Accidentally light scalars: naturalness and cosmology

Giacomo Ferrante

based on

JHEP, vol. 01, p. 075, 2024 w/ F. Brümmer, M. Frigerio & T. Hambye

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Phys. Rev. D, vol. 110, no. 10, 2024 w/ F. Brümmer & M. Frigerio

Light elementary scalars

A glossary

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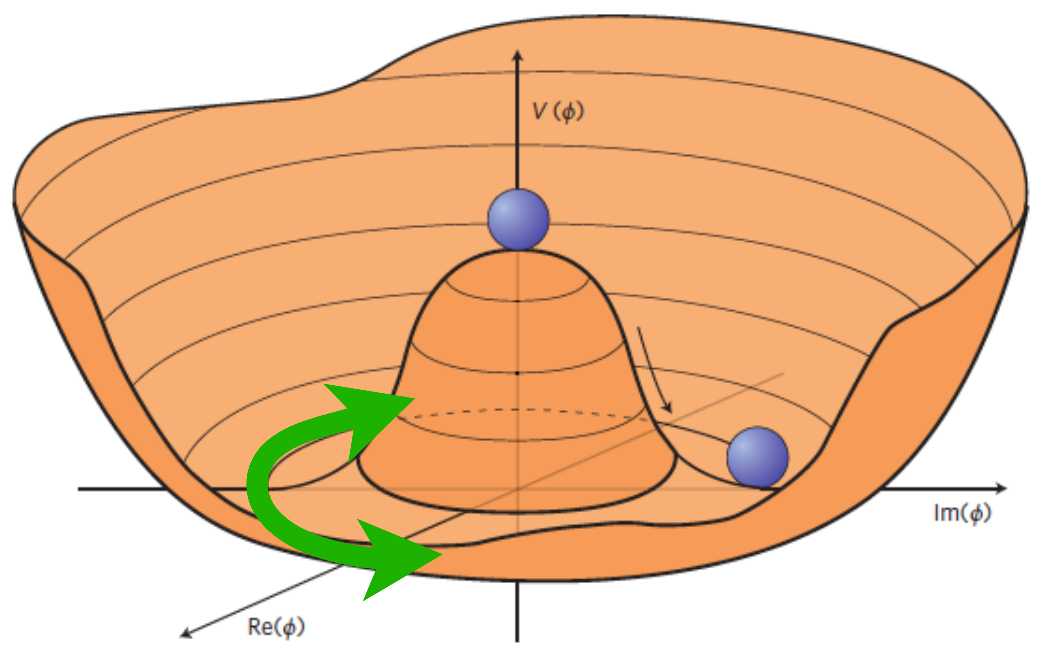
1. Nambu-Goldstone bosons:

   - SSB: $G \to H$

   - Massless at all orders



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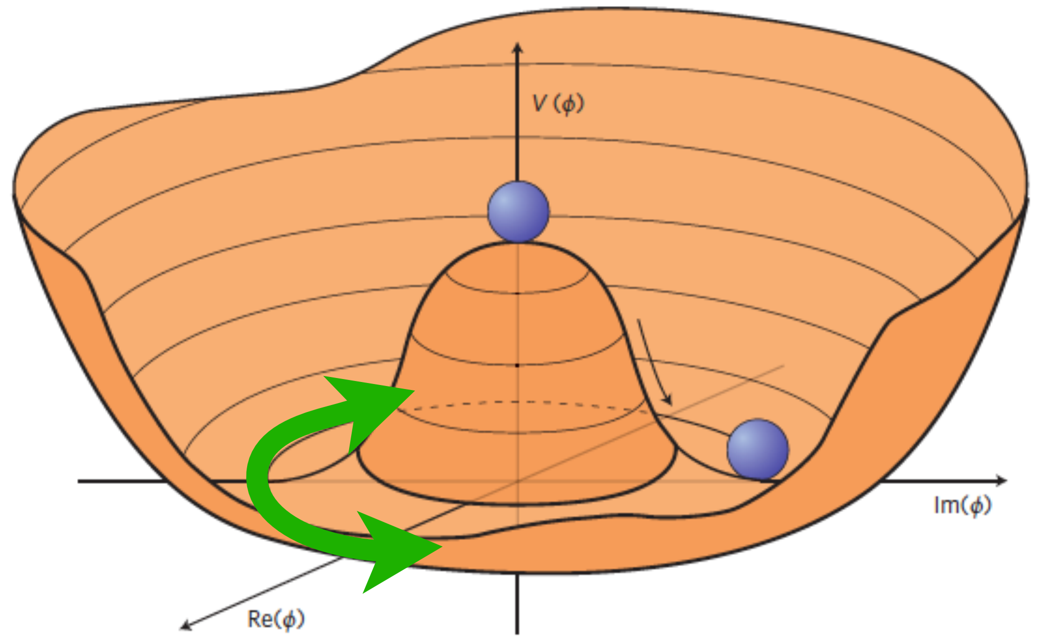

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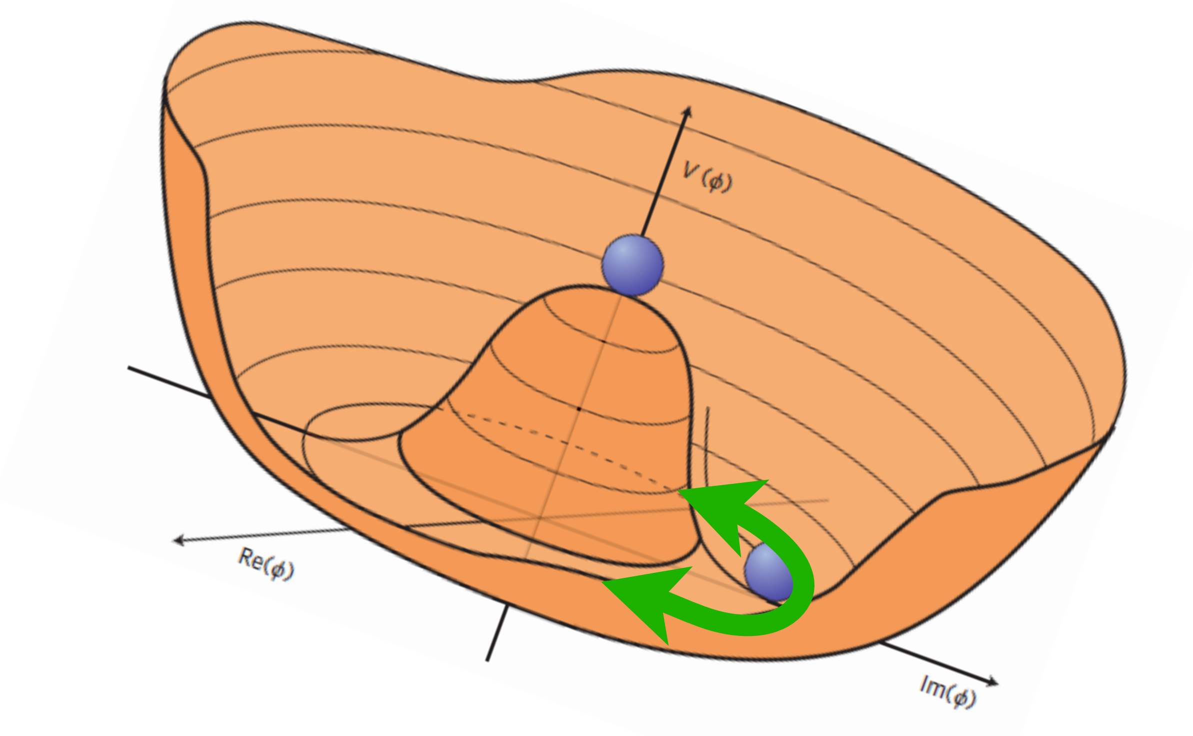
   - $F \supset G$ + explicit symmetry breaking
   - Naturally light



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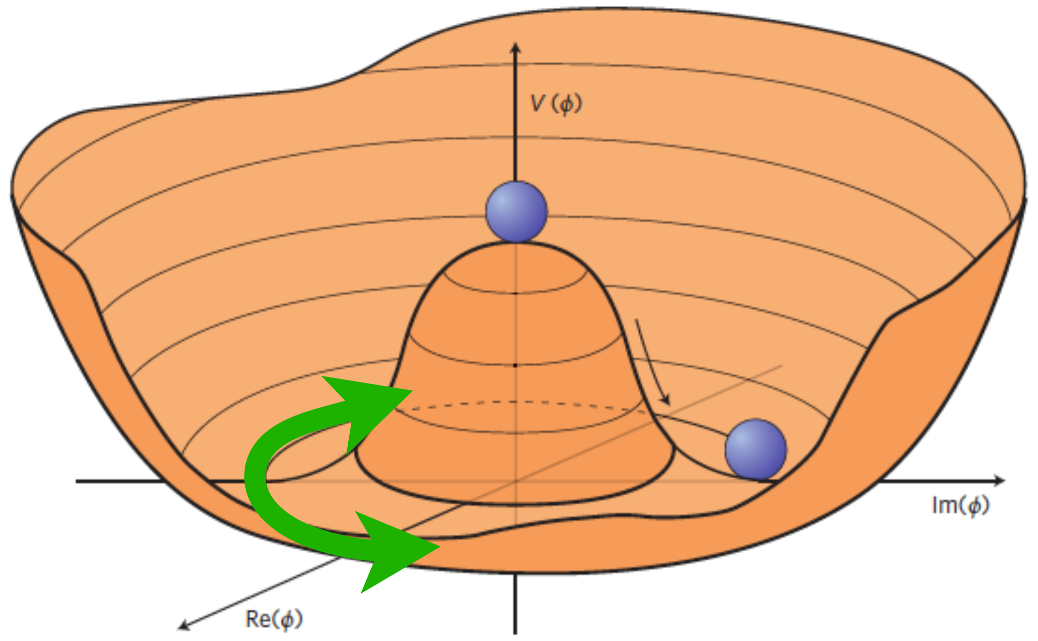

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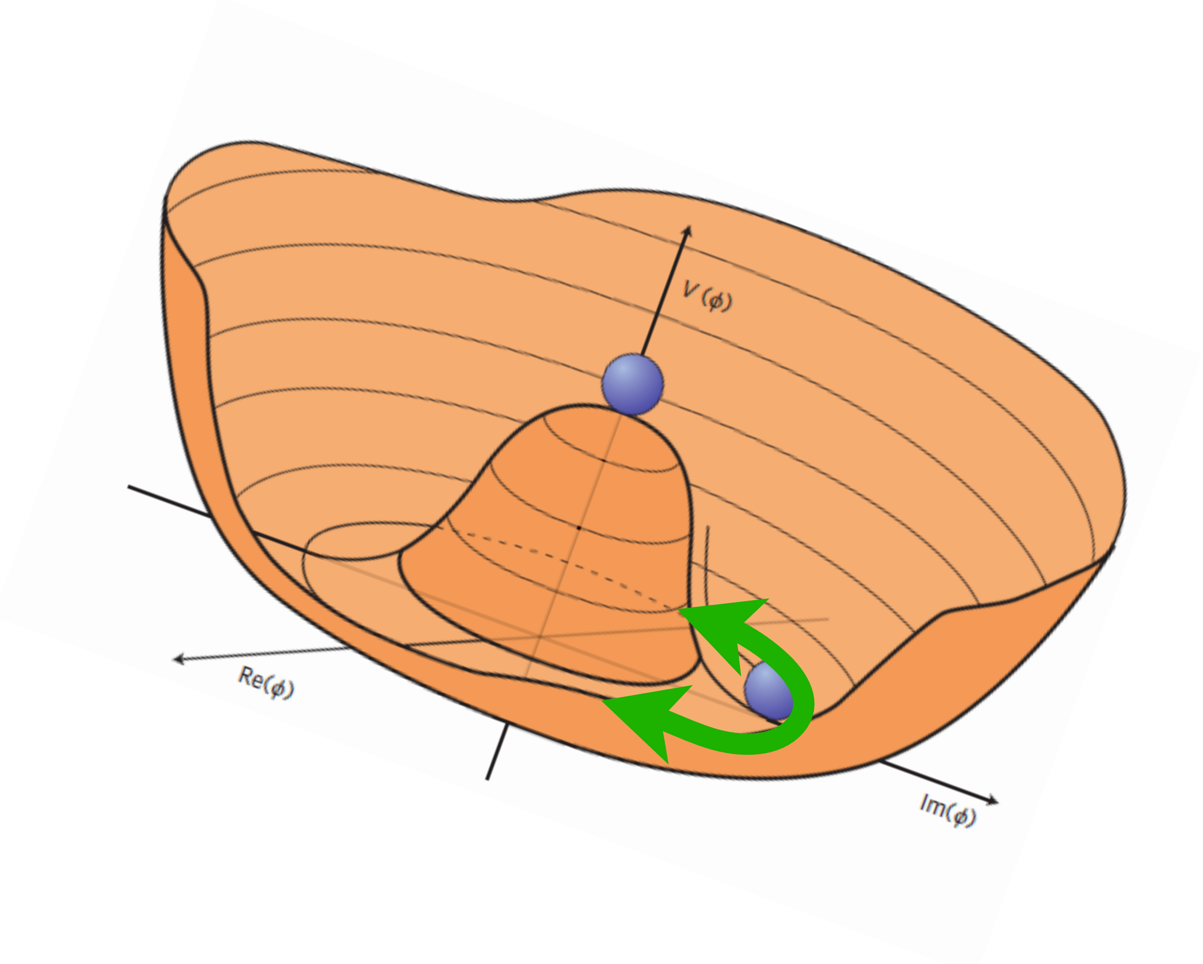

3. Accidents®

The SU(2) five-plet

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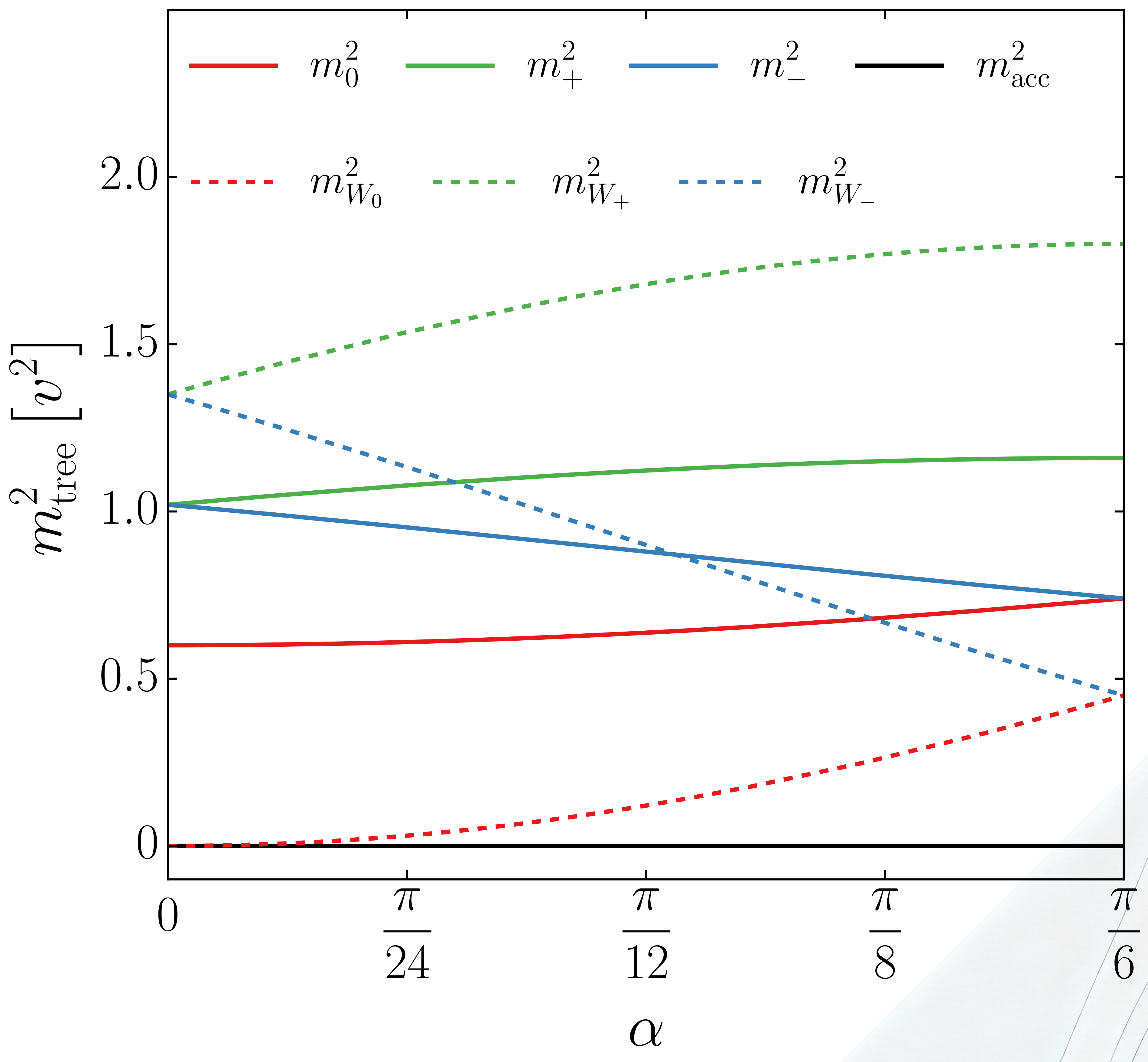

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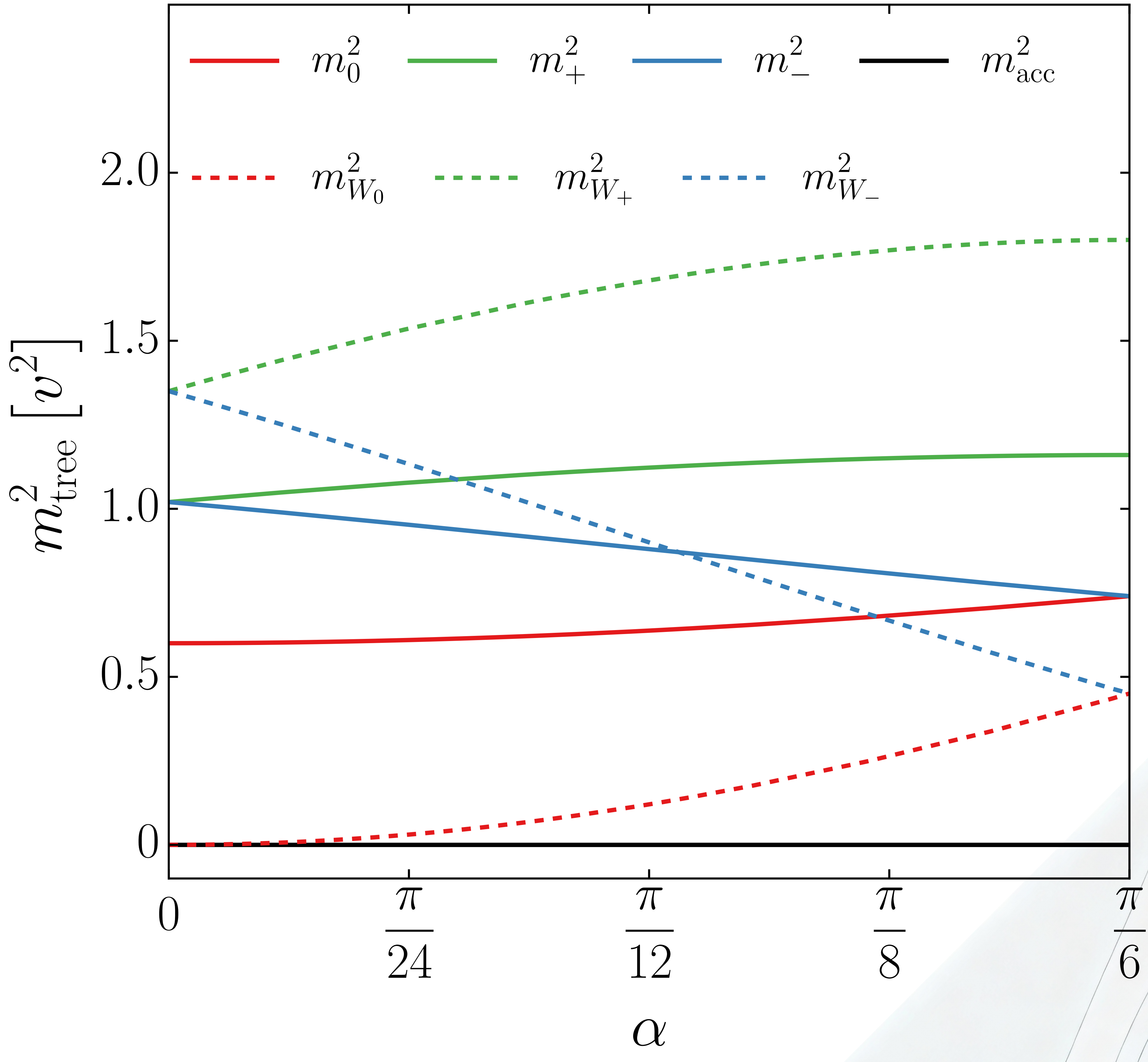

