False Vacuum Decay in Curved Spacetime

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Presentation Overview

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Introduction

False Vacuum Decay

- A **false vacuum** is a local minimum of $V(\phi)$ that is not the global minimum.
- Perturbatively stable, but can decay quantum mechanically via tunnelling.

Why care?

- The Standard Model electroweak vacuum appears metastable.
- Vacuum decay played a central role in inflationary cosmology.
- Transitions between vacua are fundamental in landscape cosmology.

Two gravitational decay channels:

- **Coleman–De Luccia (CDL):** localised bubble nucleation.
- **Hawking–Moss (HM):** the entire Hubble patch fluctuates to the barrier top.

Goal

Find exponent for decay rate in CDL and HM. Also study limiting cases.

Set-Up

False Vacua: Setup

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \phi)^2 - V(\phi) \qquad (1)$$

The potential (see figure):

- Two minima: $V' = 0$, $V'' > 0$, ϕ_-: false vacuum ϕ_+: true vacuum
- Energy gap: $\varepsilon \equiv V(\phi_-) - V(\phi_+) > 0$
- Barrier peak at $\phi_{\rm top}$, $V(\phi_{\rm top}) > V(\phi_-)$

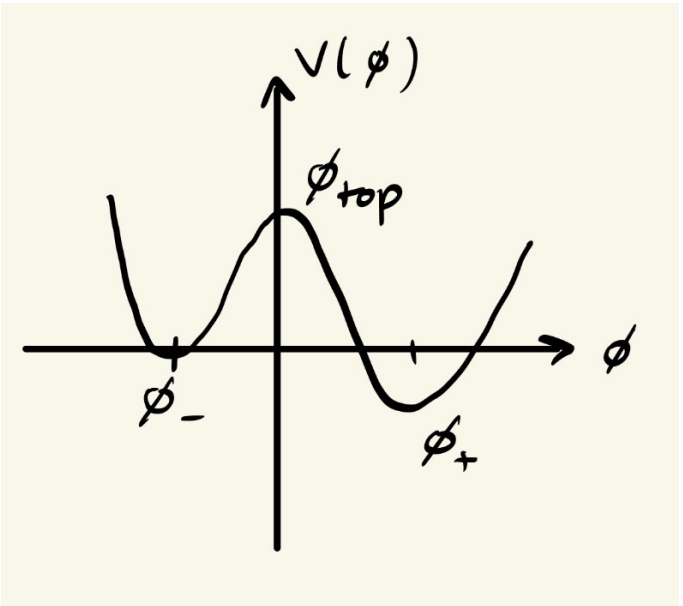

Figure: Asymmetric double-well potential $V(\phi)$

False Vacua: Setup

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \phi)^2 - V(\phi) \qquad (2)$$

The potential (see figure):

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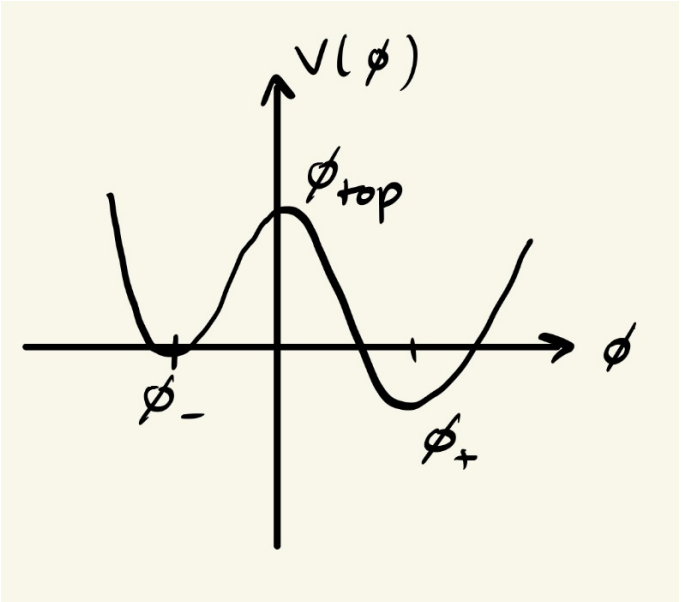

Figure: Asymmetric double-well potential $V(\phi)$

Decay by bubble nucleation:

- Bubble $< R$: surface tension wins $\rightarrow$ collapses
- Bubble $> R$: volume energy wins $\rightarrow$ expands at $\sim c$

False Vacua: Setup

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \phi)^2 - V(\phi) \qquad (3)$$

