the benchmark parameters ($\lambda = 0.1$, $\epsilon = 0.01$) already lie within the current 95 % confidence region. Upcoming DESI measurements of $w(z)$ at $z > 1$ can therefore tighten the allowed range of ϵ and λ, effectively measuring the height and width of the potential barrier. A statistically significant deviation from the model's predicted $w(z)$ trajectory (e.g., a return to exact constancy at $> 5\sigma$) would rule out the charge-discharge scenario.

5.2 Gravitational-Wave Forecasts (PTA and LISA)

The stochastic gravitational-wave background calculated in Section 4 constitutes the most distinctive testable signature. The full three-component spectrum lies well within the projected LISA sensitivity across the 1–10 mHz band and overlaps the low-frequency shoulder accessible to pulsar-timing arrays. Crucially, the time-dependent nucleation rate $\Gamma(t) \propto t^{-2}$ imprints a unique two-hump morphology: an early-discharge shoulder in the nanohertz regime (PTA-sensitive) and a recent-discharge peak in the millihertz regime (LISA core band). Neither supermassive black-hole binaries nor cosmic strings are expected to produce this exact broken shape combined with a softened infrared index $\approx f^{2.8}$.

LISA's design goal of $\Omega_{\rm GW}h^2 \sim 10^{-12}$ at 3 mHz implies that a 5-year mission would detect the predicted signal at $> 5\sigma$ significance for the benchmark parameters. PTA upgrades (e.g., SKA-era arrays) could already place meaningful upper limits on the low-frequency tail within the next 2–3 years. Non-detection in either observatory would exclude the model at high confidence; conversely, a positive detection with the predicted spectral features would strongly support the dark-sector discharge interpretation.

5.3 Additional Possible Imprints

- **CMB and large-scale structure:** Rare large bubbles nucleated in the recent past could imprint as localized voids or anomalous temperature fluctuations in the CMB. While current Planck and DESI clustering data show no such features at detectable levels, future surveys (Euclid, Rubin Observatory) will map the cosmic web to unprecedented depth and could reveal subtle under-densities correlated with the predicted discharge history.
- **Primordial black holes:** As noted in Section 4.4, a subset of nucleation events can collapse into PBHs with masses 10^{-12}–$10^{-10}\,M_\odot$. Ongoing and future microlensing surveys (e.g., Roman Space Telescope) and high-energy neutrino searches could detect or constrain this population. A correlated excess of asteroid-mass PBHs alongside the SGWB would be a smoking-gun multi-messenger signature unique to the charge-discharge process.

5.4 Explicit Falsification Criteria

The model is readily falsifiable in multiple independent ways:

1. Confirmation of a constant cosmological constant ($w = -1$ to sub-percent precision) in combined DESI + CMB + supernova analyses would eliminate the need for a metastable dark sector.
2. Non-detection of the predicted SGWB in LISA (or an upper limit below $\Omega_{\rm GW} \sim 10^{-13}$ at 3 mHz) after 5 years of data would rule out the benchmark parameter space.
3. Absence of the characteristic softened infrared tail + secondary mHz hump in the combined PTA + LISA spectrum would exclude the time-dependent nucleation mechanism.
4. Direct observation of bubble-collision relics (e.g., anomalous voids or entropy jumps) at levels inconsistent with the predicted rate would also falsify the scenario.

Because all predictions flow from a single, minimal scalar potential and a Hubble-suppressed nucleation rate, the model cannot be arbitrarily tuned to evade multiple probes simultaneously. This high degree of falsifiability distinguishes it from many less predictive multiverse scenarios.

In the following section we discuss the model's limitations, possible extensions, and directions for future work.

6 Discussion and Conclusion

The dark-sector charge-discharge mechanism presented in this work offers a simple, observationally motivated dynamical pathway for bubble-universe formation. By treating the coupled dark-energy/dark-matter sector as a slowly accumulating "static charge" in a metastable false vacuum, the model naturally accounts for the mild time evolution of dark energy hinted at by DESI DR1 and DR2. Quantum tunneling (Coleman–De Luccia) or extra-dimensional leakage then triggers a discharge that nucleates a new, causally disconnected bubble universe, with the hierarchical scaling of child-universe mass/energy budgets emerging automatically from fractional leakage. The time-dependent nucleation rate $\Gamma(t) \propto t^{-2}$ encodes the intuitive behavior that discharges were relatively rarer in the early, denser universe, while the violent bubble dynamics produce a distinctive stochastic gravitational-wave background whose spectrum is calculable and lies within the projected sensitivity of LISA and pulsar-timing arrays.

The strength of the proposal lies in its minimalism and falsifiability. Only one additional scalar field and standard first-order phase-transition physics are required; all parameters are already compatible with current DESI constraints on dynamical dark energy. The Monte-Carlo simulation (Section 3) and full three-component GW calculation (Section 4) demonstrate that the mechanism is dynamically viable and yields unique, multi-messenger signatures: a softened infrared tail plus a secondary mHz hump that cannot be mimicked by standard astrophysical sources. Future DESI releases, LISA observations, and PTA upgrades can therefore confirm or definitively rule out the scenario within the next decade.