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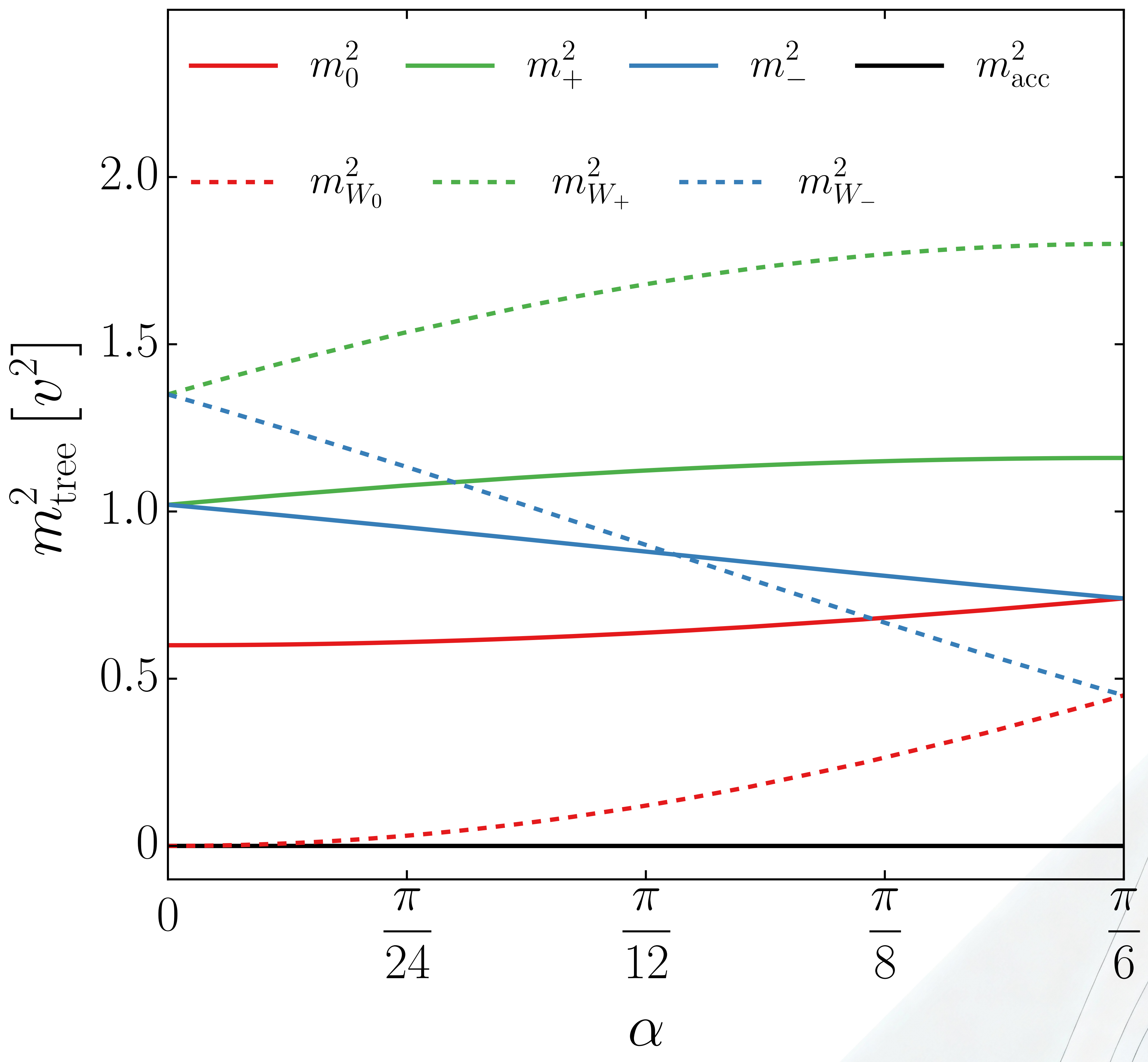

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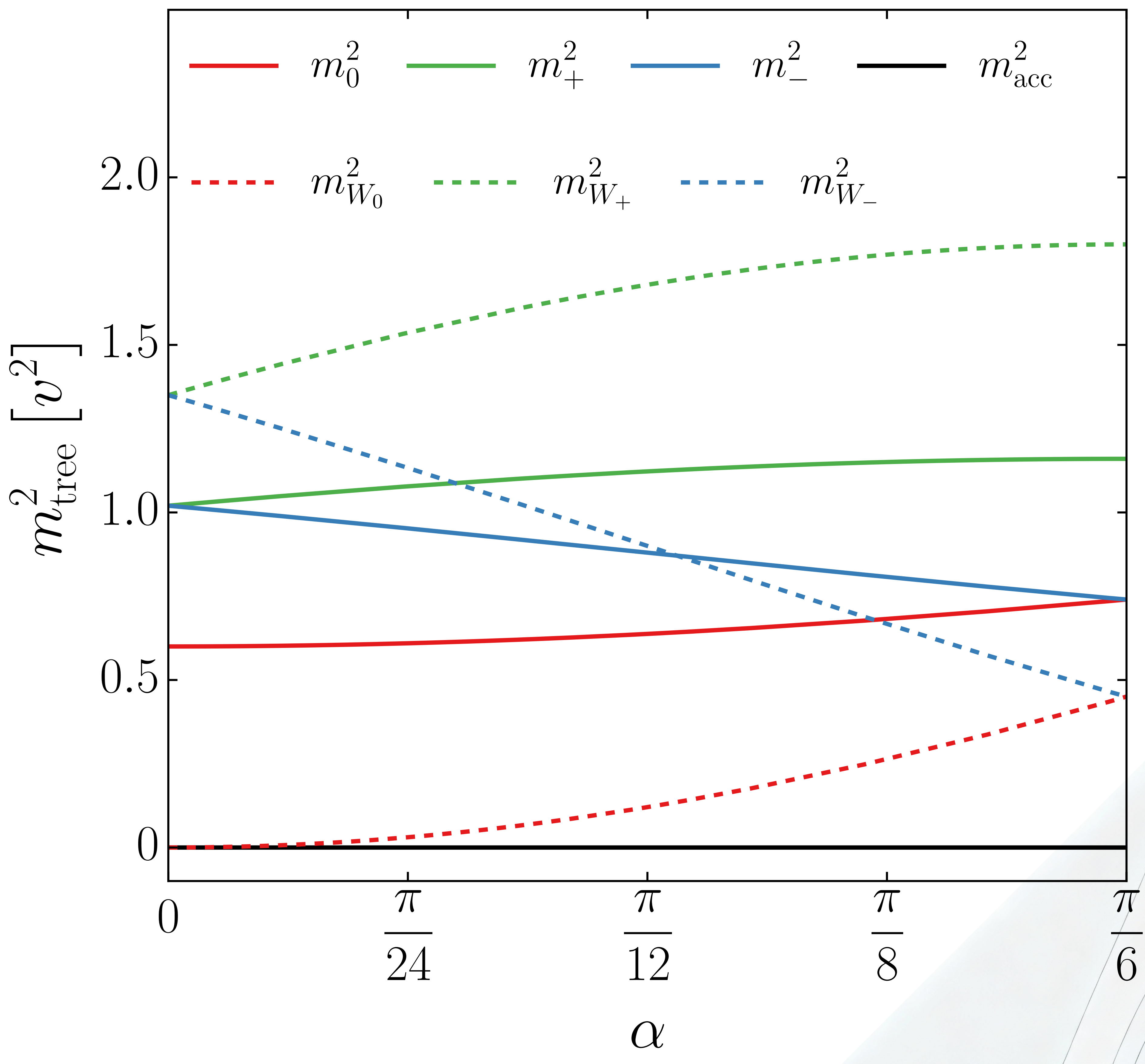

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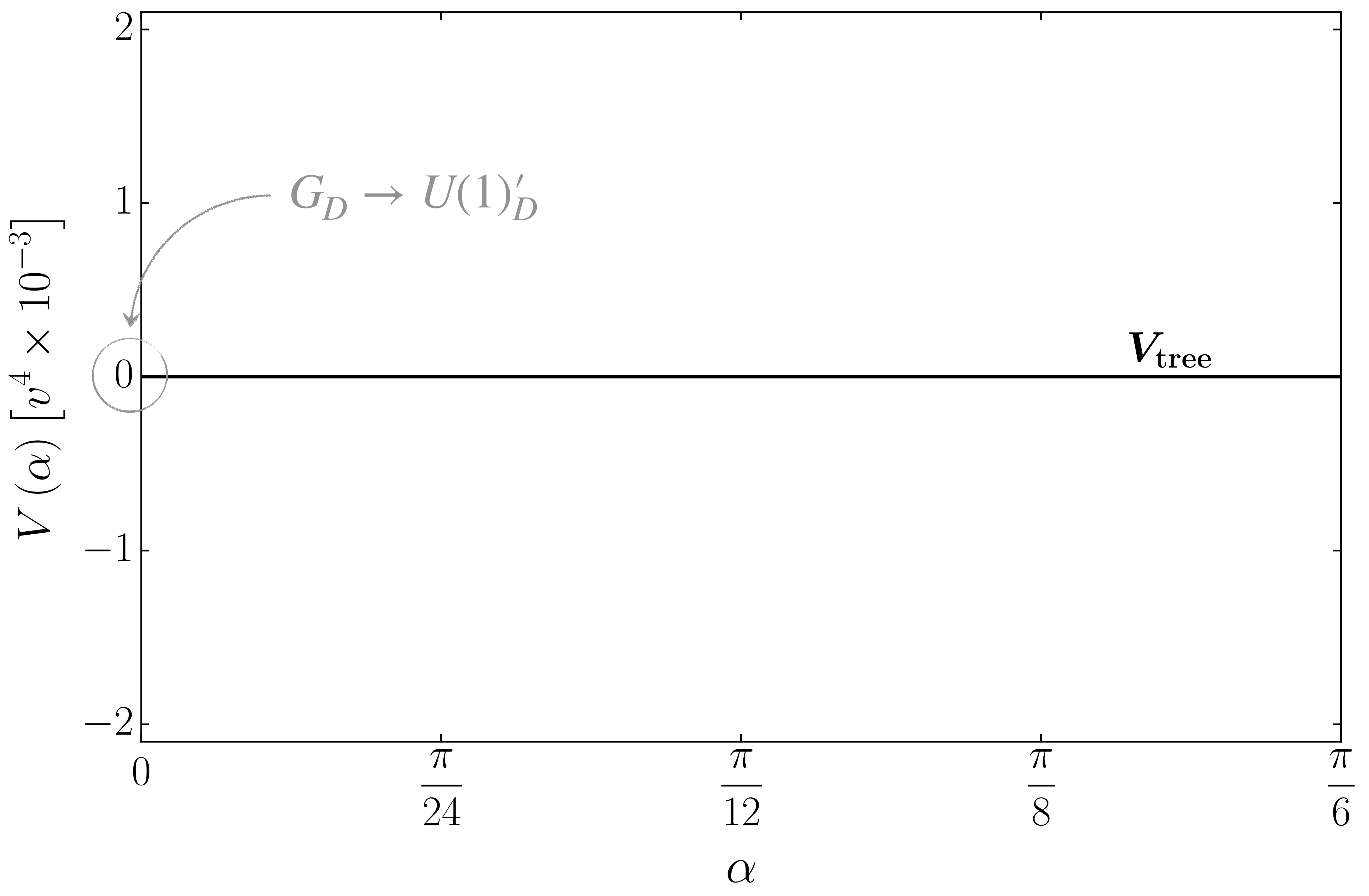

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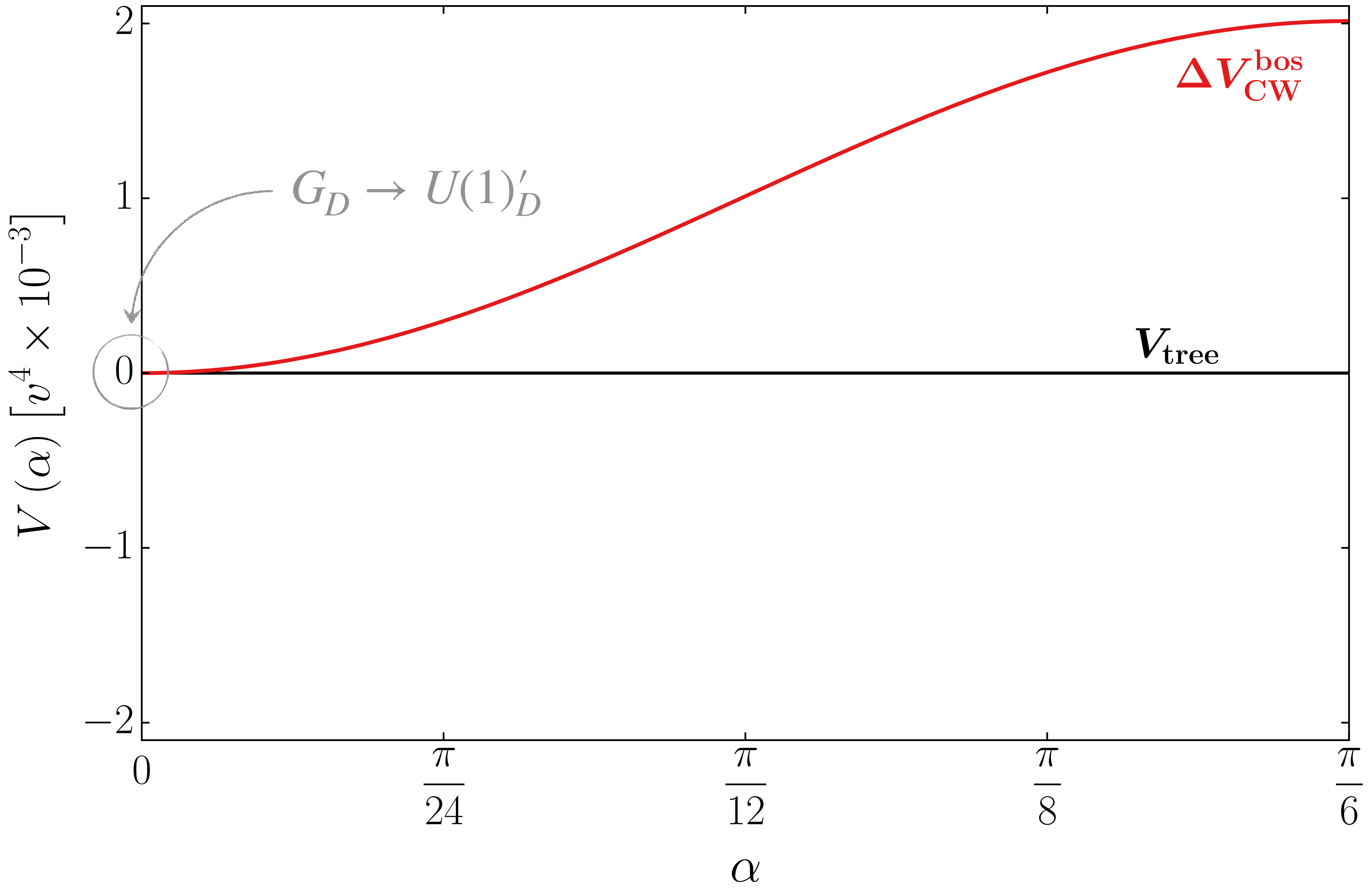

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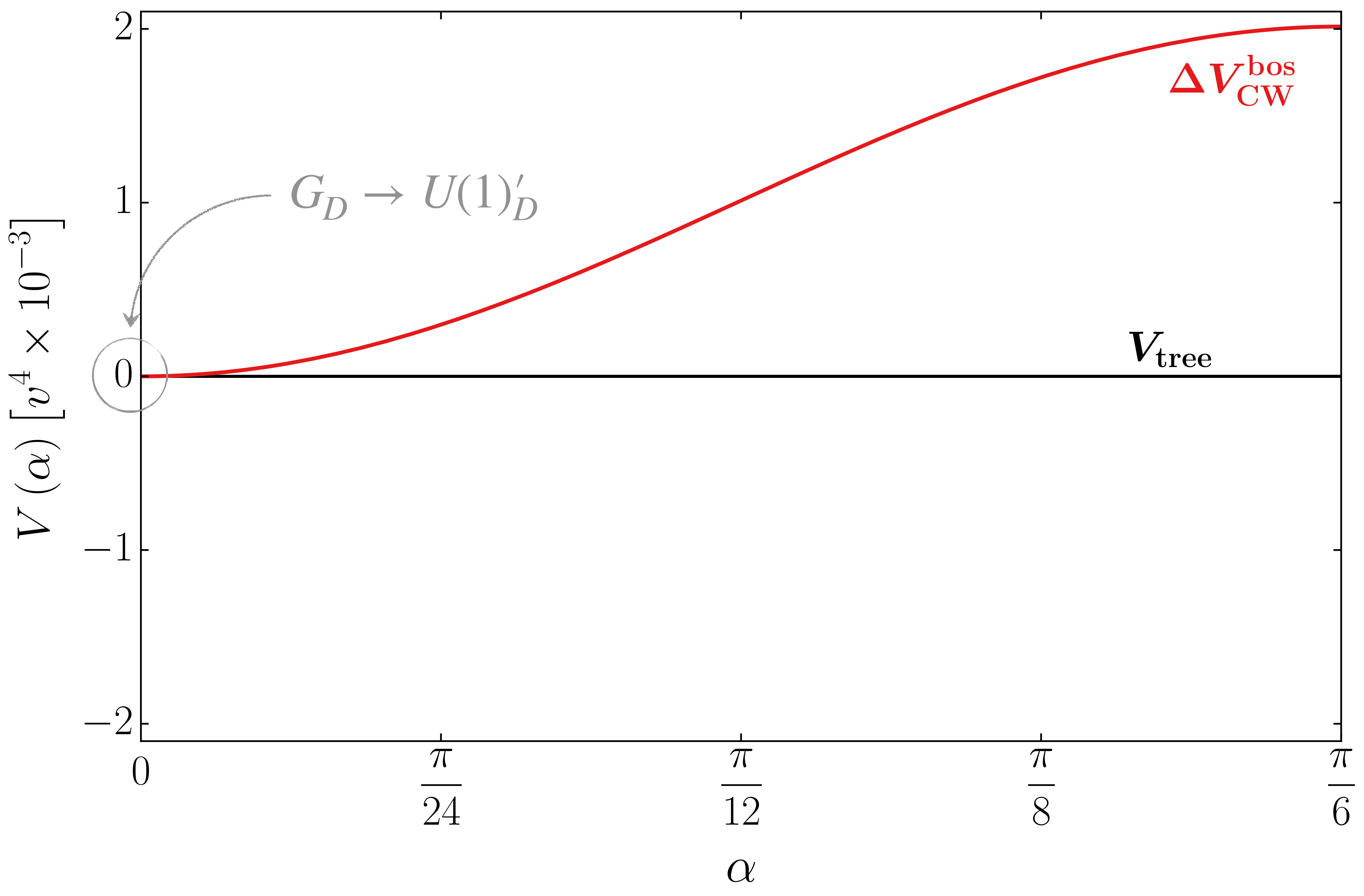

