The Signals of the Doomsday: Cosmological Signatures of the Decay of a False Higgs Vacuum

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Brookhaven Forum 2025

October 22, 2025

Based on *arXiv:2501.15848*

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Introduction and Motivation

- "Cosmic doomsday" scenarios describe late phase transitions that can reshape cosmic structure and potentially end life.
- The universe likely experienced multiple transitions—GUT, electroweak, and QCD. After the 2012 Higgs discovery, data suggest we reside in a metastable false vacuum, implying possible Higgs-potential instability.
- Though such a vacuum can persist for billions of years, small primordial black holes may catalyze decay, nucleating true-vacuum bubbles that expand nearly at light speed but slightly slow due to friction.
- Such bubbles would produce heavy Higgs particles through vacuum mismatch at the wall, yielding observable photon and neutrino signatures that may precede the wall's arrival.
- A bubble forming a billion light-years away and slowed by only 1 km/s could emit photon or neutrino precursors several years before reaching us.

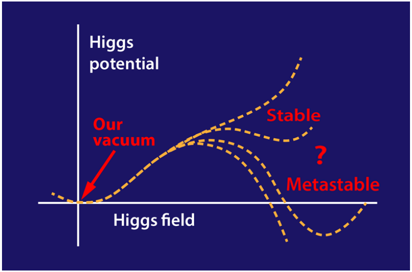
Quantum Tunneling & Euclidean Picture

- **Tunneling:** A particle with energy $E < V_0$ can still cross a barrier with small probability. Matching solutions across a square barrier gives

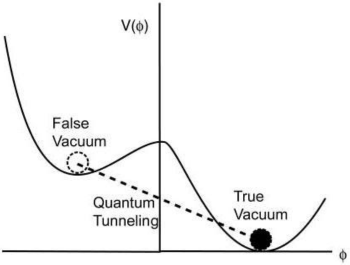
$$\frac{|T|^2}{|I|^2} = \left[1 + \frac{V_0^2 \sinh^2(\Omega d)}{4E(V_0 - E)}\right]^{-1} \sim e^{-2\Omega d}, \qquad \Omega d = \frac{1}{\hbar}\int_0^d \sqrt{2m(V_0 - E)}\, dx.$$

- **Euclidean method:** The leading suppression is obtained by mapping to a classical trajectory in imaginary time (the "bounce"), with action

$$\int \sqrt{2m\,\Delta V}\; dx = \int \sqrt{2m\,\Delta V}\,\dot{x}\, d\tau = \int \left(\Delta V + \tfrac{1}{2} m\dot{x}^2\right) d\tau = S_E.$$



Higgs potential and bounce path.



Escape from false to true vacuum

True Vacuum Bubble Propagation

- In field theory, tunneling nucleates a true-vacuum bubble expanding in nearly flat spacetime (gravity neglected).
- The scalar field obeys

$$S[\phi] = \int d^4x \left[\tfrac{1}{2}(\partial_\mu \phi)^2 - V(\phi) \right], \qquad -\partial_t^2 \phi + \nabla^2 \phi - V'(\phi) = 0.$$

- After Wick rotation ($t \to i\tau$), the $O(4)$-symmetric bounce satisfies

$$\frac{d^2\phi_c}{d\rho^2} + \frac{3}{\rho}\frac{d\phi_c}{d\rho} = V'(\phi_c).$$

- This equation provides a bounce solution with $\partial_t \phi(t=0) = 0$ and $\phi(t=0, \vec{x}) = \phi_c(\tau = 0, \vec{x})$ as

$$\phi(t, \vec{x}) = \phi_c(\rho = \sqrt{r^2 - t^2}).$$

- In the thin wall approximation

$$\phi_c(\rho) = \begin{cases} v & \text{, for } \rho > R \\ v_1 & \text{, for } \rho < R \end{cases} ,$$

  where v and v_1 are the expectation values of the Higgs field in the false and true vacuum respectively, while R is the radius of the bubble
- The nucleation rate is:

$$\Gamma \sim B\, e^{-S_E}, \;\; B \sim \mathrm{TeV}^4.$$

- Stability of our current universe requires

$$\Gamma\, t_{\mathrm{Hubble}}^4 \lesssim 1, \qquad t_{\mathrm{Hubble}} \sim 10^{10}\ \mathrm{yr}.$$