The potential (see figure):

- Two minima: $V' = 0$, $V'' > 0$, ϕ_-: false vacuum ϕ_+: true vacuum
- Energy gap: $\varepsilon \equiv V(\phi_-) - V(\phi_+) > 0$
- Barrier peak at ϕ_{top}, $V(\phi_{\text{top}}) > V(\phi_-)$

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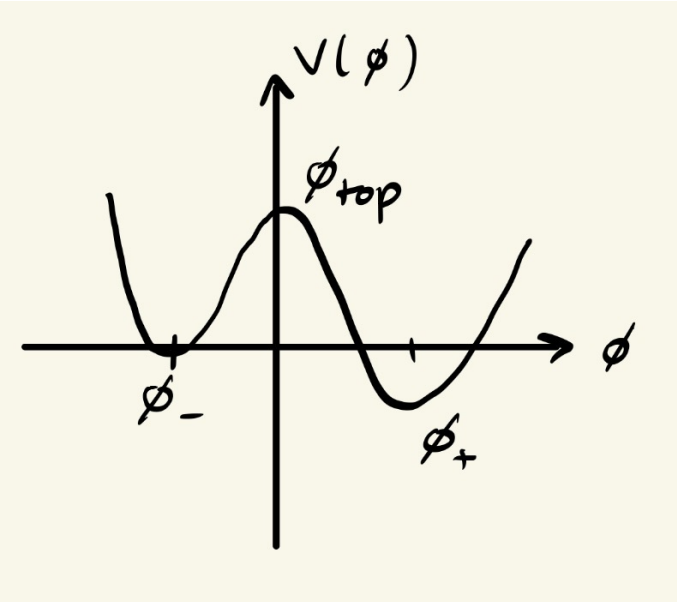

Figure: Asymmetric double-well potential $V(\phi)$

Decay rate

$$\Gamma / V = A e^{-B/\hbar} \qquad (4)$$

Decay is non-perturbative
Need Euclidean path integral

Euclidean Path Integral & the Bounce

Wick rotation: $t \to -i\tau$

$$S_M \to S_E = \int d^4x_E \left[\tfrac{1}{2}(\partial_\mu \phi)^2 + V(\phi)\right] \tag{5}$$

Both terms positive $\Rightarrow$ path integral $\int \mathcal{D}\phi\, e^{-S_E/\hbar}$ is suppression factor

Euclidean EOM:

$$\Box_E \phi = V'(\phi) \tag{6}$$

- Sign flip vs. Minkowski: ϕ moves in *inverted* potential $-V$: False vacuum $\phi_- \to$ unstable hilltop of $-V$, True vacuum $\phi_+ \to$ higher hilltop of $-V$
- Bounce: rolls from ϕ_+ hilltop, crosses valley, asymptotes to ϕ_-