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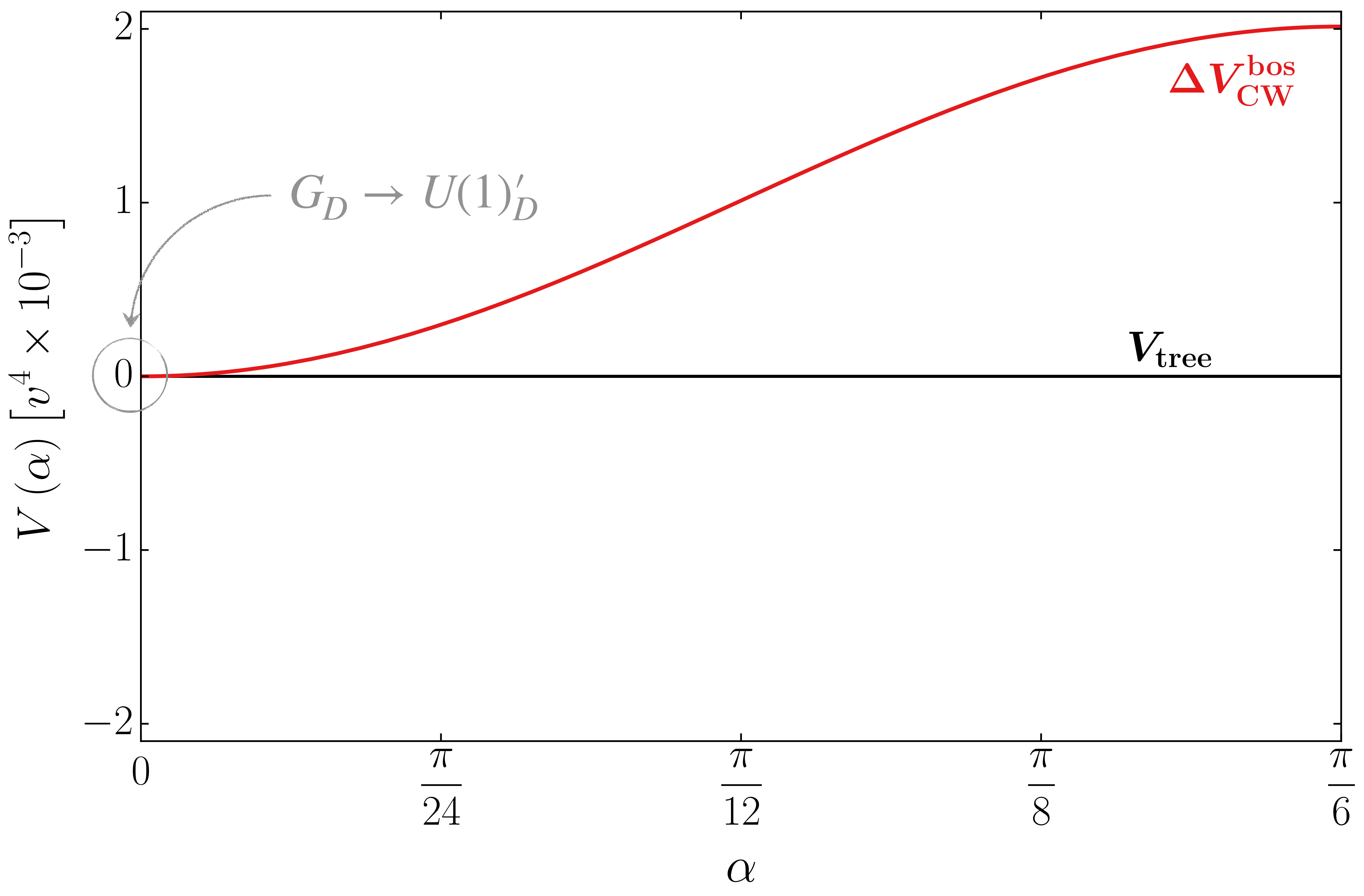

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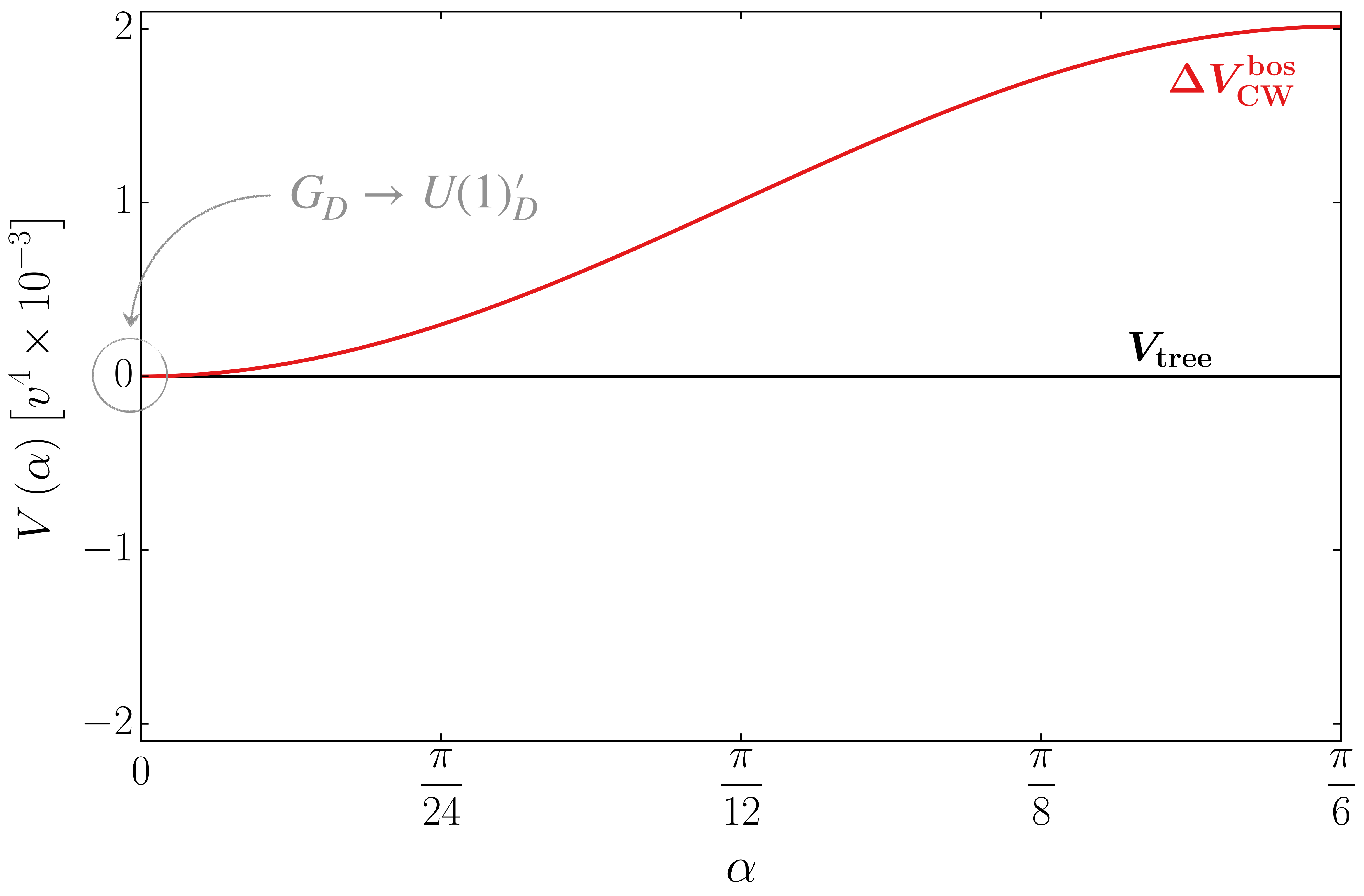

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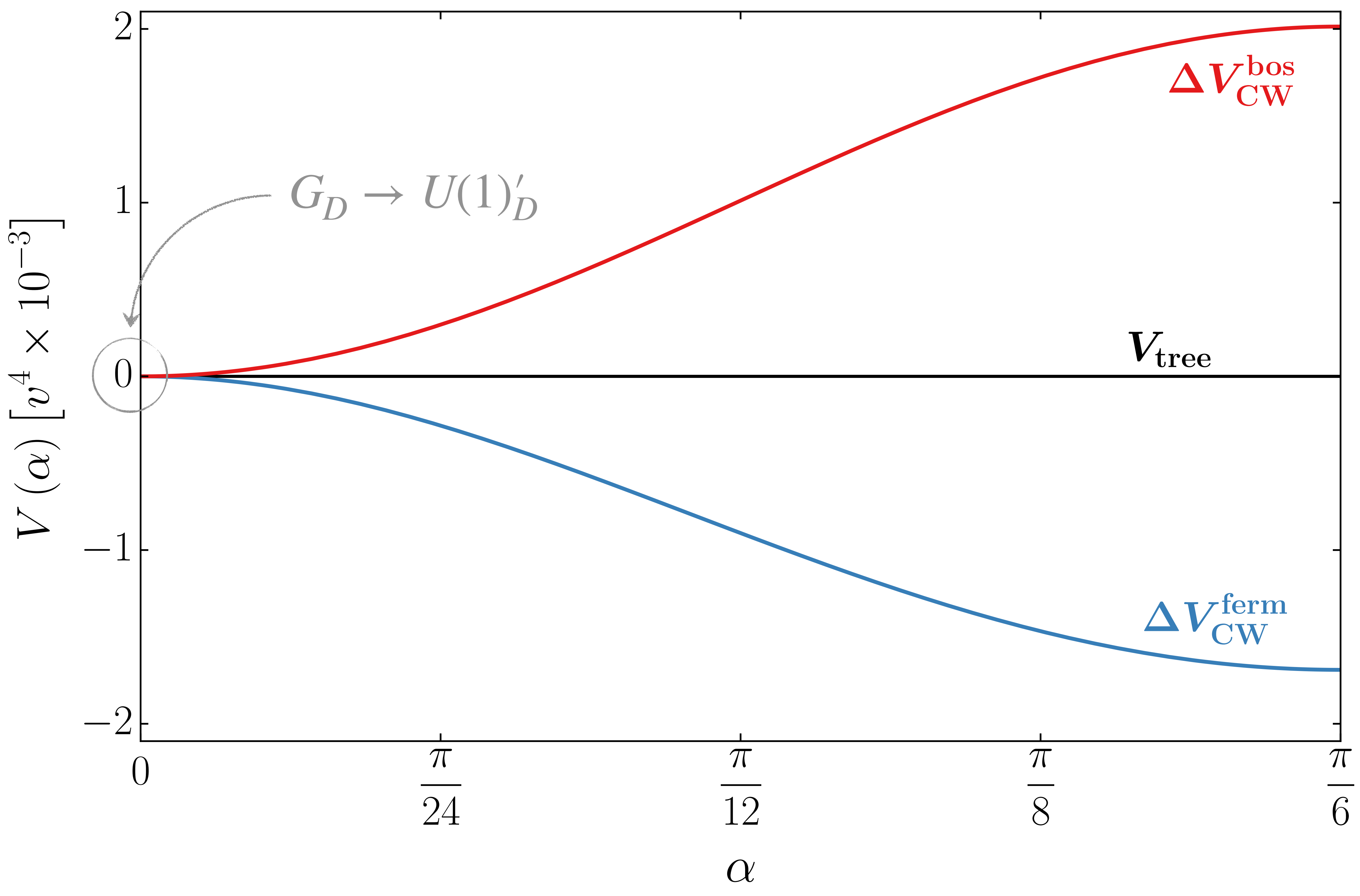

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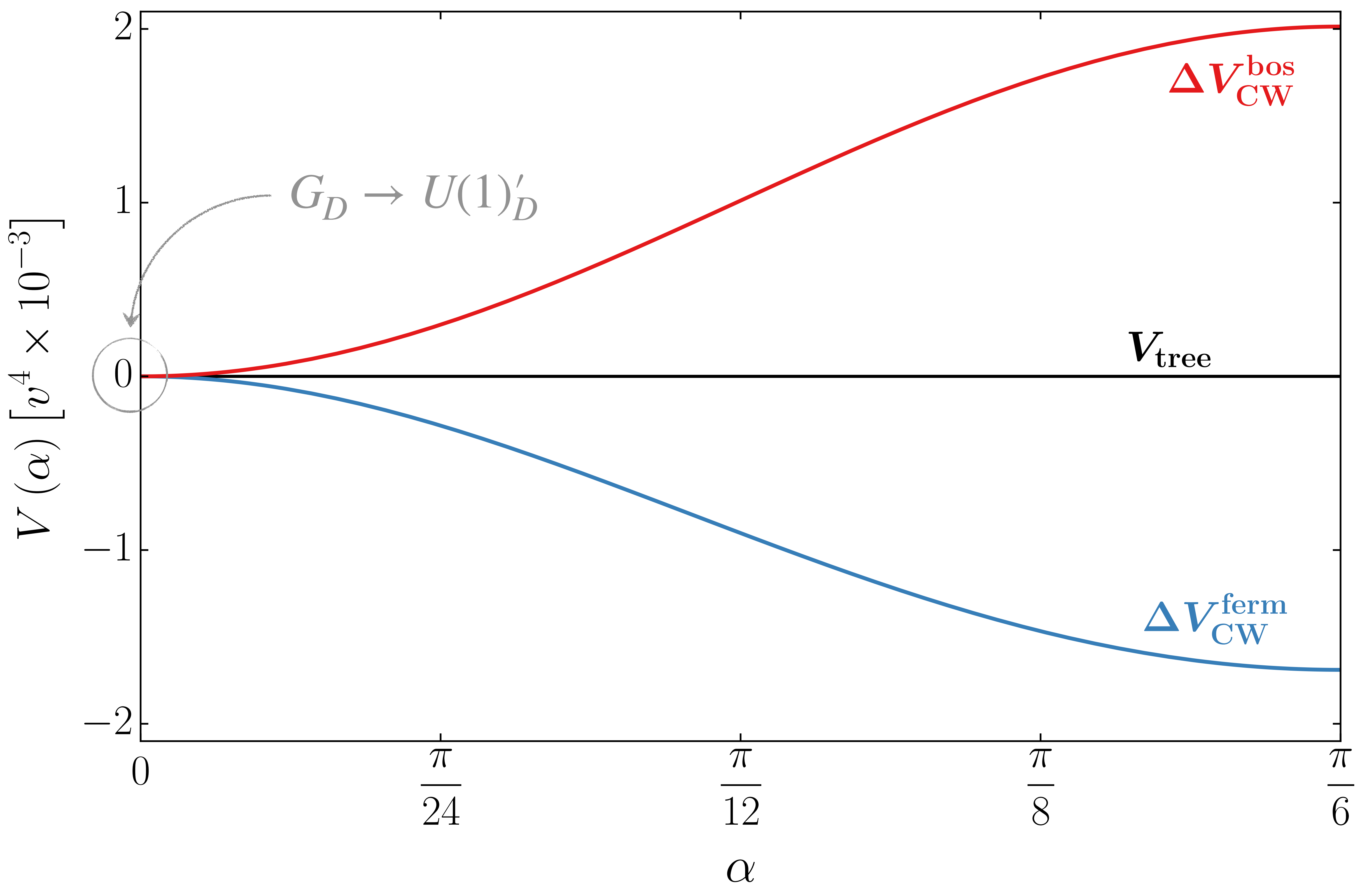

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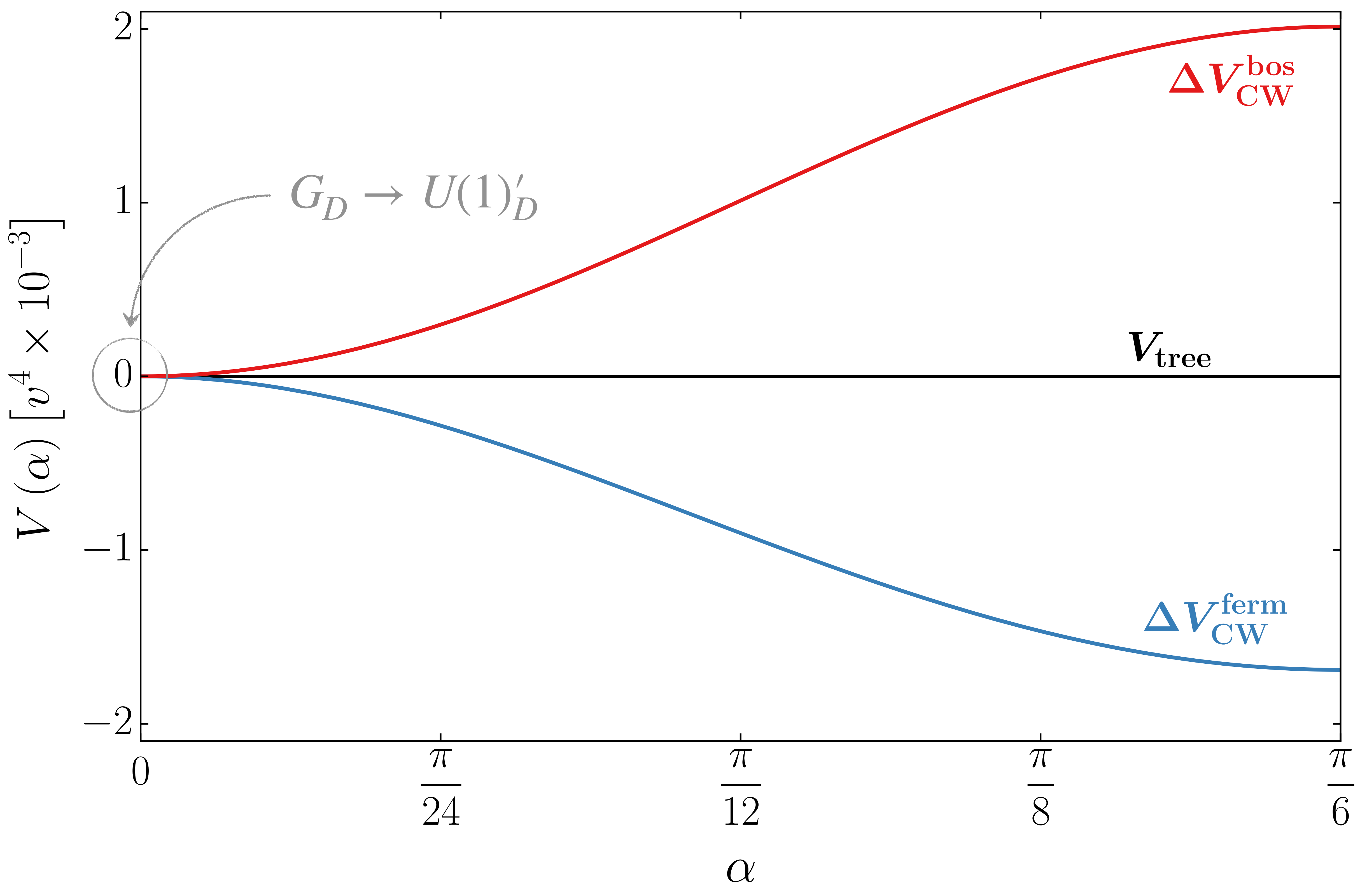