Particle Production due to vacuum mismatch

- Particle creation during first-order phase transitions can occur through several mechanisms. Here we adopt the **vacuum mismatch method**, formulated directly in Minkowski space.
- To study vacuum–induced particle creation, we decompose the scalar field into background and fluctuations:

$$\phi = \phi_c + \chi, \qquad \partial_\tau^2 \chi + \nabla^2 \chi - V''(\phi_c)\chi = 0.$$

  Across the bubble wall, $V''(\phi_c)$ changes abruptly—from M^2 in the false vacuum to μ^2 in the true vacuum—causing a sudden shift in the fluctuation mass.
- The transition occurs at $\tau = \tilde{\tau} = -R_0$, where R_0 is the bubble radius and $a = 1/R_0$ the proper acceleration, setting the natural timescale for particle creation (analogous to Unruh radiation).
- Matching the fluctuation modes and their derivatives at $\tau = \tilde{\tau}$ yields Bogoliubov coefficients, from which the particle occupation number follows:

$$N_k = \left[\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{4\omega_+ R_0} - 1 \right]^{-1}, \qquad \omega_\pm = \sqrt{k^2 + (\mu, M)^2}.$$

- This expression gives the momentum–space distribution of particles produced by the vacuum mismatch as the true–vacuum bubble expands.

Higgs Effective Potential & Gravity Corrections

- The Higgs vacuum decay is analyzed using the high-energy effective potential from two-loop Standard Model calculations:

$$V_{\rm SM}(\phi) = \frac{1}{4}\left(\lambda_* + b\,\ln^2\frac{\phi}{\phi_*}\right)\phi^4,$$

with
$-0.01 \lesssim \lambda_* \leq 0,\ 0.1 M_p \lesssim \phi_* \lesssim M_p,\ b \sim 10^{-4}$.
[arxiv:1501.04937, 1205.6497]

- This potential places our universe in a metastable vacuum. Adding higher-order operators with gravitational corrections:

$$V(\phi) = V_{\rm SM}(\phi) + \frac{\lambda_6}{6}\frac{\phi^6}{M_p^2} + \cdots\ ,$$

can yield a stable true vacuum and a first-order transition.

- For illustration:

$$b = 10^{-4},\ \lambda_* = -0.001,\ \phi_* = 0.5 M_p,\ \lambda_6 = 0.34. \quad \text{[arXiv : 2501.15848]}$$

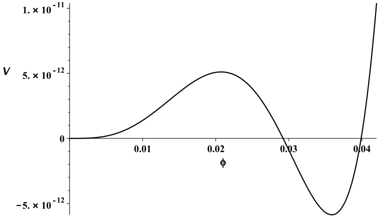


Figure: Modified potential $V(\phi)$ with false vacuum at $\phi = 0$ and true vacuum at $\phi \approx 3.6 \times 10^{-2} M_p$.

Higgs Particle Production Spectrum

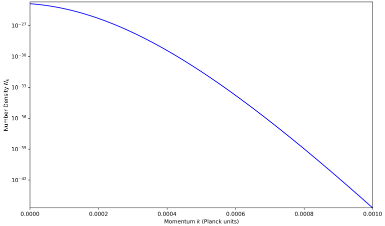


Figure: Number density of Higgs particles vs. momentum (in M_p units).