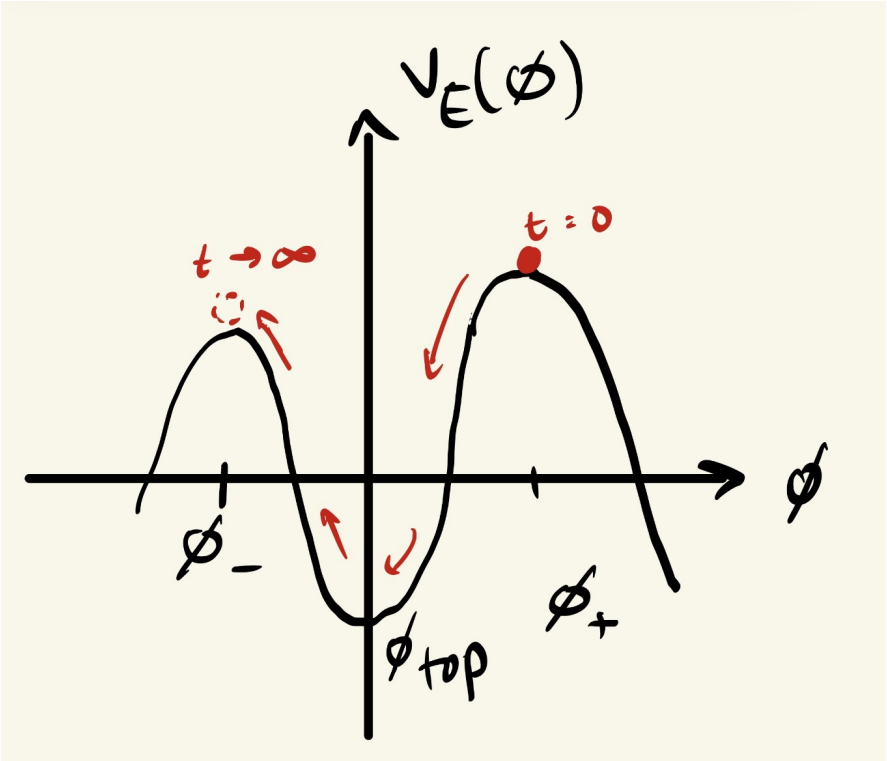

Figure: Inverted Euclidean potential

Euclidean Path Integral & the Bounce

Wick rotation: $t \to -i\tau$

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Euclidean EOM:

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- Sign flip vs. Minkowski: ϕ moves in *inverted* potential $-V$: False vacuum ϕ_- $\to$ unstable hilltop of $-V$, True vacuum ϕ_+ $\to$ higher hilltop of $-V$
- Bounce: rolls from ϕ_+ hilltop, crosses valley, asymptotes to ϕ_-

Saddle-point approximation ($S_E \gg \hbar$, i.e. $B \gg 1$):

As $\hbar \to 0$, $\int \mathcal{D}\phi\, e^{-S_E[\phi]/\hbar}$ is dominated by the saddle points of S_E (field theory analogue of WKB)

Two relevant saddle points:

1. $\phi \equiv \phi_-$ everywhere — trivial (no decay)
2. **The bounce** $\phi_b(x_E)$ — localised, non-trivial

Euclidean Path Integral & the Bounce

Wick rotation: $t \to -i\tau$

$$S_M \to S_E = \int d^4x_E \left[\tfrac{1}{2}(\partial_\mu \phi)^2 + V(\phi)\right] \tag{9}$$

Both terms positive $\Rightarrow$ path integral $\int \mathcal{D}\phi\, e^{-S_E/\hbar}$ is suppression factor

Euclidean EOM:

$$\Box_E \phi = V'(\phi) \tag{10}$$

- Sign flip vs. Minkowski: ϕ moves in *inverted* potential $-V$: False vacuum ϕ_- $\to$ unstable hilltop of $-V$, True vacuum ϕ_+ $\to$ higher hilltop of $-V$
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Saddle-point approximation ($S_E \gg \hbar$, i.e. $B \gg 1$):

Two relevant saddle points:

1. $\phi \equiv \phi_-$ everywhere — trivial (no decay)
2. **The bounce** $\phi_b(x_E)$ — localised, non-trivial,

Decay Rate (Coleman, 1977):

$$\boxed{\frac{\Gamma}{V} = A\, e^{-B/\hbar}\left[1 + \mathcal{O}(\hbar)\right]} \tag{11}$$

where $B = S_E[\phi_{\text{bounce}}] - S_E[\phi_-]$ (12)

Removes infinite background & $B > 0$: rate exponentially suppressed

Bounce in Flat Spacetime

Boundary Conditions & O(4) Symmetry

Boundary condition

$$\phi(x_E) \longrightarrow \phi_- \qquad \text{as} \quad |x_E| \to \infty \tag{13}$$

The field returns to the *false* vacuum at Euclidean infinity: far from the nucleation region the field has not tunnelled and remains at ϕ_-.

O(4) symmetry (Coleman 1977)

The action-minimising solution depends only on $r = \sqrt{\tau^2 + |\mathbf{x}|^2}$. The EOM reduces to

$$\phi'' + \frac{3}{r}\phi' = V'(\phi), \tag{14}$$

with regularity $\phi'(0) = 0$ and $\phi(\infty) = \phi_-$.

Mechanical Analogy & Existence of the Bounce

Rewrite (14): $\phi'' = -\frac{3}{r}\phi' + V'(\phi)$.

Analogy: particle in inverted potential $-V(\phi)$ with time-dependent friction $3/r$.

Mechanics	**Field theory**
"time"	r
position	ϕ
potential	$-V(\phi)$
friction	$3/r$ (large at small r, $\to 0$ late)

In $-V$: ϕ_- is a lower hilltop, ϕ_+ a higher one.