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Dark matter

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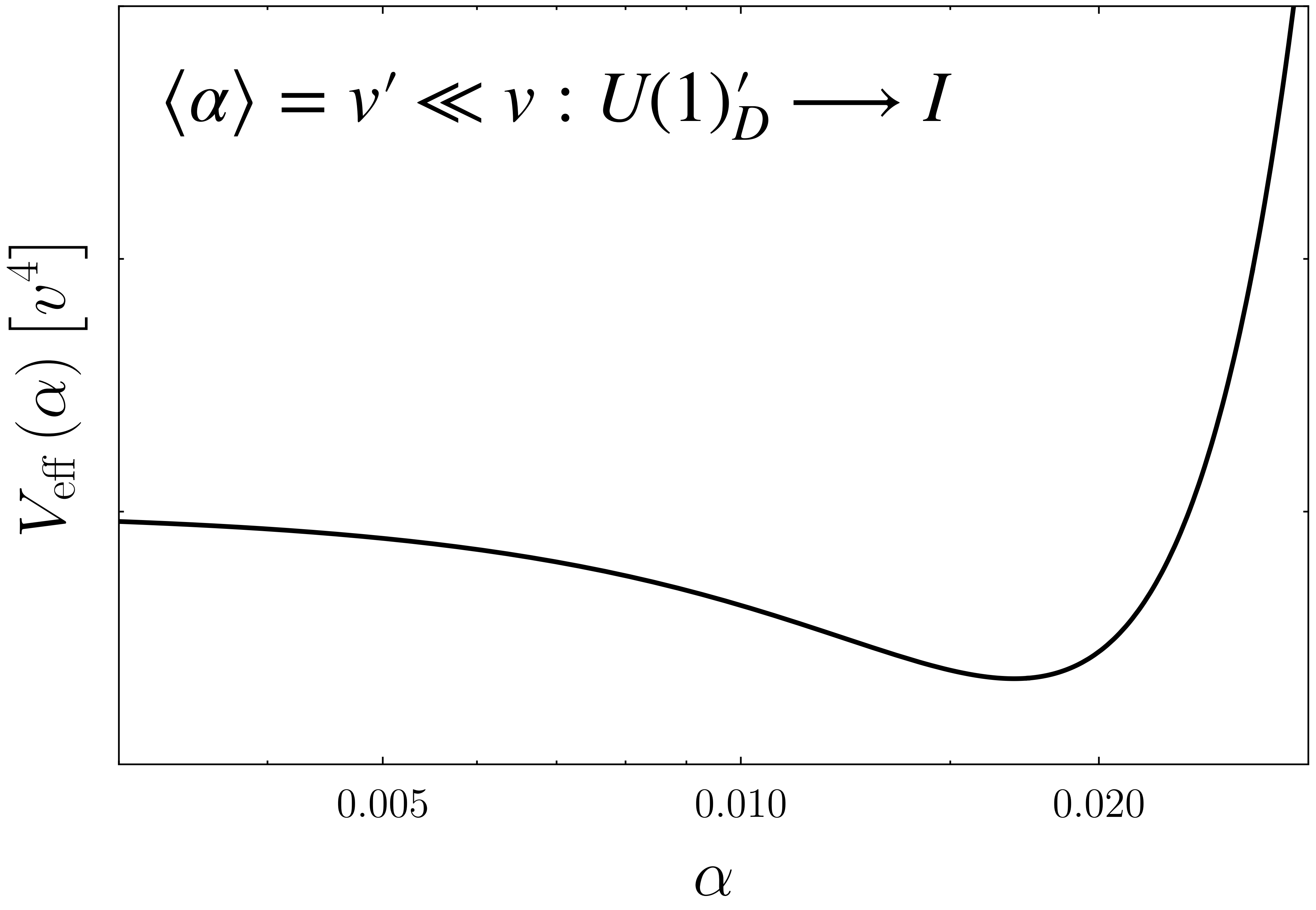

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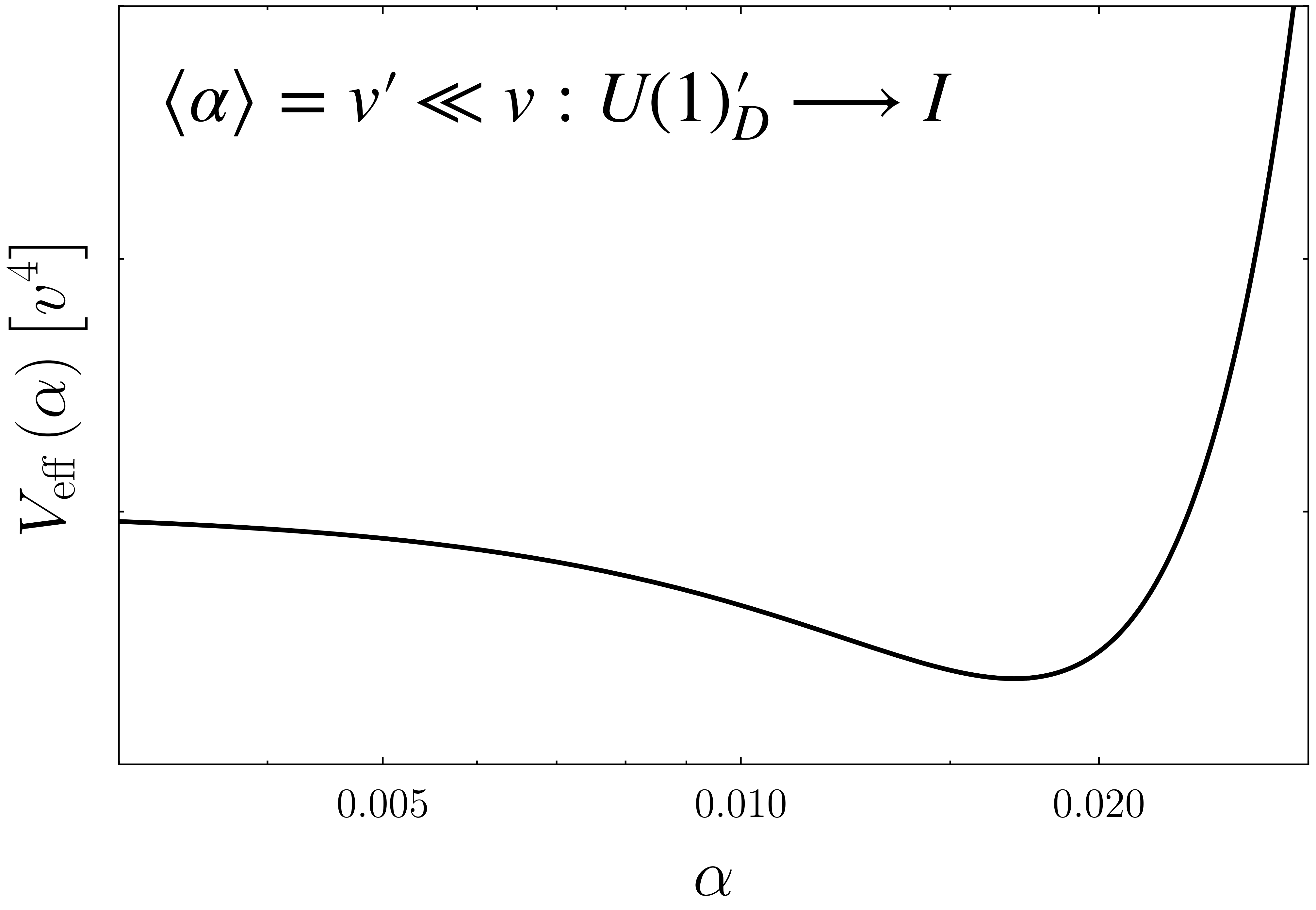

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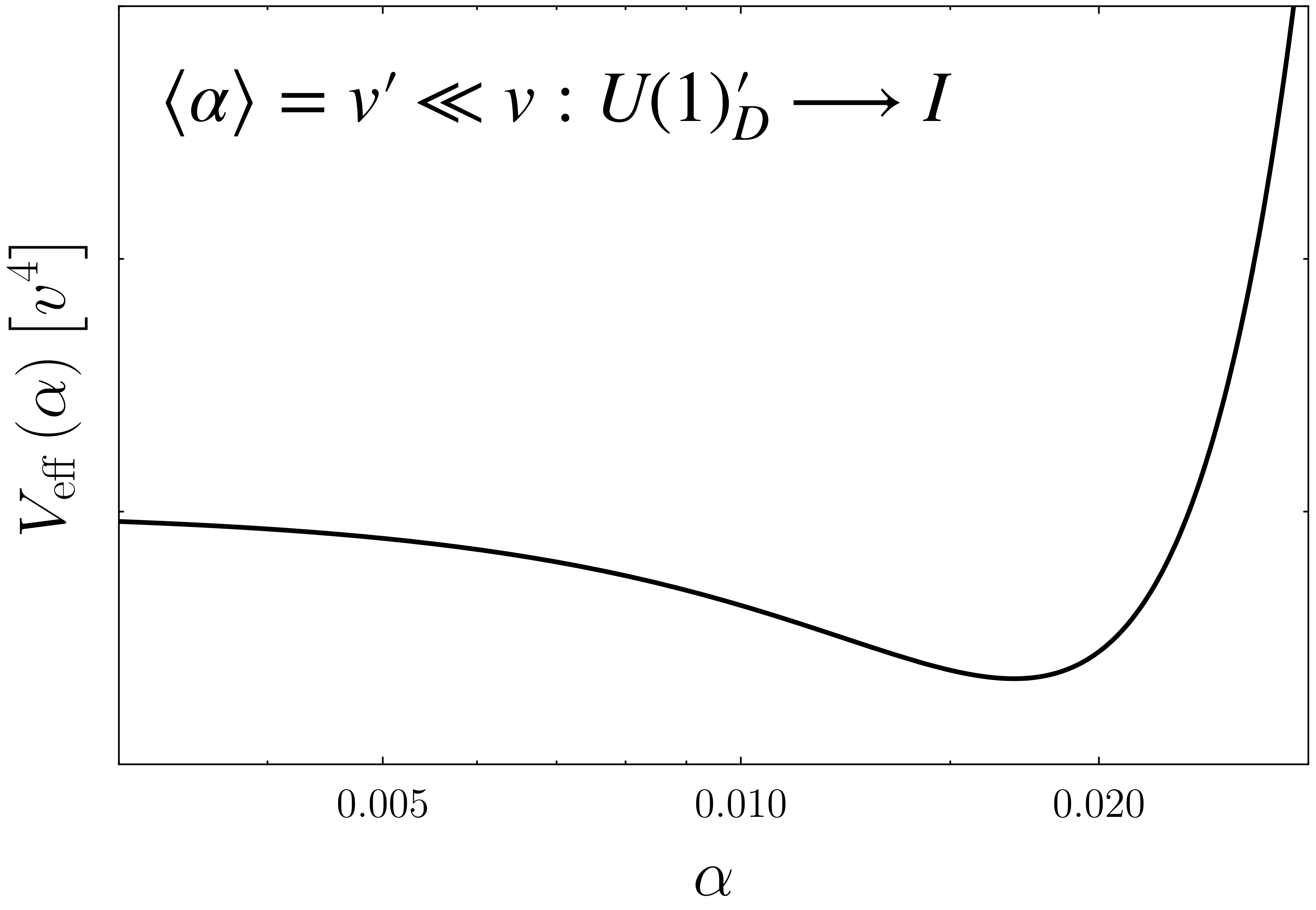

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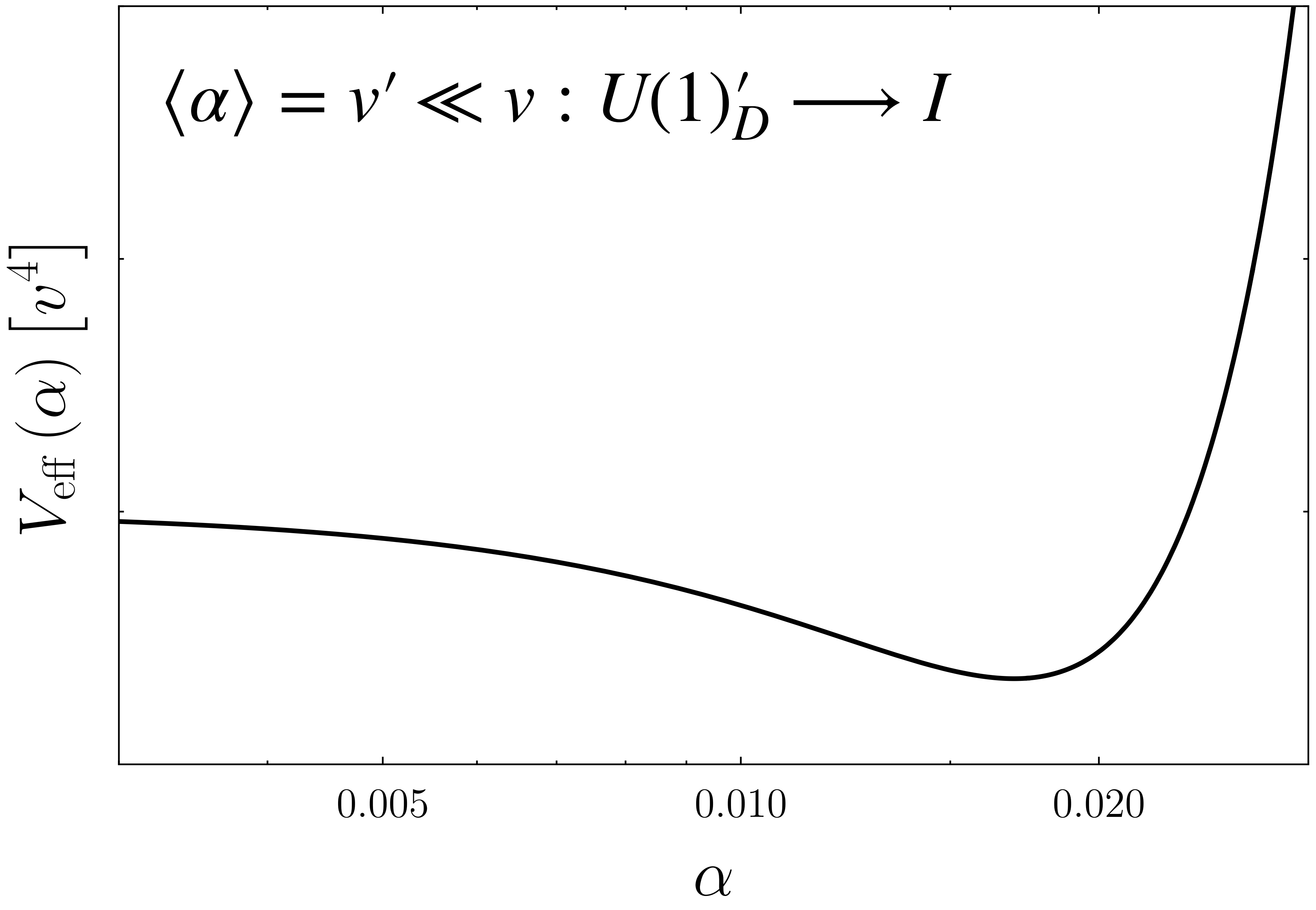

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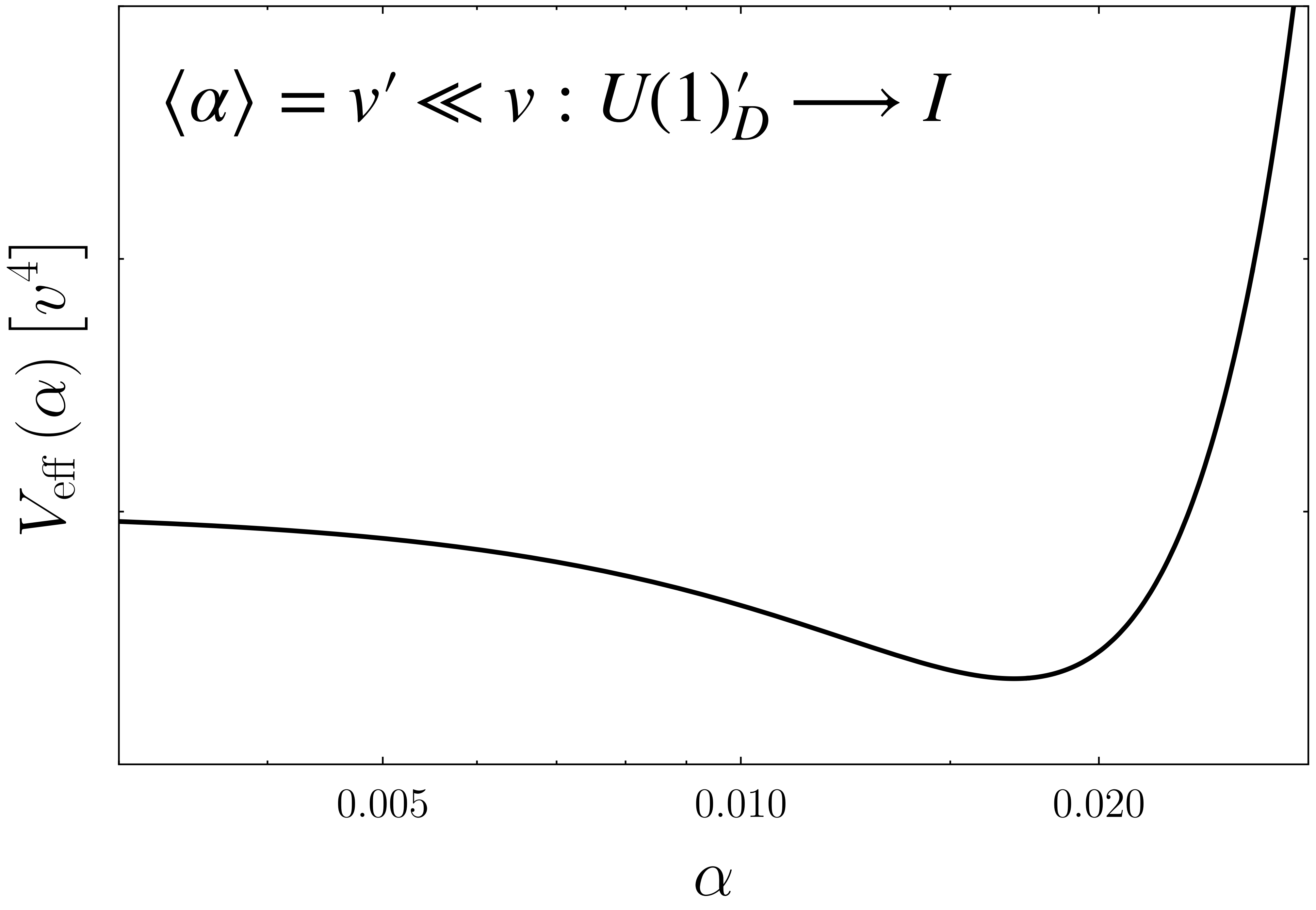

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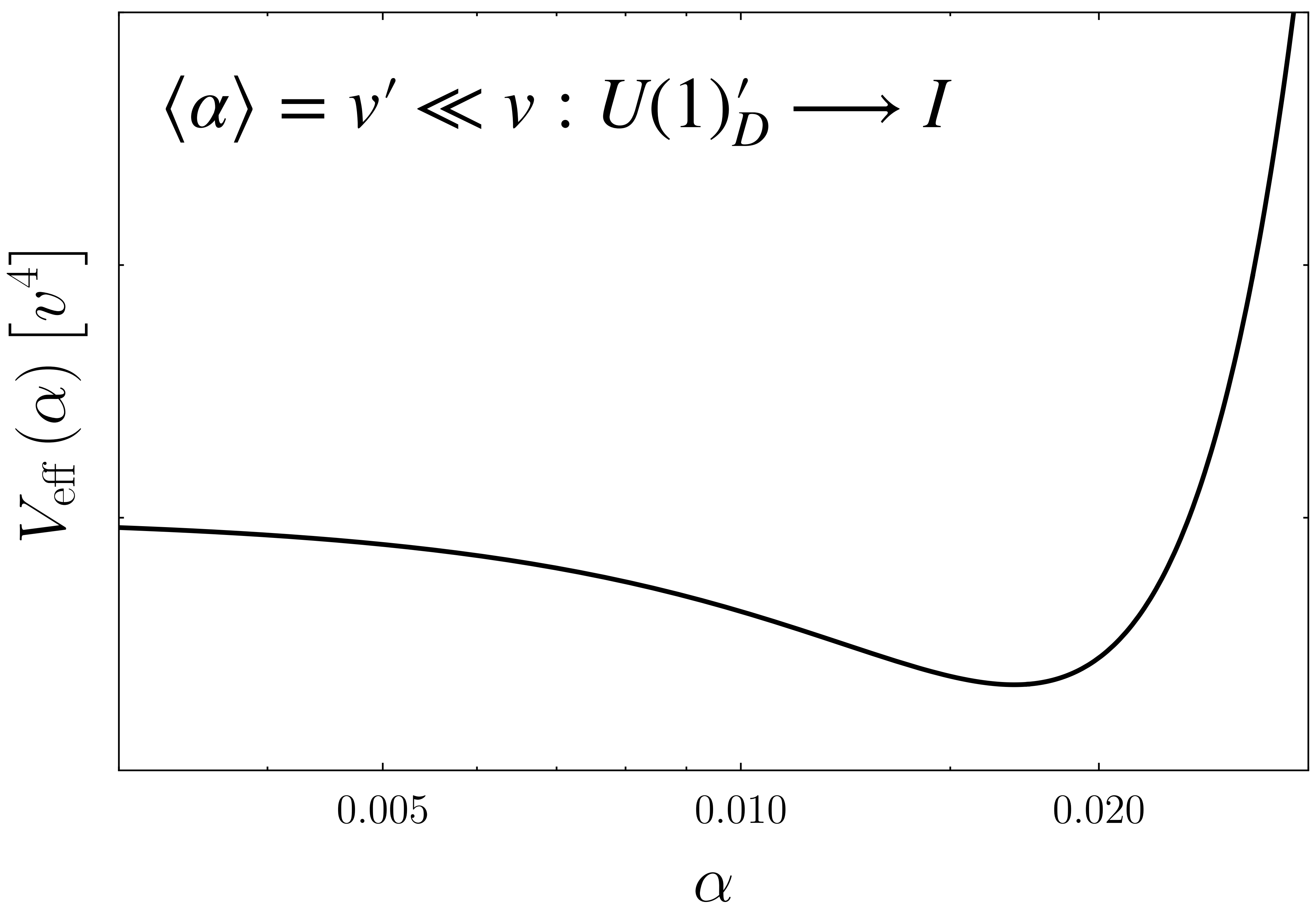