- Produced Higgs spectrum:

$$N_k = \frac{dN}{dV\, d^3\vec{k}} = \frac{1}{\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{4\omega_+ R_0} - 1},$$

with $\omega_\pm = \sqrt{\mu^2 + k^2},\ \sqrt{M^2 + k^2}$.

- False-vacuum mass $M = 125.09\,\text{GeV}$; true-vacuum $\mu = 7.16 \times 10^{-4} M_p$.
- Bubble radius at nucleation: $R_0 = 2 \times 10^4\, M_p^{-1}$.
- At-rest approximation ($k = 0$) yields

$$N_k(0) \simeq 1.365 \times 10^{-25} \quad (\text{per } M_p^3).$$

Higgs Energy Density Inside Bubble

- The local energy density carried by the produced Higgs quanta is

$$\mathcal{E} = \int_0^\infty \omega_+(k)\, N_k \,\frac{d^3k}{(2\pi)^3},$$

where

- Evaluating this integral with $\mu = 7.16 \times 10^{-4} M_p$, $R_0 = 2 \times 10^4\, M_p^{-1}$ gives

$$\mathcal{E} \approx 2.4 \times 10^{-42}\, M_p^4 = 8.6 \times 10^{31}\, \mathrm{GeV}^4.$$

- For any bubble of macroscopic volume, this is an enormous total energy ultimately transferred into decay products.
- Such a bubble would glow intensely in its decay products $\rightarrow$ "very shiny" — detectable if particles escape.
- Inside the bubble, the Higgs becomes heavy in the new vacuum, while outside it remains light. Since a heavy Higgs cannot exist in the false vacuum, it decays almost instantly, and its decay products must travel through the old vacuum to reach distant observers.

Higgs Decay Branching Ratios

- The partial decay widths and branching ratios were computed using the **HDECAY** package for Standard Model Higgs decays, extended to the heavy-mass regime.
- The resulting spectra and secondary particle yields were then simulated with **PYTHIA 8**, which models the subsequent hadronization, and photon/neutrino production.

Fermionic Branching Ratios

M_H	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$t\bar{t}$	$\tau^+\tau^-$	$\mu^+\mu^-$
1.75×10^{15}	6.08×10^{-31}	2.85×10^{-32}	1.72×10^{-34}	1.57×10^{-27}	1.35×10^{-30}	4.77×10^{-33}

Bosonic Branching Ratios & Total Width

M_H	GG	$\gamma\gamma$	$Z\gamma$	WW	ZZ	Γ_{tot}
1.75×10^{15}	1.08×10^{-4}	9.46×10^{-7}	9.90×10^{-7}	6.95×10^{-1}	3.49×10^{-1}	2.30×10^{39}

Photon & Neutrino Spectra from Higgs Decay

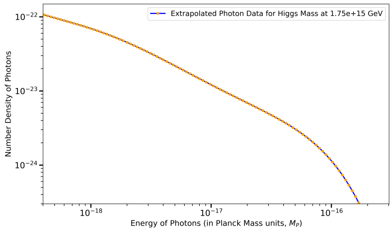


Figure: Photon spectrum from Higgs decay ($N_k(0) \simeq 1.365 \times 10^{-25}$).

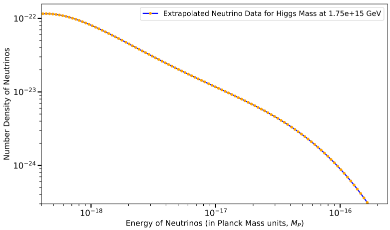


Figure: Neutrino spectrum from Higgs decay ($N_k(0) \simeq 1.365 \times 10^{-25}$).

- Branching ratios and width from `HDecay` fed into `Pythia` for hadronization up to 10^7 GeV; extrapolated to 1.75×10^{15} GeV.
- Final state dominated by photons and neutrinos $\rightarrow$ prime long-range signature; stable particles negligible.
- Higgs behaves as a broad resonance (width $> M_H$) at these scales.