Available trajectories:

- $\phi_0 = \phi_+$: particle never moves $\Rightarrow$ *undershoot*
- ϕ_0 slightly below ϕ_+: excess KE $\Rightarrow$ *overshoot*
- By continuity $\exists\ \phi_0^*$ with trajectory arriving exactly at ϕ_- **— the bounce**

The Decay Exponent B

Action difference for the O(4)-symmetric bounce $\phi_b(r)$:

$$B = 2\pi^2 \int_0^\infty r^3 \left[\tfrac{1}{2}\phi_b'^2 + V(\phi_b) - V(\phi_-)\right] dr. \tag{15}$$

Using the bounce equation (14) to integrate by parts gives:

$$\boxed{B = \pi^2 \int_0^\infty r^3 \, \phi_b'^2 \, dr > 0.} \tag{16}$$

- $B > 0$ for any non-trivial bounce, confirming $e^{-B} < 1$ and the rate is exponentially suppressed.
- $B = 0$ only for the trivial (constant) solution — no tunnelling.
- For general potentials the bounce, and hence B, must be found **numerically**

Can we ever find an analytic solution? $\longrightarrow$ *the thin-wall limit.*

Thin-Wall Approximation

Regime: $\varepsilon \ll V(\phi_{\text{top}}) - V(\phi_-)$ (nearly degenerate vacua).

$\Rightarrow$ large bubble radius R, friction $3/r \approx 3/R$ negligible inside the wall.

Wall profile satisfies $\frac{1}{2}\phi'^2 = V(\phi) - V(\phi_-)$, giving **surface tension**

$$\sigma = \int_{\phi_-}^{\phi_+} \sqrt{2\big[V(\phi) - V(\phi_+)\big]}\, d\phi. \quad (17)$$

Action as a function of bubble radius R:

$$B(R) = \underbrace{-\tfrac{\pi^2}{2}\varepsilon R^4}_{\text{interior (volume gain)}} + \underbrace{2\pi^2 \sigma R^3}_{\text{wall (surface cost)}} \quad (18)$$

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Action as a function of bubble radius R:

$$B(R) = \underbrace{-\tfrac{\pi^2}{2}\varepsilon R^4}_{\text{interior (volume gain)}} + \underbrace{2\pi^2\sigma R^3}_{\text{wall (surface cost)}} \quad (20)$$

Extremising: $R_* = 3\sigma/\varepsilon$.

Coleman result:

$$\boxed{B_{\text{flat}} = \frac{27\pi^2\sigma^4}{2\,\varepsilon^3}} \quad (21)$$

- $\varepsilon \to 0$: $B \to \infty$ (stable false vacuum)
- $\sigma \to 0$: $B \to 0$ (unsuppressed decay)
- Rate $\propto e^{-\sigma^4/\varepsilon^3}$: far more sensitive to barrier shape than energy splitting

Bounce in Curved Spacetime: CDL

Why Gravity Changes the Bounce

Coleman bounce lives on Euclidean $\mathbb{R}^4$ and approaches the false vacuum at spatial infinity.

With gravity, vacuum energy curves spacetime:

- False vacuum energy V_- acts as a cosmological constant.
- Euclidean false vacuum becomes a four-sphere S^4.
- Boundary condition changes:
  $\phi(\text{north pole}) \to \phi_+, \qquad \phi(\text{south pole}) \to \phi_-.$

The size of gravitational corrections is controlled by

$$\alpha_{\text{grav}} \sim (H_- R)^2 \sim \frac{V}{M_{\text{Pl}}^4}. \tag{22}$$

- $H_- R \ll 1$: locally flat $\Rightarrow$ Coleman result recovered.
- $H_- R \sim 1$: bubble occupies a Hubble volume and gravity becomes important.

Euclidean Action and O(4)-Symmetric Metric

Minimally coupled Euclidean action:

$$S_E = -\frac{1}{2\kappa^2}\int d^4x\sqrt{g}\,R + \int d^4x\sqrt{g}\left[\tfrac{1}{2}(\partial\phi)^2 + V(\phi)\right] \tag{23}$$

Minus sign in front of R: Lorentzian $+R/(2\kappa^2)$ acquires a sign flip under $R_L \to -R_E$ after Wick rotation.

Most general O(4)-symmetric Euclidean metric:

$$ds^2 = d\xi^2 + \rho(\xi)^2\, d\Omega_3^2 \tag{24}$$

ξ = proper radial distance, $\rho(\xi)$ = scale factor, $d\Omega_3^2$ = unit S^3 metric
Flat space: $\rho = \xi$

Ricci scalar for this metric:

$$R = 6\left(\frac{1-\dot\rho^2}{\rho^2} - \frac{\ddot\rho}{\rho}\right) \qquad [= 0 \text{ for } \rho = \xi\,] \checkmark \tag{25}$$

CDL Equations of Motion

Varying S_E gives two coupled ODEs for $\{\phi(\xi),\, \rho(\xi)\}$:

Scalar equation:

$$\ddot{\phi} + \frac{3\dot{\rho}}{\rho}\,\dot{\phi} = V'(\phi) \tag{26}$$

Identical to flat-space ODE with $3/r \to 3\dot{\rho}/\rho$. Reduces exactly when $\rho = \xi$.