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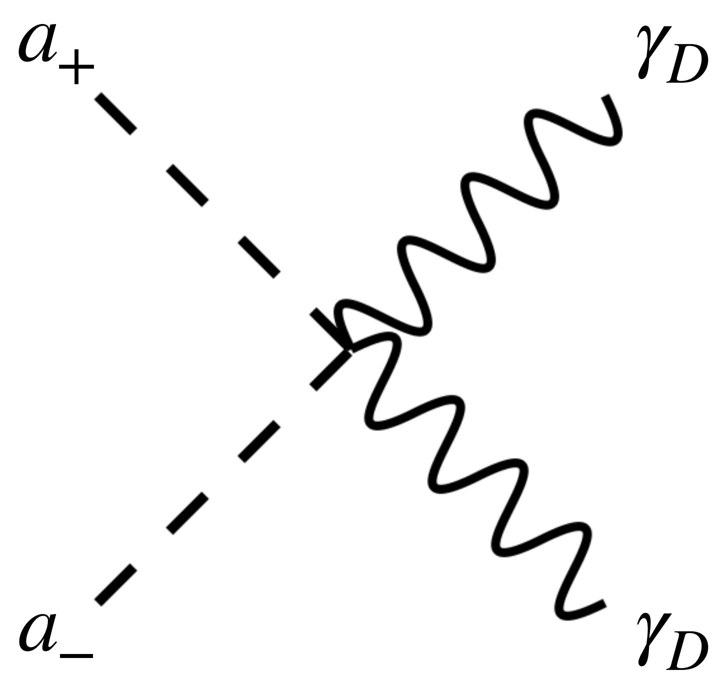

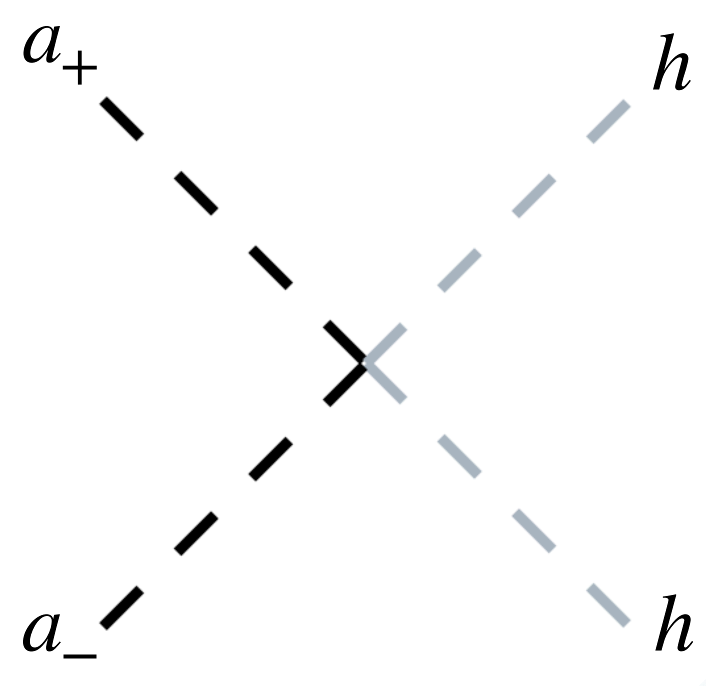

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The inflationary paradigm

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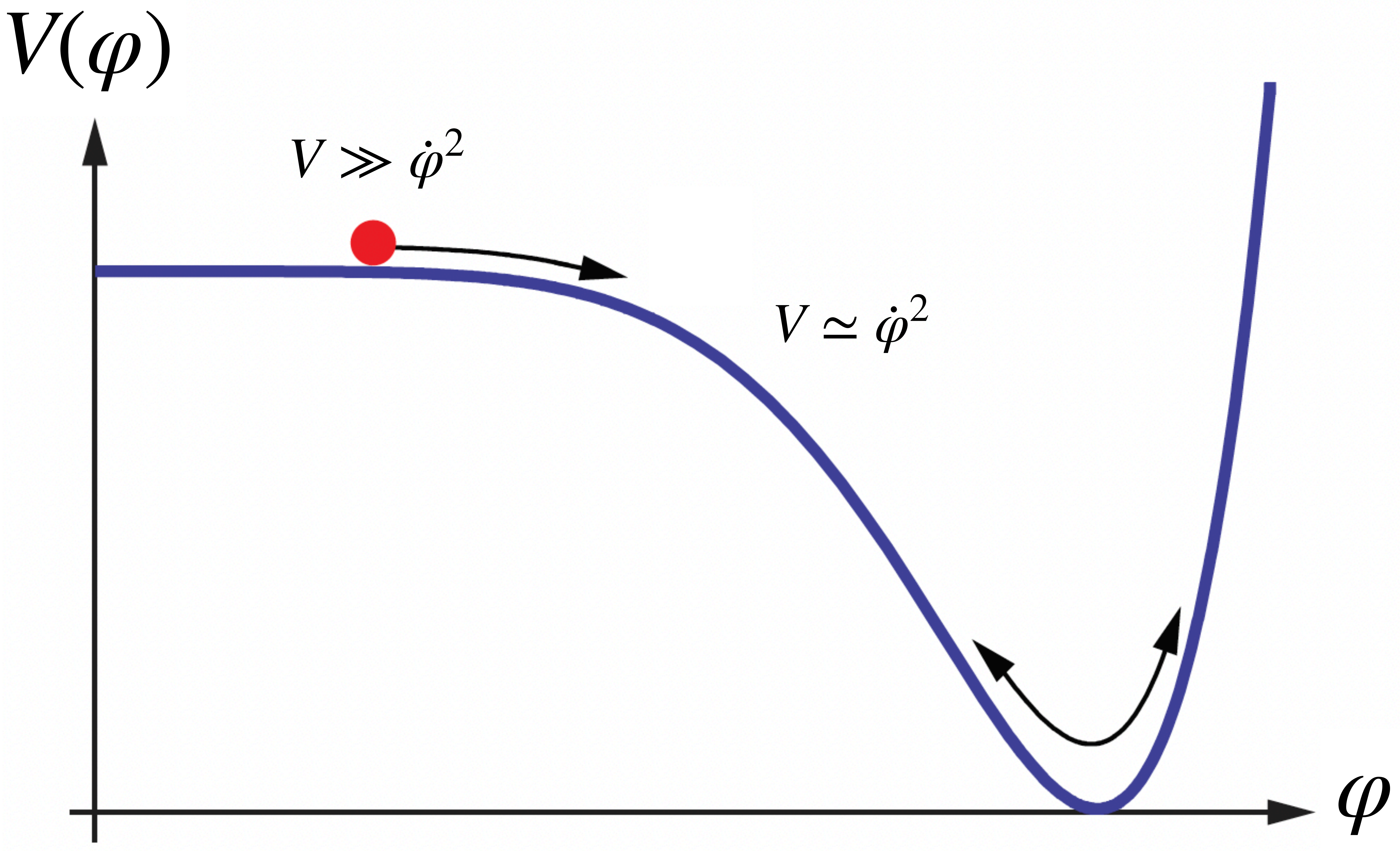

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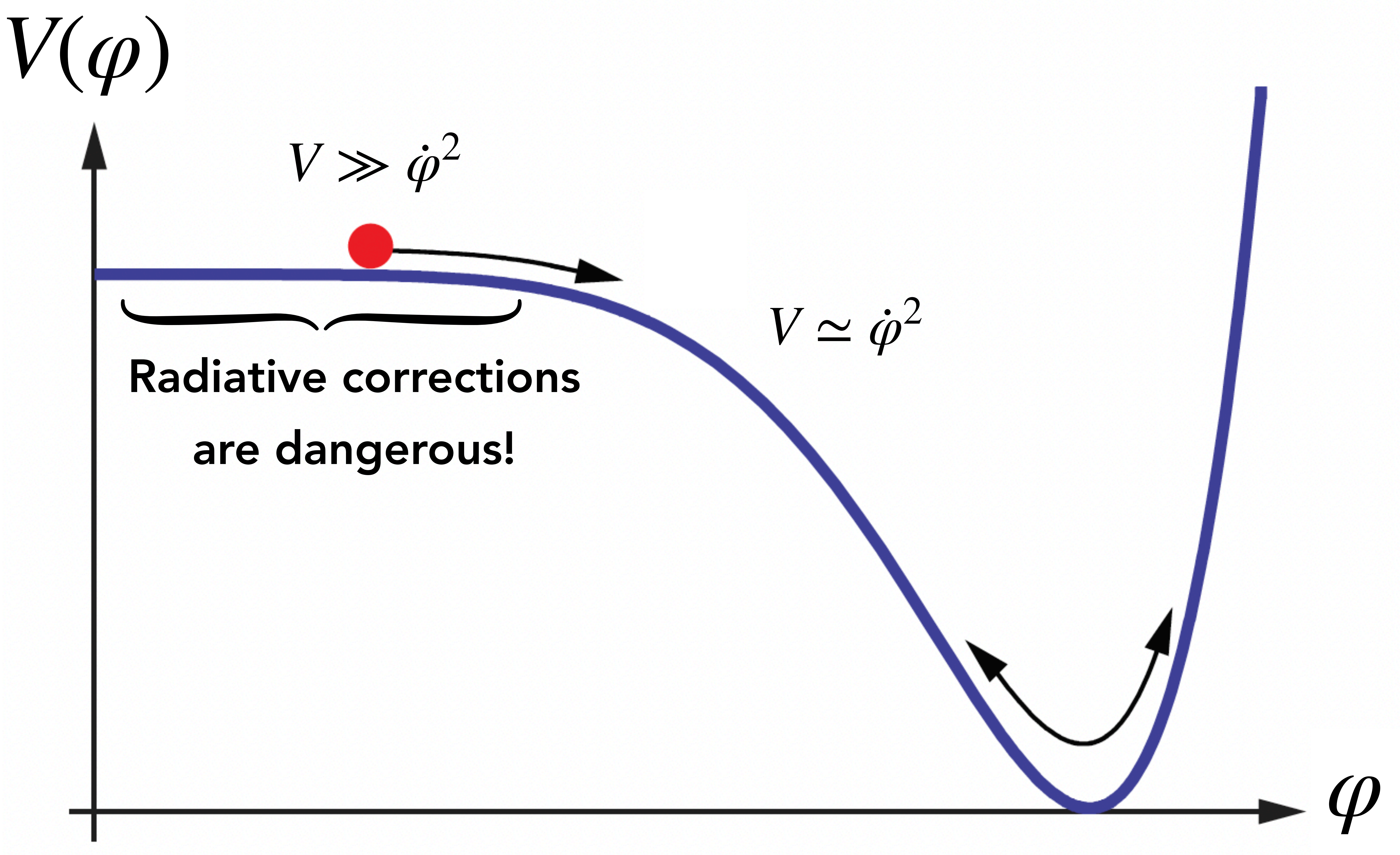

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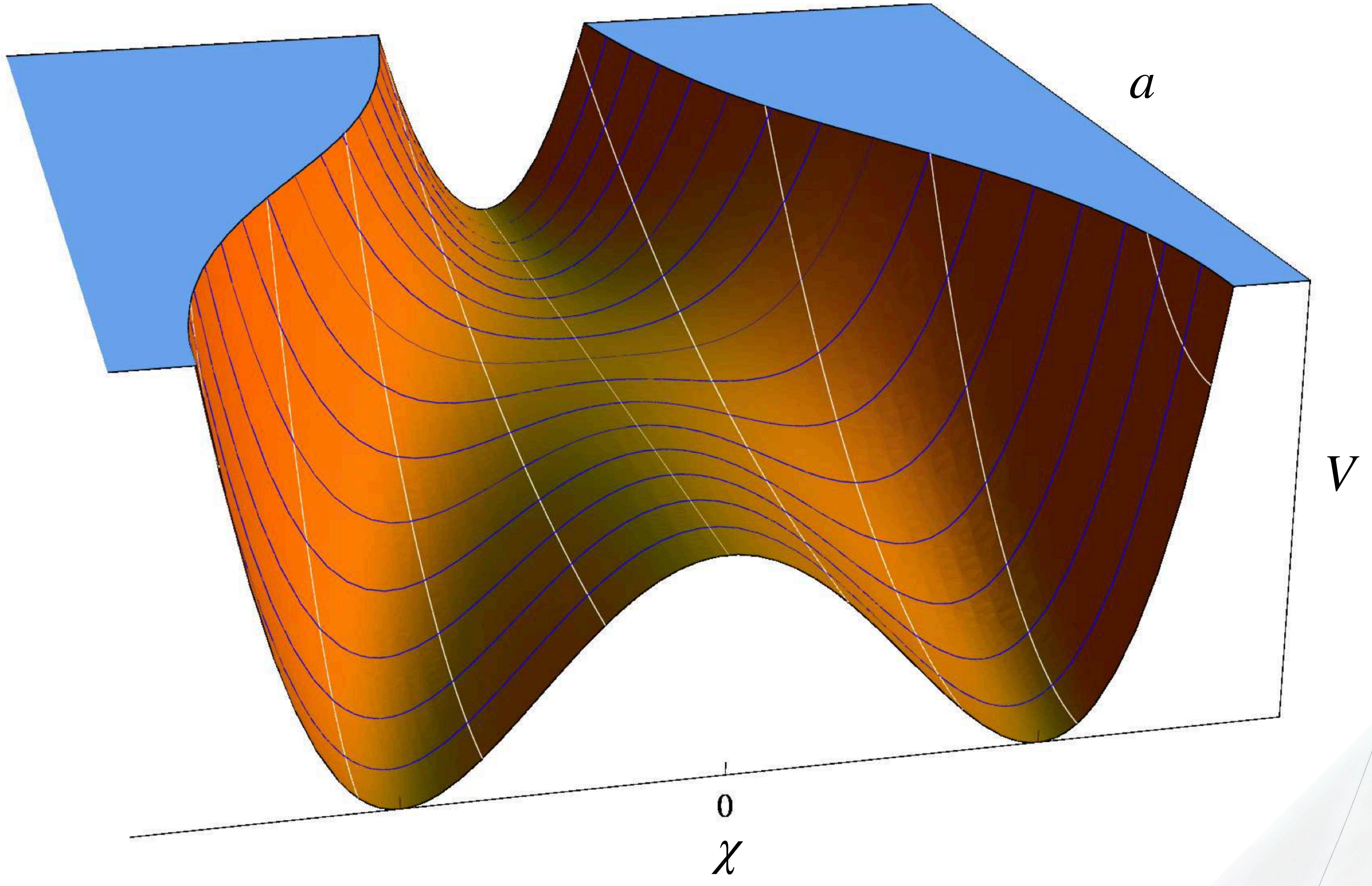

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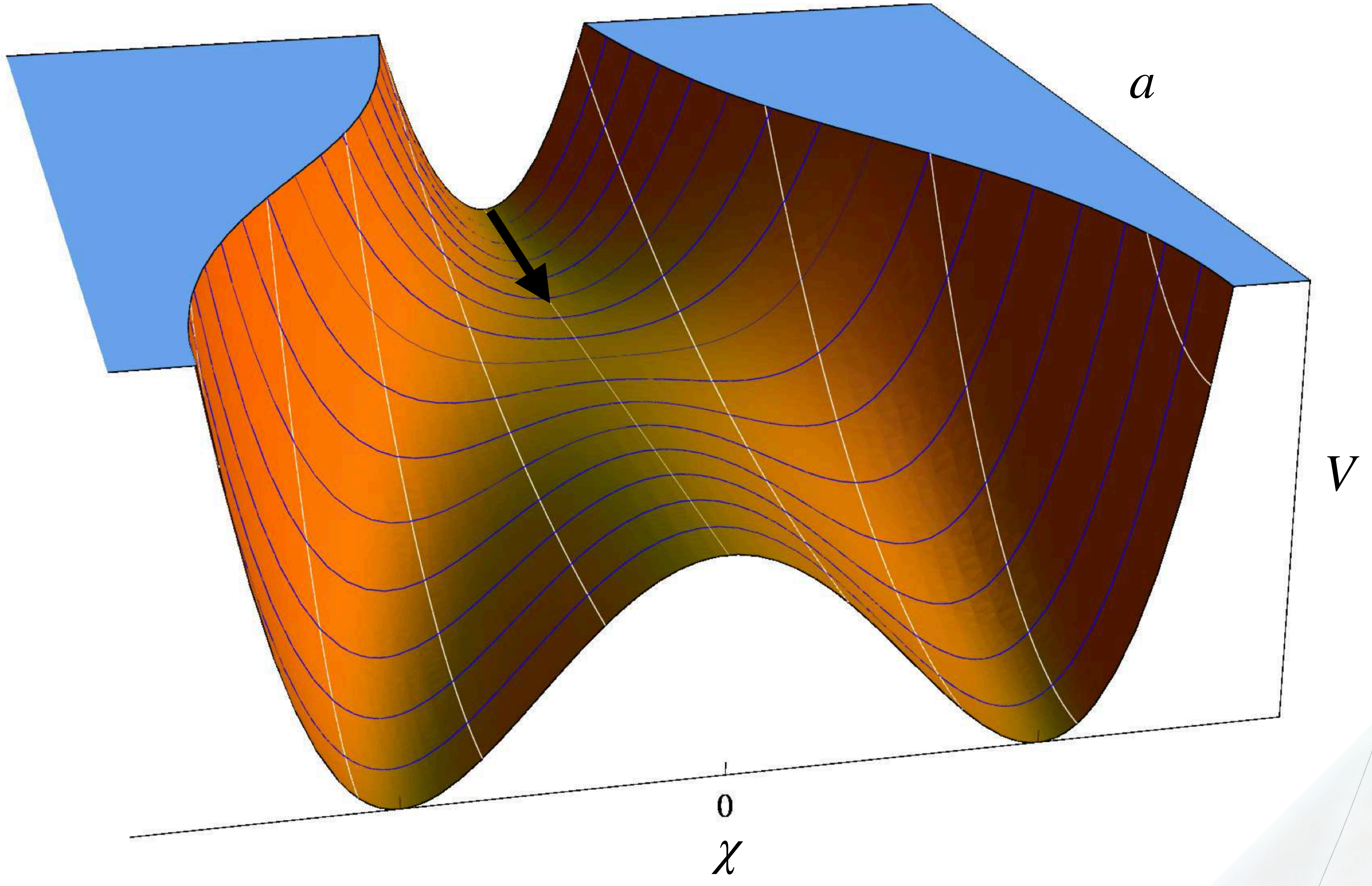