Relativistic bubble-wall dynamics in a viscous medium

- If a true-vacuum bubble expanded exactly at c, no signal could overtake it. In practice, interactions with the surrounding matter, radiation, and self-produced particles generate **friction**, reducing its speed below c.
- The forces acting per unit area combine vacuum pressure, curvature, and friction:

$$F_{\text{net}} = \underbrace{\Delta V}_{\text{vacuum drive}} - \underbrace{\tfrac{2\sigma}{R}}_{\text{Laplace curvature}} - \underbrace{\eta\,\gamma v}_{\text{friction}}.$$

  The first term accelerates expansion; the latter two oppose it.
- Equating inertia with total force gives the **relativistic thin-wall equation of motion**:

$$\boxed{\sigma\,\gamma^3 \frac{dv}{dt} = \Delta V - \frac{2\sigma}{R} - \eta\,\gamma v.}$$

  The γ^3 factor shows how inertia grows as $v \to c$.
- At large R, curvature becomes negligible. Force balance then fixes the **terminal velocity**:

$$\Delta V = \eta\,\gamma v \Rightarrow \gamma_{\text{term}} \simeq \frac{\Delta V}{\eta}, \qquad v_{\text{term}} \simeq 1 - \frac{1}{2\gamma_{\text{term}}^2}.$$

  This establishes that realistic walls move *almost* but never exactly at the speed of light.

Proper-time formulation

- To connect with particle production, we express motion in the wall's **proper time** τ and rapidity y:

$$v = \tanh y, \quad \gamma = \cosh y, \quad \gamma v = \sinh y, \qquad \frac{dt}{d\tau} = \gamma, \ \frac{dR}{d\tau} = \sinh y.$$

- Expressing the dynamics in proper time τ with normalized drive and drag parameters $A = \Delta V/\sigma$ and $B = \eta/\sigma$, the wall's evolution follows

$$\boxed{\frac{dy}{d\tau} = A - \frac{2}{R(\tau)} - B \sinh y(\tau)} \quad \equiv \quad \alpha(\tau),$$

where $\alpha(\tau)$ is the wall's proper acceleration that governs the rate of particle production during vacuum decay.

- The bubble reaches its terminal state on the characteristic timescale

$$\tau_{\mathrm{term}} = \frac{1}{B} = \frac{\sigma}{\eta}.$$

Instantaneous Higgs production and integrated yield

- The vacuum mismatch near the wall produces Higgs quanta via a mechanism analogous to the Unruh effect, controlled by $\alpha(\tau)$.
- For zero momentum ($k = 0$), the **instantaneous occupation number** is

$$N_{k=0}(\tau) = \left[\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{\frac{4\omega_+}{\alpha(\tau)}} - 1 \right]^{-1}, \qquad \omega_+ = \mu,\ \omega_- = M.$$

  Larger $\alpha(\tau)$ sharply enhances production; as $\alpha \to 0$, it shuts off.
- The **total number of Higgs particles** produced up to τ accumulates the instantaneous rate over the wall's expanding area:

$$\frac{dN_{\text{tot}}}{d\tau} = N_{k=0}(\tau)\, 4\pi R(\tau)^2 \sinh y(\tau), \qquad N_{\text{tot}}(0) = 0.$$

- The yield is governed by a competition between the exponential sensitivity to $\alpha(\tau)$ and the geometric amplification from $4\pi R^2$.

Integrated particle yields

- The parameter δ measures how close the wall velocity is to c. Smaller δ means faster walls, higher $\gamma_{\rm term}$, and stronger acceleration for a longer period.
- The table below shows representative numerical results obtained by integrating up to $\tau_{\rm term} = \sigma/\eta$ for different δ values.