CDL constraint (from Einstein equations):

$$\dot{\rho}^2 = 1 + \frac{\kappa^2\rho^2}{3}\left[\tfrac{1}{2}\dot{\phi}^2 - V(\phi)\right] \tag{27}$$

In vacuum regions ($\dot{\phi} \approx 0$, $V \approx V_\pm$):

$$\dot{\rho}^2 = 1 - H_\pm^2\rho^2 \implies \rho(\xi) = H_\pm^{-1}\sin(H_\pm\xi) \qquad \text{closes at } \xi = \pi/H_\pm \tag{28}$$

Boundary conditions (regularity at poles):

$$\rho(0) = 0, \quad \dot{\rho}(0) = +1, \quad \dot{\phi}(0) = 0 \qquad \text{(north pole)} \tag{29}$$

$$\dot{\rho}(\bar{\xi}) = -1 \qquad \text{(south pole)} \tag{30}$$

$\dot{\rho}(0) = +1$ no conical singularity; $\dot{\rho}(\bar{\xi}) = -1$ exterior on descending branch.

The On-Shell Action

Eliminate V using the constraint, integrate by parts (boundary terms vanish since $\rho = 0$ at both poles):

$$S_E[\phi_b, \rho_b] = 2\pi^2 \int_0^{\bar{\xi}} d\xi \left[\rho_b^3 \dot{\phi}_b^2 - \frac{6\rho_b \dot{\rho}_b^2}{\kappa^2} \right] \tag{31}$$

V no longer appears — absorbed into the geometry via the constraint.

False-vacuum background ($\dot{\phi} = 0$, $\rho_- = H_-^{-1} \sin(H_- \xi)$):

$$S_E[\phi_-, \rho_-] = -\frac{12\pi^2}{\kappa^2 H_-^2} \underbrace{\int_0^{\pi} \sin\theta \cos^2\theta \, d\theta}_{= 2/3} = -\frac{8\pi^2}{\kappa^2 H_-^2} = -S_{\mathrm{dS}}(H_-) \tag{32}$$

Round S^4 of radius H_-^{-1}; equals *minus* the Gibbons–Hawking de Sitter entropy $S_{\mathrm{dS}}(H) = \pi/(GH^2) = 8\pi^2/(\kappa^2 H^2)$.

Thin-Wall Result and Post-Nucleation

Thin-wall geometry: interior $\rho_+ = H_+^{-1}\sin(H_+\xi)$, exterior $\rho_- = H_-^{-1}\sin(H_-(\bar{\xi}-\xi))$
Israel junction conditions at the wall $\Rightarrow$ **CDL junction condition** :

$$\sqrt{1-H_+^2\bar{\rho}^2}+\sqrt{1-H_-^2\bar{\rho}^2}=\frac{\kappa^2\sigma\bar{\rho}}{2} \tag{33}$$

Implicit equation for the gravitational bubble radius $\bar{\rho}$. Flat-space limit $\kappa \to 0$: recovers $\bar{\rho} \to 3\sigma/\varepsilon$.

CDL decay exponent :

$$\boxed{B_{\mathrm{CDL}} = 2\pi^2\bar{\rho}^3\sigma - \frac{12\pi^2}{\kappa^2}\left[\frac{1-\sqrt{1-H_+^2\bar{\rho}^2}}{H_+^2}-\frac{1+\sqrt{1-H_-^2\bar{\rho}^2}}{H_-^2}\right]} \tag{34}$$

Wall energy (same form as flat space) + gravitational corrections from difference in curved 4-volumes. $\kappa \to 0$: recovers B_{flat}.

Post-nucleation: analytically continue through the equatorial S^3 ($\dot{\rho}=0$) $\to$ Lorentzian O(3,1)-symmetric solution. Nucleated bubble = open ($k=-1$) FRW universe expanding at $\sim$.