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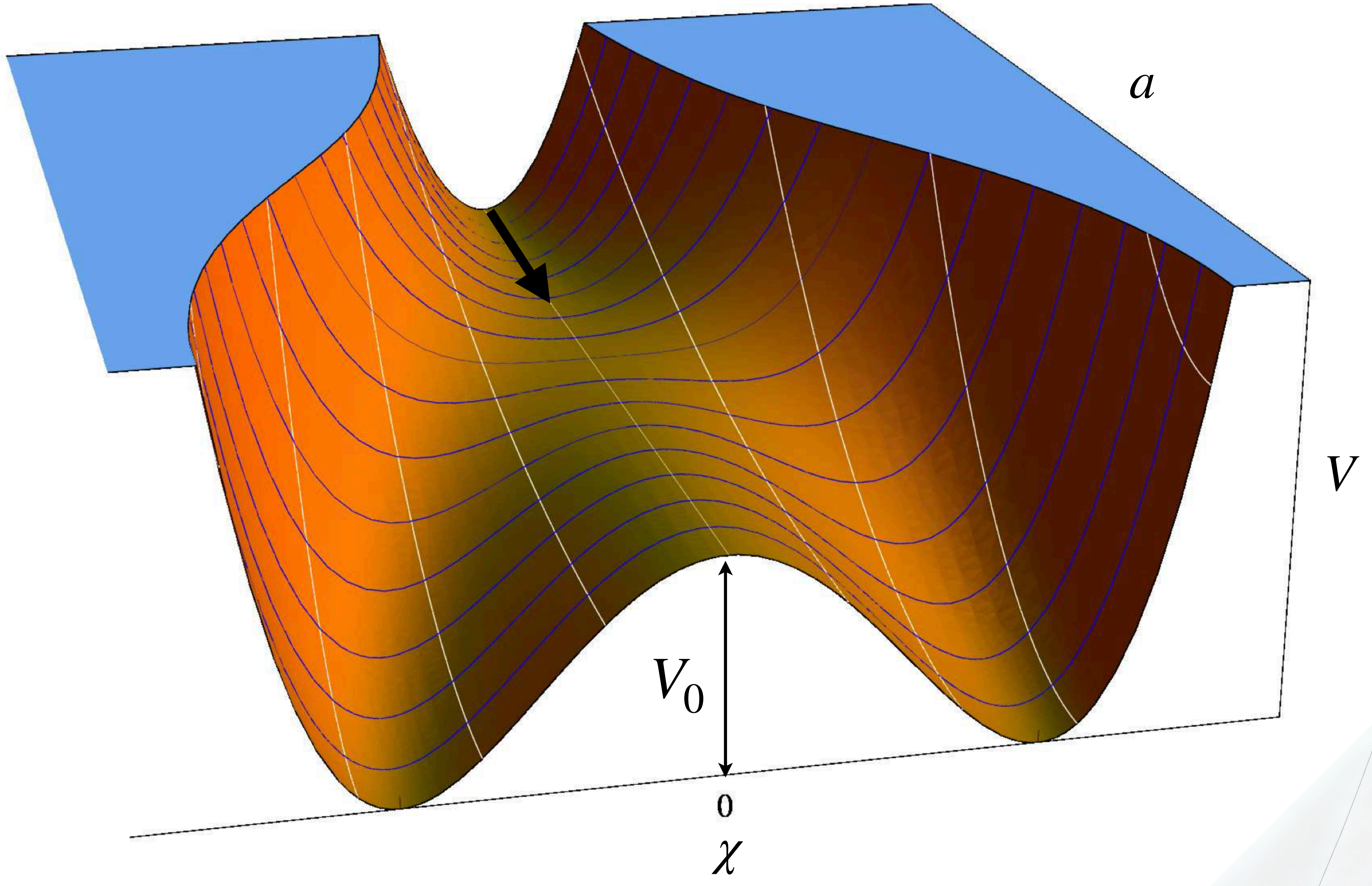

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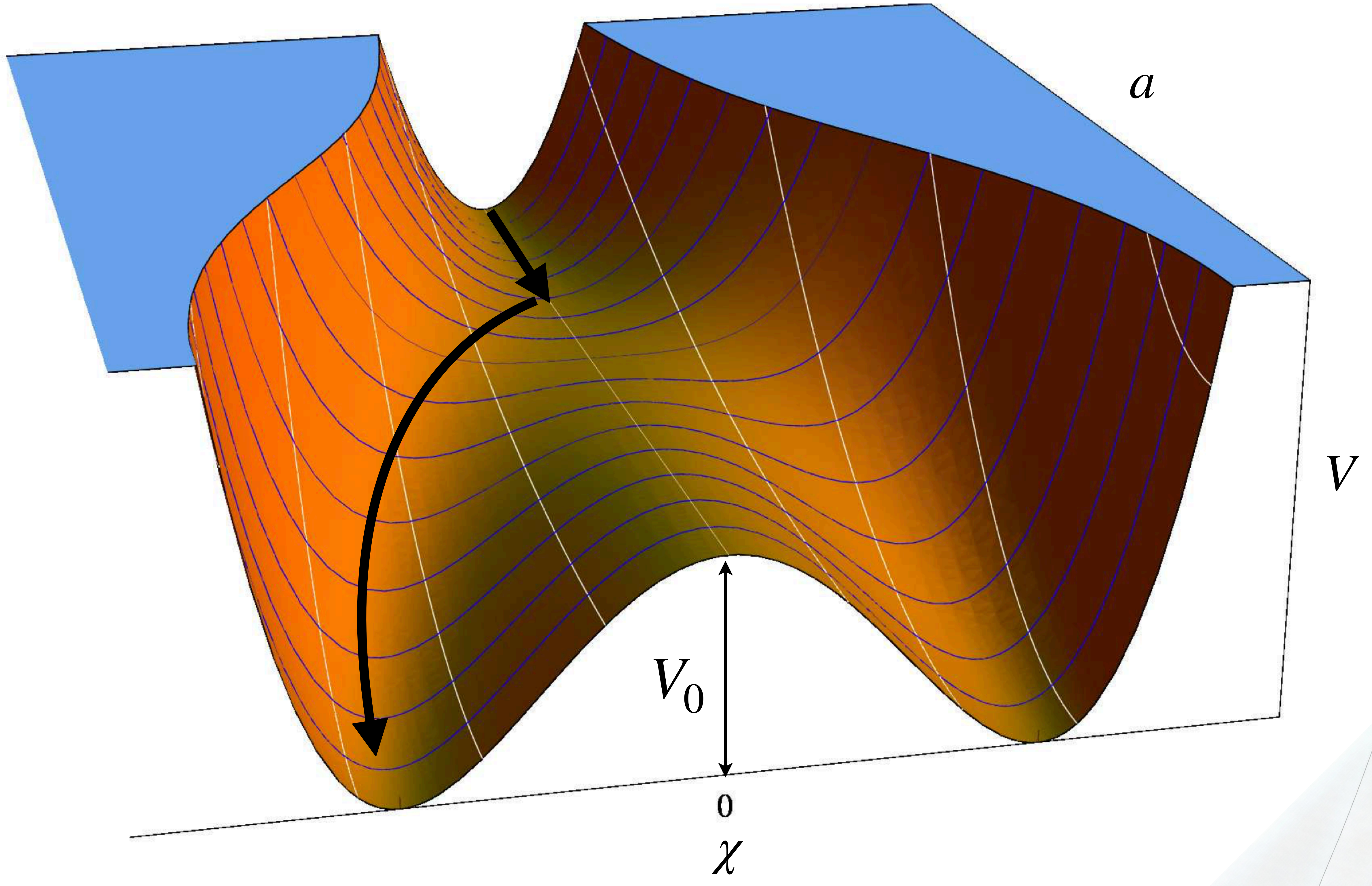

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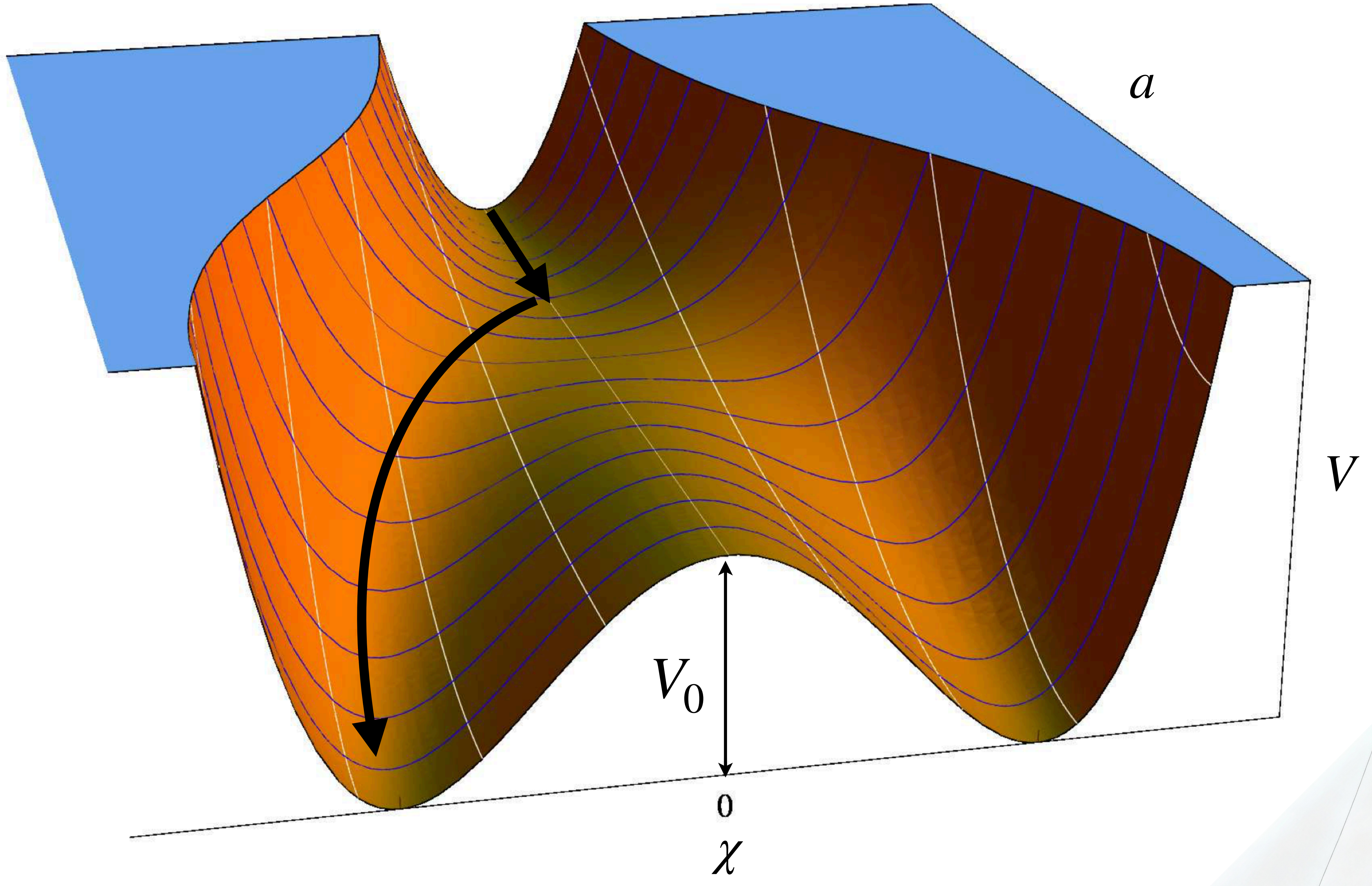

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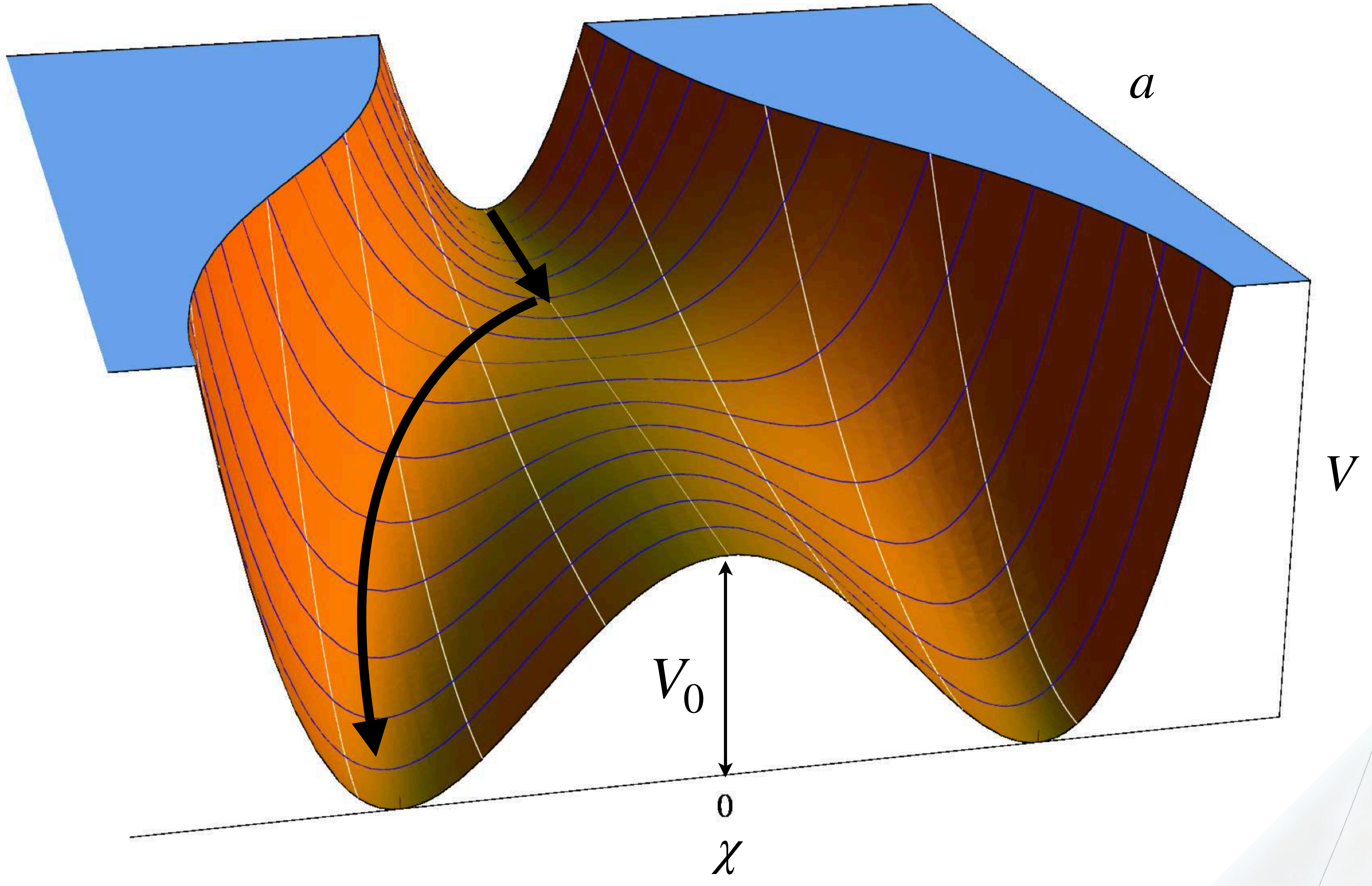

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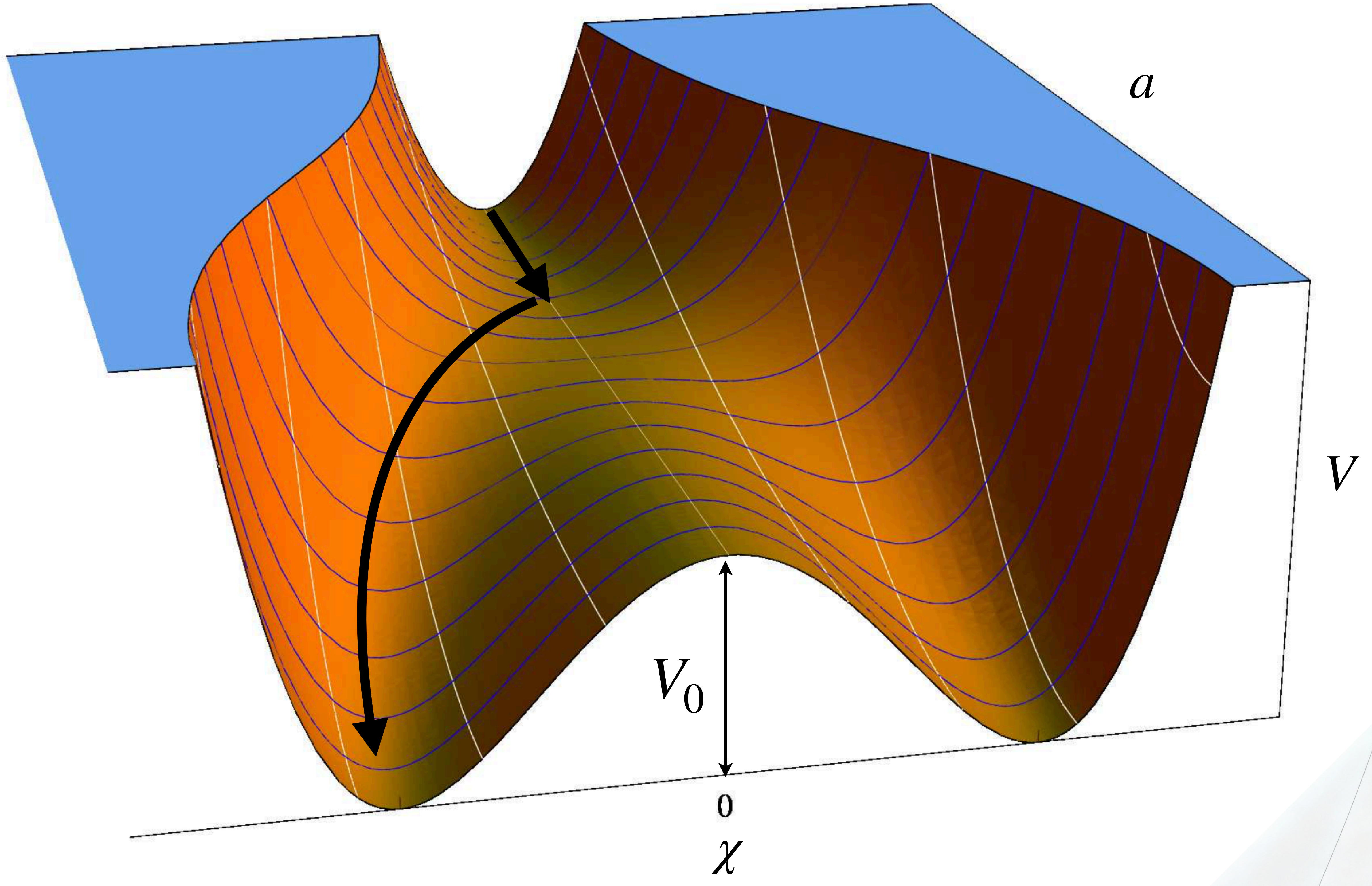
$$V = V(\phi) + \frac{\lambda_\chi}{4}\left(|\chi|^2 - v_\chi^2\right)^2 + \zeta\, T^a_{AB} T^b_{BC}\, \phi^{*A}\phi^C \chi^*_a \chi_b$$

Inflation: $\begin{cases} \langle \phi \rangle = v(a) & \text{(Accidentally flat direction)} \\ \langle \chi \rangle = 0 \end{cases}$

$$V_{\rm inf} = V_0 + \frac{c_1 f^4}{64\pi^2}\cos\left(\frac{a}{f}\right) - \frac{1}{2}\left[\overbrace{\mu_\chi^2 - \zeta v^2 \sin^2\left(\frac{a}{6f}\right)}^{=\, m^2_{\chi_3}(a)}\right]|\chi_3|^2 + \dots$$

Adapted from [M. Civiletti et al., 2013]