δ	$\eta\,[M_{\rm p}^4]$	$\tau_{\rm term}\,[M_{\rm p}^{-1}]$	$R_{\rm fin}\,[M_{\rm p}^{-1}]$	$N_{\rm tot}^{(\rm int)}$
10^{-8}	8.3×10^{-16}	7.1×10^{7}	7.2×10^{7}	1.0×10^{8}
10^{-9}	2.6×10^{-16}	2.2×10^{8}	2.3×10^{8}	3.5×10^{9}
10^{-10}	8.3×10^{-17}	7.1×10^{8}	7.1×10^{8}	1.1×10^{11}

- As δ decreases, the wall spends more time in the ultra-relativistic regime, sustaining higher $\alpha(\tau)$ and sweeping a larger volume before friction halts acceleration.
- Faster walls produce exponentially more Higgs particles but we would get lesser time for a signal.
- These Higgs bosons then decay to Standard Model products—dominantly photons and neutrinos—whose spectra are shown next.

Photon spectra vs. energy

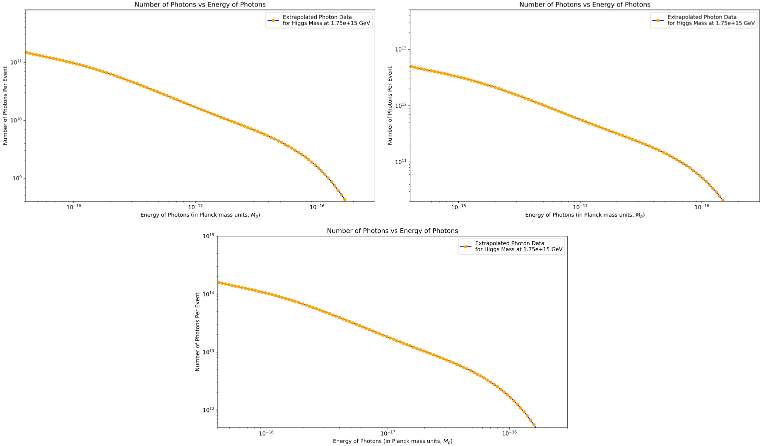


Figure: Photon spectra from Higgs decays at $\delta = 10^{-8}, 10^{-9}, 10^{-10}$. Higher wall speeds enhance both yield and energy.

Neutrino spectra vs. energy

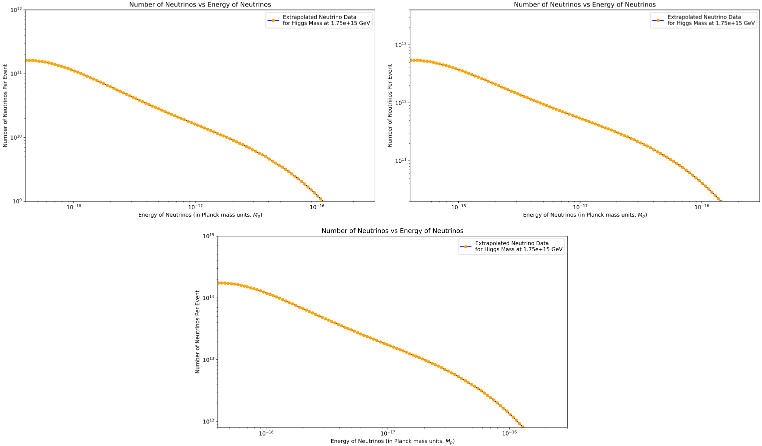


Figure: Neutrino spectra from Higgs decays for the same δ values. Neutrinos follow a similar enhancement pattern.

Arrival delay: photons / neutrinos vs. bubble wall

- Because friction limits $v_{\rm wall} < c$, photons and neutrinos emitted during expansion can arrive *before* the wall itself.
- The delay between the signals and the wall is given generally by

$$\boxed{\Delta t(z) = \frac{\delta}{1-\delta}\int_0^z \frac{dz'}{H(z')}}, \qquad v = (1-\delta)c,\ \ \delta \ll 1.$$

The integral accounts for cosmic expansion through the Hubble rate $H(z)$.