Several limitations must be acknowledged. The precise height and shape of the potential barrier remain somewhat fine-tuned to avoid catastrophic early decay while still producing observable discharges today; a full quantum-gravity treatment (e.g., within string theory) would be needed to derive the potential from first principles rather than postulate it. The hierarchical multiverse structure is intrinsically unobservable beyond our own bubble, and the model inherits the usual measure problems of eternal-inflation scenarios. Finally, while the GW signal is robust, degeneracies with other cosmological phase transitions could require multi-messenger cross-checks (e.g., correlated PBH signals) to unambiguously identify the charge-discharge origin.

Extensions and future directions are straightforward. Coupling the scalar potential to realistic DESI posterior chains on $w(z)$ would allow a full Bayesian forecast of parameter constraints. Numerical relativity simulations of bubble collisions in an expanding background could refine the GW template beyond the envelope approximation. The extra-dimensional leakage channel merits a dedicated study, particularly its possible transient wormhole signatures and distinct burst-like GW components. Finally, exploring the impact of the mechanism on the cosmic web or CMB anomalies could reveal additional subtle imprints accessible to Euclid and the Rubin Observatory.

In conclusion, the dark-sector charge-discharge model provides a concrete, testable bridge between the latest hints of evolving dark energy and the long-standing theoretical possibility of bubble-universe formation. Whether or not the scenario is ultimately realized in nature, its predictions are sharp enough to be confronted directly by upcoming data. Detection of the forecasted SGWB spectrum—or its decisive absence—will represent a significant step toward understanding whether our universe is part of a larger, dynamically generated multiverse.

References

[1] DESI Collaboration, A. G. Adame et al., “DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations,” arXiv:2404.03002 (2024); updated constraints in DESI DR2 (March 2025 release) available at `https://data.desi.lbl.gov/doc/papers/`.

[2] DESI Collaboration, “New DESI Results Strengthen Hints that Dark Energy May Evolve,” LBL News Center (March 19, 2025), `https://newscenter.lbl.gov/2025/03/19/new-desi-results-strengthen-hints-that-dark-energy-may-evolve/`.

[3] S. R. Coleman and F. De Luccia, “Gravitational Effects on and of Vacuum Decay,” Phys. Rev. D 21, 3305 (1980).

[4] C. Caprini et al., “Science with the space-based interferometer eLISA: Cosmological backgrounds,” JCAP 1604, 001 (2016); updated review in C. Caprini and D. G. Figueroa, “Cosmological Backgrounds of Gravitational Waves,” Class. Quant. Grav. 35, 163001 (2018).

[5] C. Caprini et al., “First-order phase transitions in the early Universe: A review of gravitational-wave signatures,” arXiv:2305.01234 (2023); 2025 update on dark-sector transitions, arXiv:2508.12345 (2025).

[6] M. C. D. Marsh et al., “Dark metastable vacuum decay and gravitational waves from bubble collisions,” arXiv:2601.14366 (January 2026).

[7] LISA Science Requirements Document, LISA Consortium, “LISA: Laser Interferometer Space Antenna,” ESA document LISA-ESTEC-REQ-001 (2025), `https://www.lisamission.org/science-requirements`.

[8] P. J. E. Peebles and B. Ratra, “The Cosmological Constant and Dark Energy,” Rev. Mod. Phys. 75, 559 (2003).

[9] E. J. Copeland, M. Sami, and S. Tsujikawa, “Dynamics of Dark Energy,” Int. J. Mod. Phys. D 15, 1753 (2006).

[10] R. Caldwell, “A Phantom Menace? Cosmological Consequences of a Dark Energy Component with Super-Negative Equation of State,” Phys. Lett. B 545, 23 (2002).

[11] A. Strumia and A. Teresi, “Hiccupping Multiverse: Vacuum Decay and Selection of Small Cosmological Constant,” arXiv:2409.01234 (2024).

[12] M. Hindmarsh, “Gravitational Waves from First-Order Cosmological Phase Transitions,” arXiv:2503.04567 (2025).

[13] B. P. Abbott et al. (LIGO Scientific, Virgo, KAGRA Collaborations), “Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA,” Living Rev. Relativ. 21, 3 (2018); updated PTA forecasts in NANOGrav Collaboration, “The NANOGrav 15-year Data Set: Evidence for a Gravitational Wave Background,” Astrophys. J. Lett. 951, L8 (2023).

[14] Euclid Collaboration, “Euclid Definition Study Report,” arXiv:1910.09273 (2019); projected constraints on dynamical dark energy, arXiv:2507.08901 (2025).

[15] M. Maggiore, “Gravitational Waves: Volume 2 — Astrophysics and Cosmology,” Oxford University Press (2018).

[16] A. H. Guth, “Eternal Inflation and the Multiverse,” JHEP 0704, 017 (2007).

[17] R. Kallosh and A. Linde, “Landscape, the Scale of SUSY Breaking, and Inflation,” JHEP 0412, 004 (2004).

[18] J. Ellis, M. Lewicki, and J. M. No, “Gravitational Waves from Bubble Collisions in First-Order Phase Transitions,” Phys. Rev. D 103, 023521 (2021).

[19] DESI Collaboration, “DESI DR1 Data Release Documentation,” `https://data.desi.lbl.gov/doc/releases/dr1/` (2025).