Accident inflation

$f \equiv v/6$

$$\cancel{V_{\text{eff}}(a) \simeq \frac{c_1 f^4}{64\pi^2} \cos\frac{a}{f}}$$

[Planck, 2018]

$$\Downarrow$$

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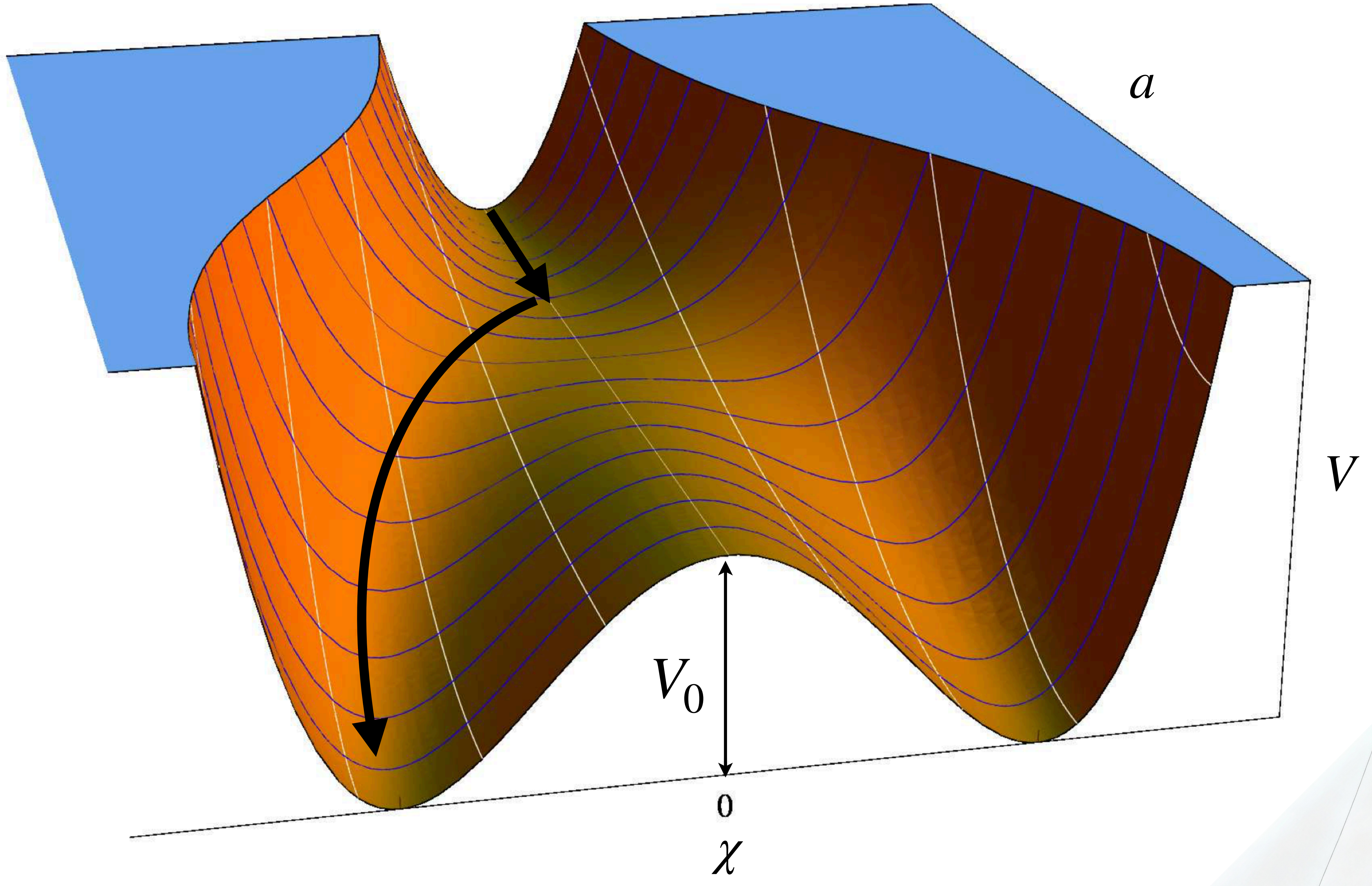
Inflaton = Accident $\Longrightarrow$ Naturally flat

Adapted from [M. Civiletti et al., 2013]



Summary and Conclusions

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Systematic way of studying accidentally flat direction?

The SM Higgs as an accident?

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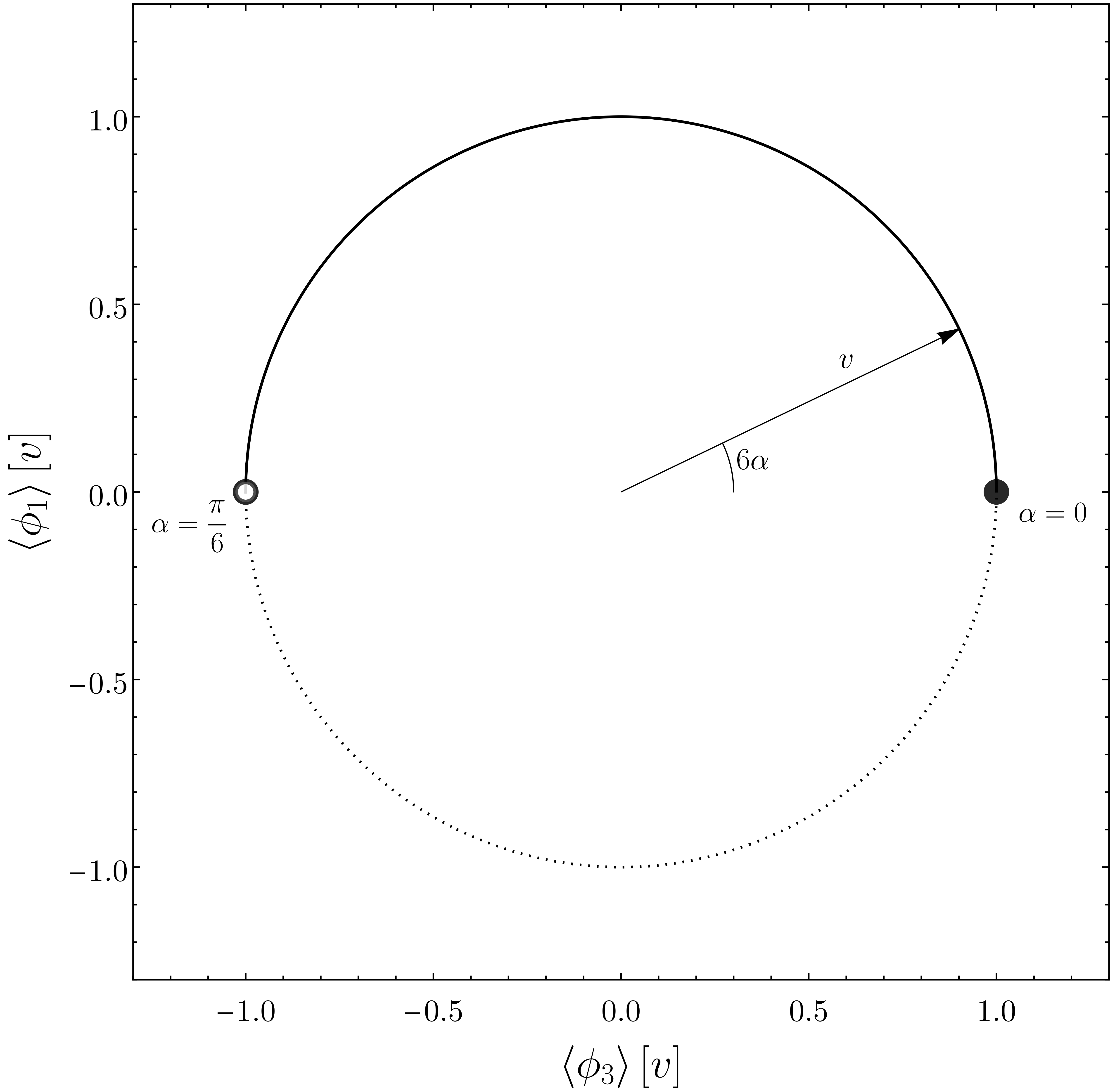
Thank you for your attention!

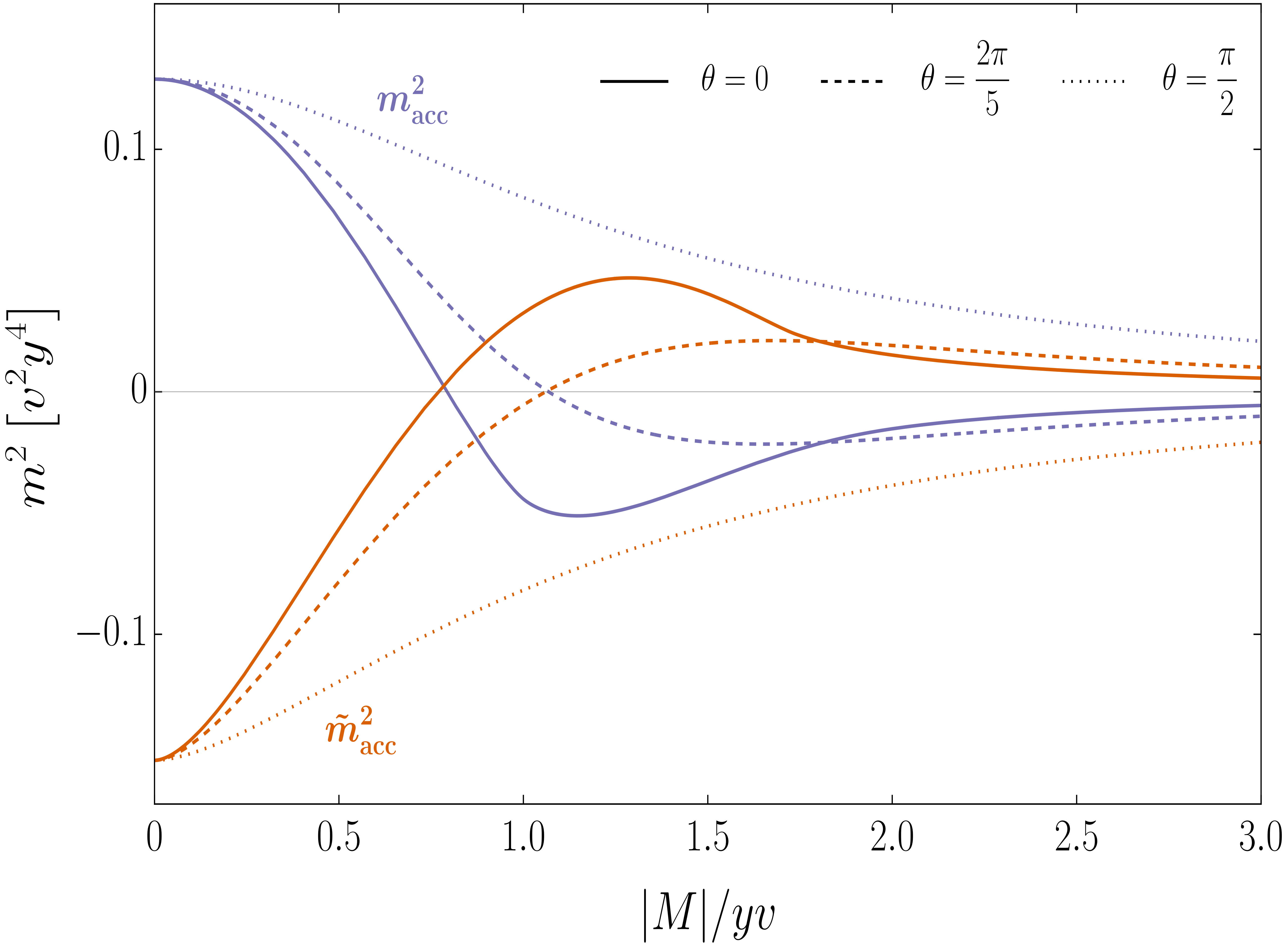
Backup Slides

Vacuum Manifold



One-loop effective potential

Fermion contribution

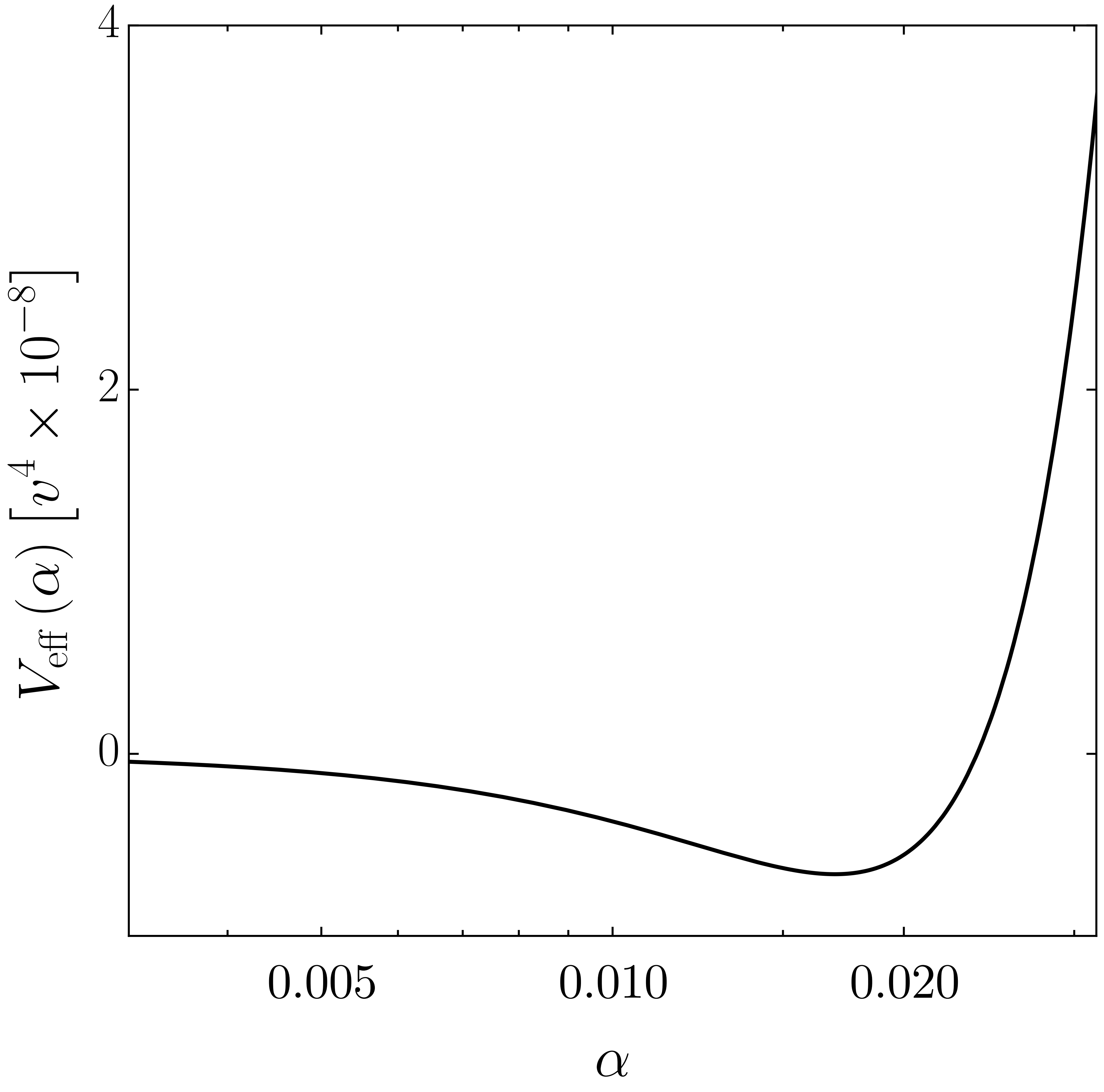


$$\psi \sim 3_{+1/2}\,, \quad \chi \sim 3_{-1/2}$$

$$\mathscr{L} \supset y\left(\psi^T \Phi\, \psi + \chi^T \Phi^* \chi\right) + M\, \psi^T \chi + \mathrm{h.c.}$$

Accident Higgs

Abelian case



$$V_{\text{eff}}(\alpha) = \sum_i \Delta V^i_{\text{CW}}(\alpha) \simeq c_1 \cos(6\alpha) + c_2 \cos(12\alpha)$$

$\downarrow$

Tuning $c_1 \sim c_2$:

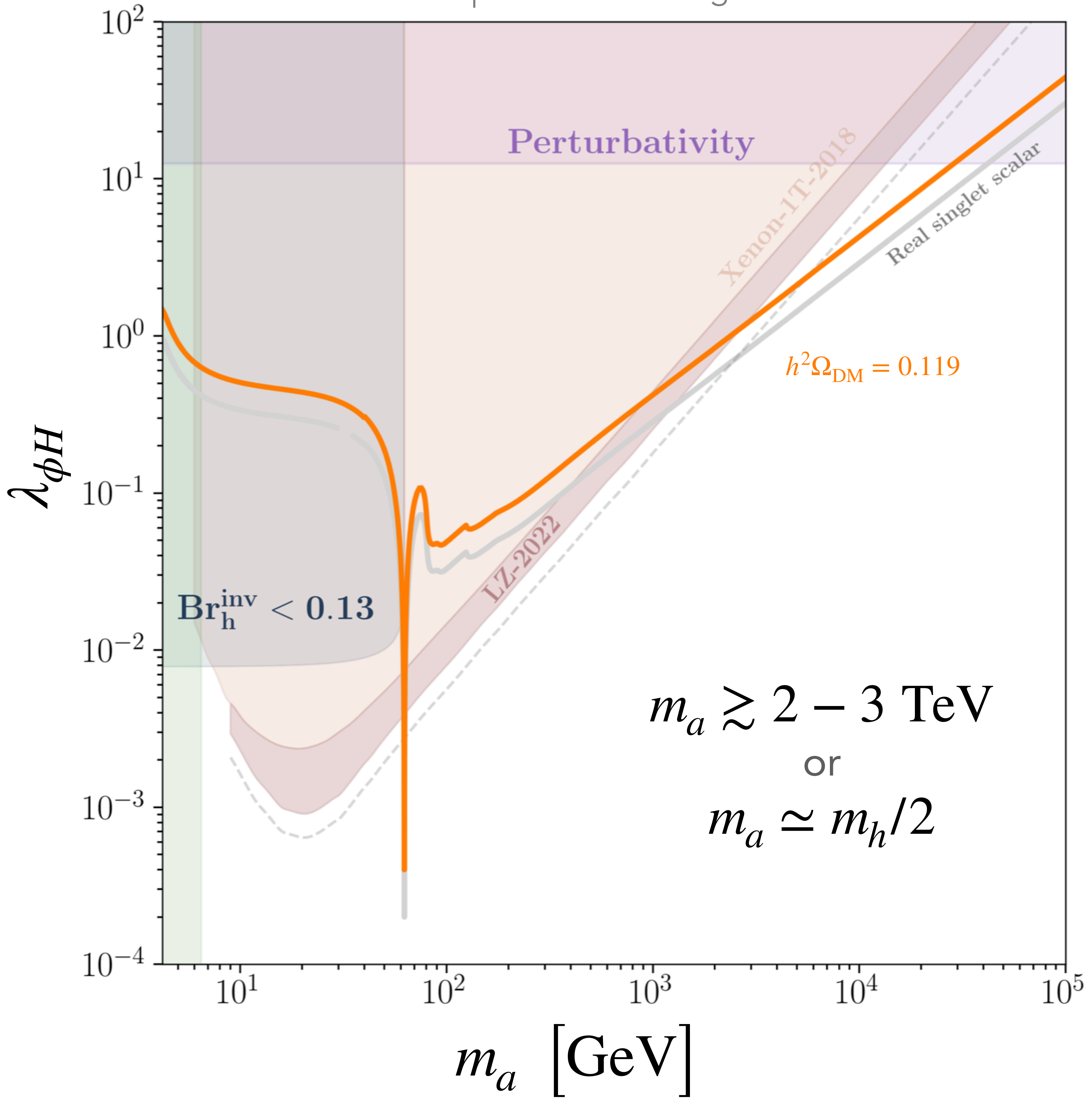
breaking of $\mathrm{U}(1)'_D$ at a scale $v' \ll v$

The (Abelian) Higgs is naturally light!