- At low redshift, this simplifies to the flat-space expression

$$\Delta t \simeq \delta\,\frac{D}{c},$$

where D is the proper distance to the source.

- Even a tiny velocity deficit produces substantial advance times:

δ	D (ly)	Lead time Δt
10^{-8}	1.0×10^{8}	$\sim$ 1 year
10^{-9}	1.0×10^{8}	$\sim$ 36 days
10^{-10}	1.0×10^{8}	$\sim$ 3.6 days

- Therefore, γ-ray and neutrino bursts could precede the wall by days to years, potentially offering an observable early-warning signature of vacuum decay.

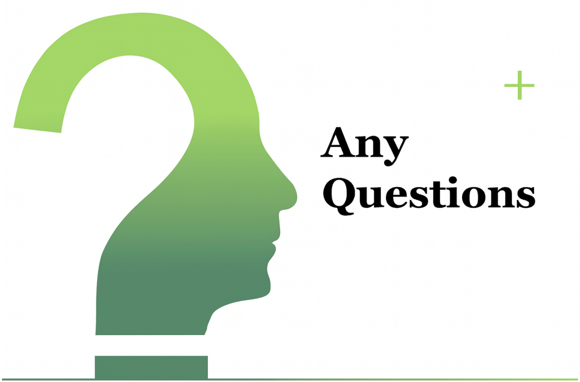
Conclusions and Important Remarks

- As the bubble expands, the vacuum shifts from false to true, generating particles continuously. The spectra shown are *local* and must be redshifted to compare with observations.
- The wall velocity evolves as

$$v_b \sim \frac{t}{\sqrt{t^2 + R_0^2}},$$

  approaching but never reaching c for $t \gg R_0$; studies suggest it remains well below c [arXiv:2504.21213].
- The wall, a coherent state of Higgs quanta, interacts with surrounding plasma, interstellar matter, and even its own decay products, further reducing its speed.
- A late-time first-order electroweak transition may leave multi-messenger imprints—gravitational waves, and gamma-ray or neutrino bursts—detectable by next-generation observatories.
- The analysis assumes no new physics beyond the Standard Model. Modifications to the Higgs potential or the absence of primordial black holes [arXiv:1909.00773] could stabilize the vacuum and preclude such decay.
- **Outlook:** Our upcoming work extends this framework to explore *cosmological signatures of late-time* $\mathrm{SU(3)_C}$ *and* $\mathrm{U(1)_{EM}}$ *symmetry breaking*, focusing on bubble-wall dynamics, spectral emissions, and gravitational-wave backgrounds. Results will appear shortly in arXiv preprints [arXiv:2xxx.xxxxx, arXiv:2xxx.xxxxx].

Question???



Backup: Early-Time Expansion of Proper Acceleration

- Immediately after nucleation, when $\tau \ll R_0$, the bubble wall is almost at rest, and curvature dominates over friction. Starting from the general dynamical equation,

$$\frac{dy}{d\tau} = A - \frac{2}{R(\tau)} - B \sinh y(\tau),$$

  we expand perturbatively to capture the early evolution.
- For weak friction ($BR_0 \ll 1$), we can approximate the kinematics as

$$\sinh y \simeq \alpha(0)\,\tau, \qquad R(\tau) \simeq R_0 + \frac{1}{2}\alpha(0)\,\tau^2,$$

  where $\alpha(0) = (dy/d\tau)_{\tau=0}$ is the initial acceleration.
- Substituting these into the above equation and expanding in powers of τ gives the **series form**

$$\boxed{\alpha(\tau) \simeq \frac{1}{R_0} - \frac{B}{R_0}\tau + \frac{\tau^2}{R_0^3} + O(\tau^3)}.$$

- The three terms respectively describe:
  - $\frac{1}{R_0}$ — curvature-induced initial push,
  - $-\frac{B}{R_0}\tau$ — frictional retardation, and
  - $\frac{\tau^2}{R_0^3}$ — slow geometric recovery as R increases.