Hawking Moss Instanton

The Hawking–Moss Instanton

Besides the Coleman–De Luccia (CDL) bounce, the Euclidean equations admit a second O(4)-symmetric solution.
Take the scalar field to be homogeneous:

$$\phi(\xi) = \phi_{\rm top}, \qquad V'(\phi_{\rm top}) = 0. \tag{35}$$

The Euclidean Einstein equation becomes

$$\dot{\rho}^2 = 1 - H_{\rm top}^2 \rho^2, \qquad H_{\rm top}^2 = \frac{\kappa^2 V_{\rm top}}{3}, \tag{36}$$

with solution

$$\rho(\xi) = H_{\rm top}^{-1} \sin(H_{\rm top}\xi). \tag{37}$$

Geometry: a round four-sphere S^4 of radius $H_{\rm top}^{-1}$.

Physical picture:

- CDL: localized bubble nucleation.
- Hawking–Moss: an entire Hubble-sized region fluctuates to the top of the barrier.

Hawking–Moss Decay Rate

The on-shell Euclidean action is

$$S_E^{\mathrm{HM}} = -\frac{8\pi^2}{\kappa^2 H_{\mathrm{top}}^2}. \tag{38}$$

Subtracting the false-vacuum background gives

$$\boxed{B_{\mathrm{HM}} = \frac{24\pi^2}{\kappa^4}\left(\frac{1}{V_-} - \frac{1}{V_{\mathrm{top}}}\right)} \tag{39}$$

Hawking–Moss Decay Rate

The on-shell Euclidean action is

$$S_E^{\mathrm{HM}} = -\frac{8\pi^2}{\kappa^2 H_{\mathrm{top}}^2}. \tag{40}$$

Subtracting the false-vacuum background gives

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Entropy interpretation

$$S_{\mathrm{dS}} = \frac{\pi}{GH^2} = \frac{8\pi^2}{\kappa^2 H^2}, \qquad \Rightarrow B_{\mathrm{HM}} = S_{\mathrm{dS}}(H_-) - S_{\mathrm{dS}}(H_{\mathrm{top}}). \tag{42}$$

Thermal interpretation

$$T_{\mathrm{dS}} = \frac{H_-}{2\pi} \qquad \Rightarrow B_{\mathrm{HM}} = \frac{V_{\mathrm{top}} - V_-}{T_{\mathrm{dS}}} \times (\text{numerical factors}). \tag{43}$$

Thermal activation of a Hubble-sized region to the top of the potential barrier, followed by classical evolution.

Limiting Cases

Limiting Cases and Consistency Checks

Limit	CDL Channel	HM Channel
$G \to 0$	$B_{\mathrm{CDL}} \to B_{\mathrm{flat}} = \dfrac{27\pi^2\sigma^4}{2\varepsilon^3}$	$B_{\mathrm{HM}} \to \infty$
$\varepsilon \to 0$	Strongly suppressed ($B_{\mathrm{CDL}} \to \infty$ in the thin-wall limit)	B_{HM} remains finite
$V_{\pm} \to 0$	$B_{\mathrm{CDL}} \to B_{\mathrm{flat}}$	$B_{\mathrm{HM}} \to \infty$
True AdS vacuum	Can be completely quenched above a critical wall tension	Unchanged (depends only on V_{-} and V_{top})

Takeaway

Vacuum decay in gravity is richer than in flat space: Coleman tunnelling becomes Coleman–De Luccia tunnelling, and de Sitter spacetime admits the additional Hawking–Moss channel.

Summary and Conclusions

Summary and Conclusions

- Vacuum decay is described semiclassically by Euclidean instantons:

$$\Gamma/V \sim A\, e^{-B/\hbar}. \tag{44}$$

- In flat space, decay proceeds via the Coleman bounce with the following thin wall action

$$B_{\text{flat}} = \frac{27\pi^2\sigma^4}{2\varepsilon^3}. \tag{45}$$

- Including gravity modifies the bounce, giving the Coleman–De Luccia (CDL) decay channel, which in thin wall limit gives

$$B_{\text{CDL}} = 2\pi^2\bar{\rho}^3\sigma - \frac{12\pi^2}{\kappa^2}\left[\frac{1-\sqrt{1-H_+^2\bar{\rho}^2}}{H_+^2}\,\frac{1+\sqrt{1-H_-^2\bar{\rho}^2}}{H_-^2}\right]. \tag{46}$$

- De Sitter space admits an additional Hawking–Moss instanton; a homogeneous fluctuation to the top of the barrier:

$$B_{\text{HM}} = \frac{24\pi^2}{\kappa^4}\left(\frac{1}{V_-} - \frac{1}{V_{\text{top}}}\right). \tag{47}$$

- Gravity can enhance, suppress, or completely quench decay

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