Backup: Minimum Acceleration and Physical Interpretation

- From the quadratic approximation above, the acceleration reaches a temporary minimum at

$$\tau_\star \simeq \frac{1}{2} B R_0^2, \qquad \alpha_{\rm min} \simeq \frac{1}{R_0} - \frac{1}{4} B^2 R_0 .$$

  This point marks the strongest deceleration phase just before relativistic acceleration resumes.

- **Physical picture:**
  - The wall initially "hesitates" — curvature tries to expand it, while friction momentarily slows it down.
  - After $\tau_\star$, curvature term dominates again, and $\alpha(\tau)$ rises toward its asymptotic value.

- The duration of this hesitation phase determines when vacuum–mismatch particle production begins in earnest.
  - For small B, the wall quickly attains high α and becomes relativistic early.
  - For larger B, it remains subrelativistic longer, delaying the onset of particle creation.

- Thus, the early-time series provides analytic control over how curvature and friction set the wall's acceleration history immediately after nucleation—crucial for predicting photon and neutrino yields.

Backup: Motivation of the Euclidean Method (I)

Tunneling is a distinctively quantum phenomenon. A particle with insufficient energy to surmount a barrier can still be found on the other side with small probability. We solve the time-independent Schrödinger equation for a square barrier:

$$E\,\Psi = -\frac{\hbar^2}{2m}\,\frac{d^2\Psi}{dx^2} + V(x)\,\Psi,$$

with

$$V(x) = \begin{cases} 0, & x < 0\ \&\ x > d, \\ V_0, & 0 < x < d, \end{cases} \qquad V_0 > E.$$

The wavefunction solutions are oscillatory outside and exponential inside:

$$\Psi(x) = \begin{cases} Ie^{i\omega x} + Re^{-i\omega x}, & x < 0, \\ Ae^{\Omega x} + Be^{-\Omega x}, & 0 < x < d, \\ Te^{i\omega x}, & x > d, \end{cases}$$

where $\omega^2 = \frac{2mE}{\hbar^2}$, $\Omega^2 = \frac{2m(V_0 - E)}{\hbar^2}$. Matching continuity of Ψ and Ψ' yields the transmission probability

$$\frac{|T|^2}{|I|^2} = \left[1 + \frac{V_0^2\sinh^2(\Omega d)}{4E(V_0 - E)}\right]^{-1} \sim\ e^{-2\Omega d}.$$

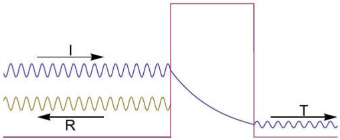


Figure: Fig. 1: Sketch of 1D Schrödinger tunneling.

The factor

$$\Omega d = \frac{1}{\hbar}\int_0^d \sqrt{2m(V_0 - E)}\,dx$$

strongly suppresses tunneling.

Backup: Motivation of the Euclidean Method (II)

To compute the leading exponential suppression, we map tunneling onto a classical trajectory in imaginary time.

- Consider a particle "rolling" under the inverted potential. Using Using $\frac{1}{2} m\dot{x}^2 = \Delta V$, we get the action integral

$$\int \sqrt{2m\,\Delta V}\; dx = \int \sqrt{2m\,\Delta V}\,\dot{x}\; d\tau = \int \left(\Delta V + \tfrac{1}{2} m\dot{x}^2\right) d\tau = S_E$$

  is precisely the Euclidean action governing the trajectory.
- The most probable escape path ("bounce") of the particle is the classical solution in Euclidean time moving from the (now unstable) local maximum to an exit point and back again. This trajectory is referred to as the "bounce."
- In field theory, this generalizes to finding an $O(4)$-symmetric bounce solution in the inverted potential, which dominates the tunneling amplitude.