Accident dark matter

$$a_\pm a_\pm \leftrightarrow h\, h$$

Adapted from M. Frigerio et al. 2212.11918



$$a_\pm a_\pm \leftrightarrow \gamma_D \gamma_D$$

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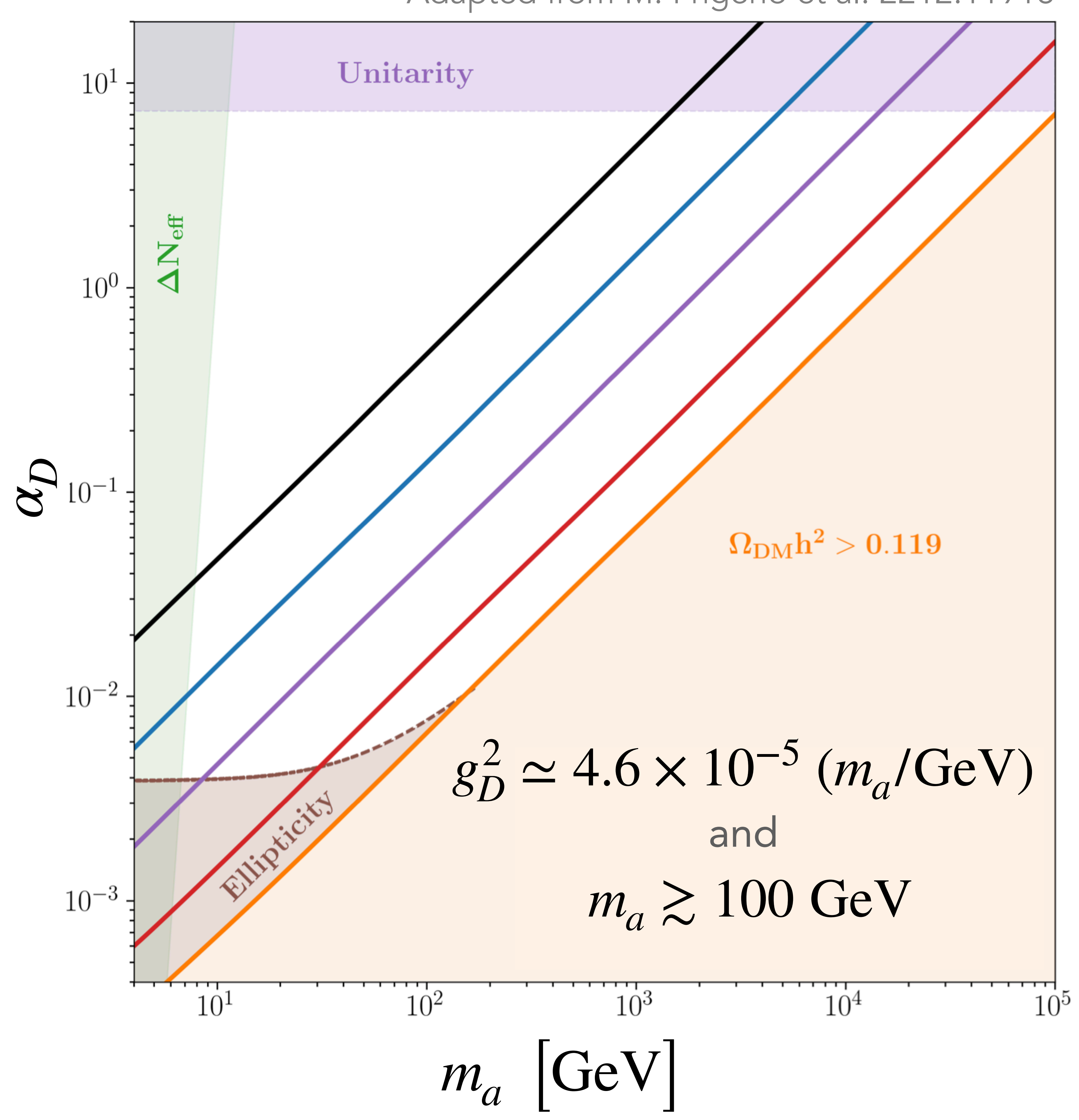


The SU(3) ten-plet

$$V = -\mu^2 S + \frac{1}{2}(\lambda S^2 + \delta A^a A^a) \longrightarrow$$ Invariant ONLY under $SU(3)_D \times U(1)_D$

- ESP: $SU(3)_D \times U(1)_D \longrightarrow U(1)_3 \times U(1)_8$ & 6 accidents
- Generic point: $SU(3)_D \times U(1)_D \longrightarrow I$ & 2 accidents

Scalar one-loop corrections $\longrightarrow$ The ESP is stabilised

The inflationary paradigm

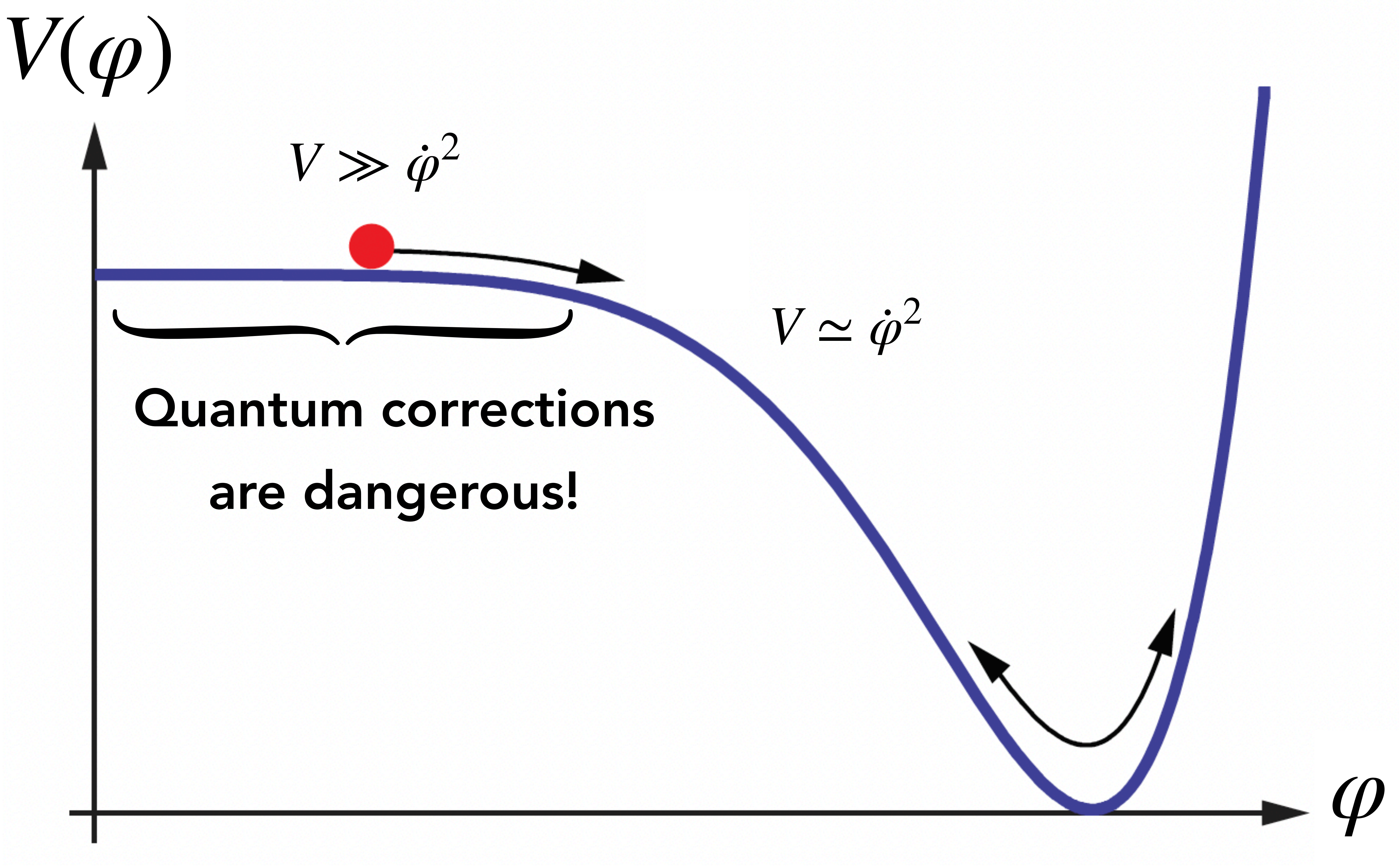
$$\begin{cases} \epsilon \equiv \dfrac{M_{\rm Pl}^2}{2}\left(\dfrac{V'}{V}\right)^2 \ll 1 \\ \eta \equiv M_{\rm Pl}^2 \dfrac{V''}{V} \ll 1 \end{cases}$$

$$\updownarrow$$

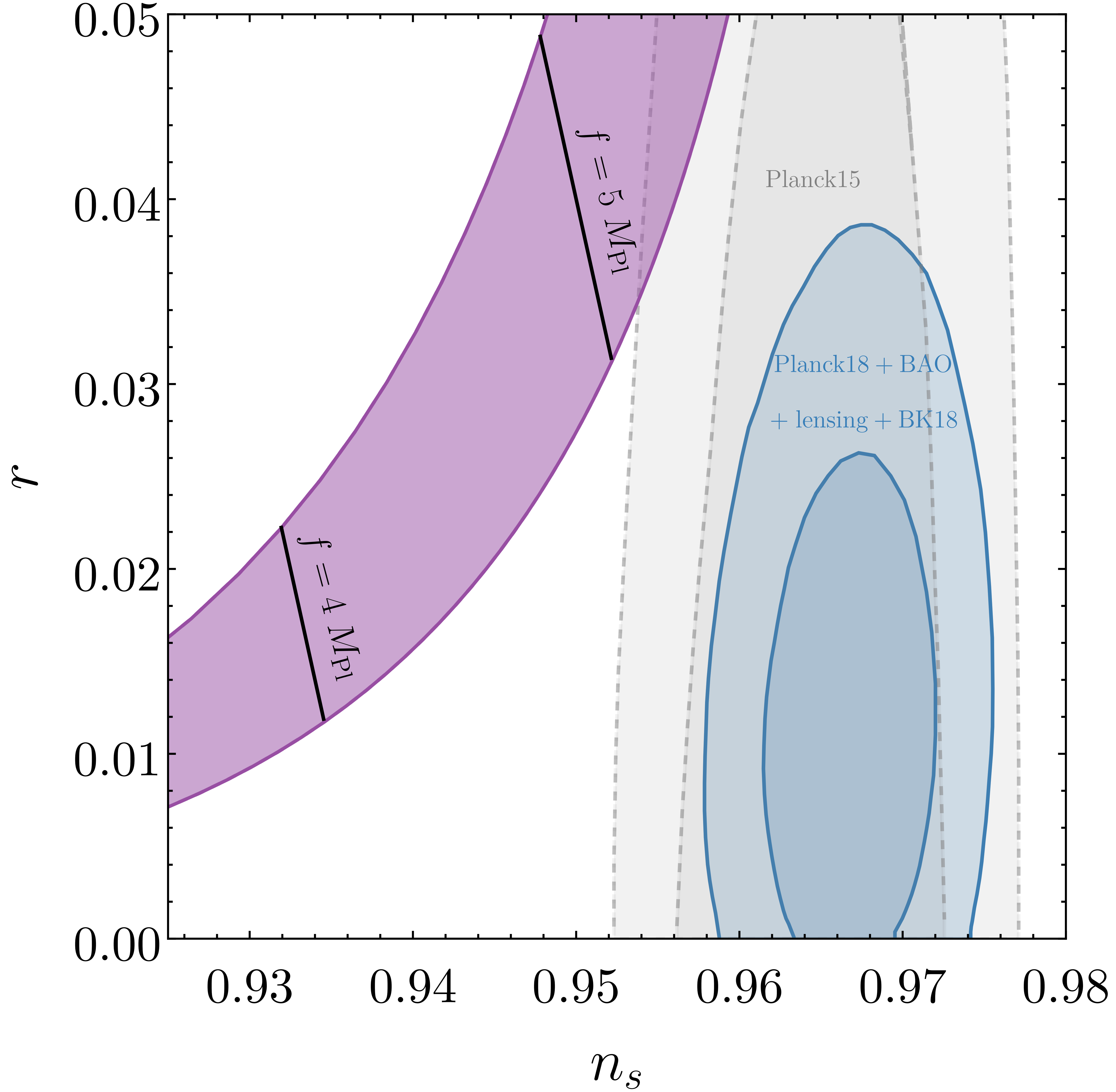
$$\delta\varphi \quad \Longrightarrow \quad P_s = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}, \quad r = \frac{P_t}{P_s}$$

CMB constrains $V(\varphi)$

"The Physics of Inflation", D. Baumann

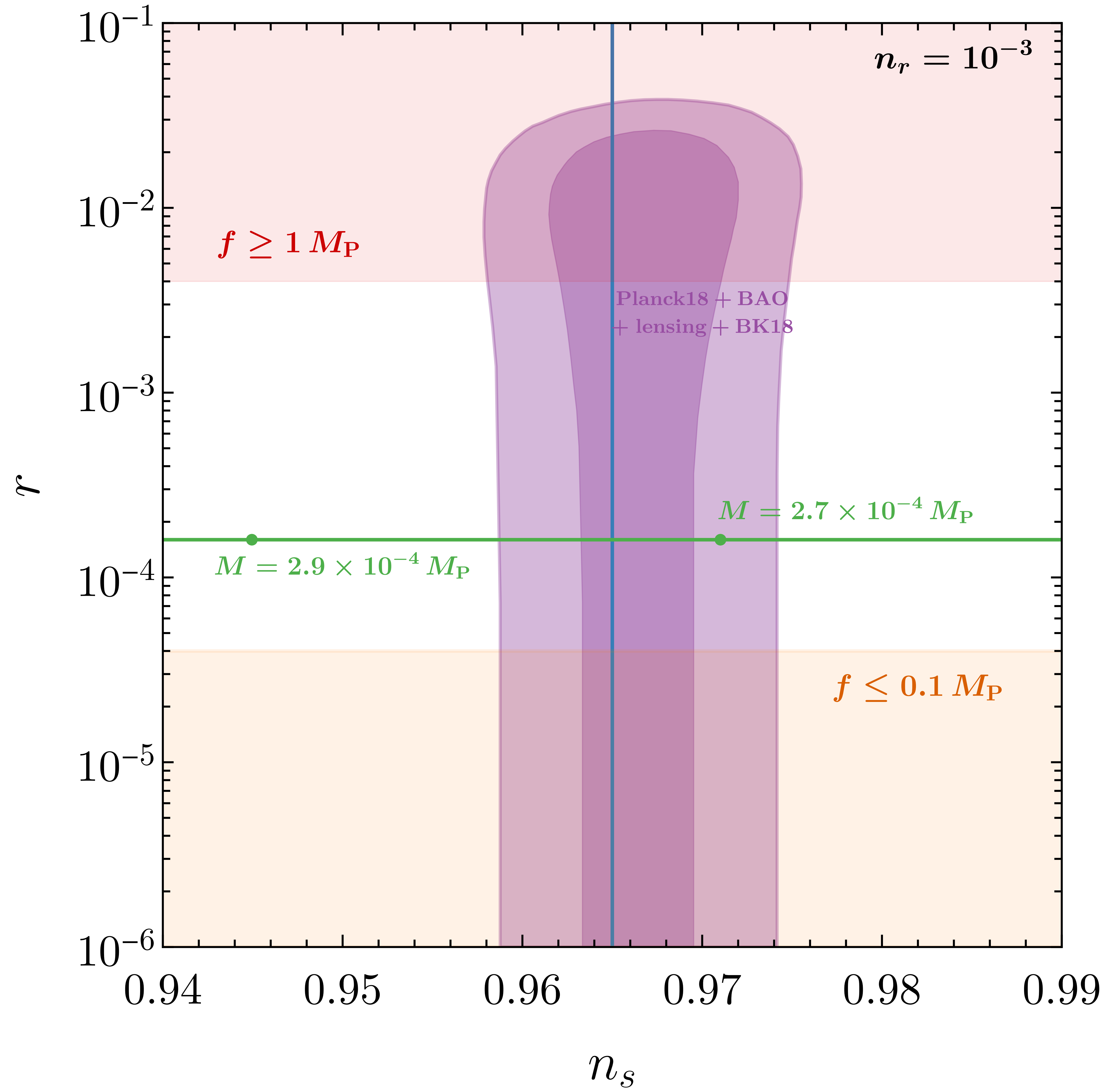


Natural inflation

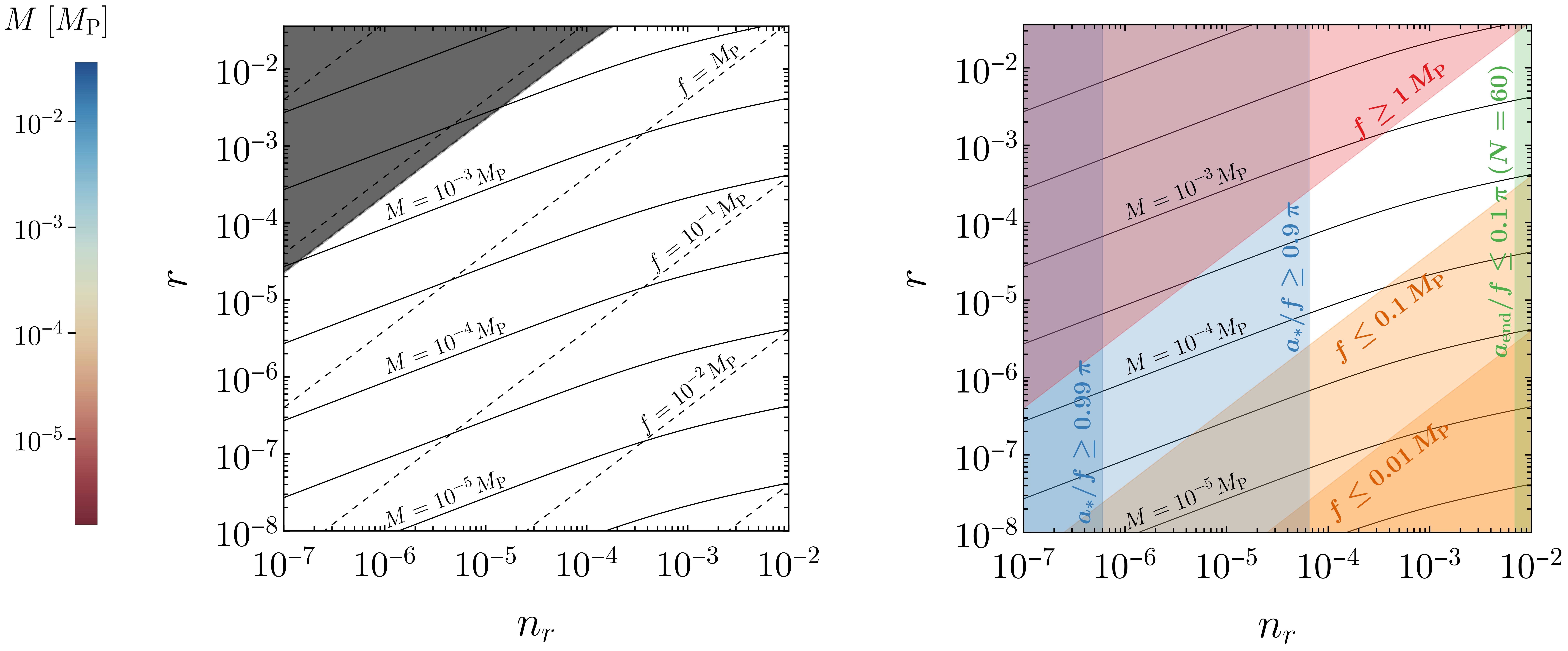


Accident inflation

CMB



Parameter Space



Tachyonic preheating

End of inflation: $m^2_{\chi^3} < 0$

Tachyonic Preheating

G. N. Felder et al. Phys. Rev. Lett. 87, 011601 (2001)

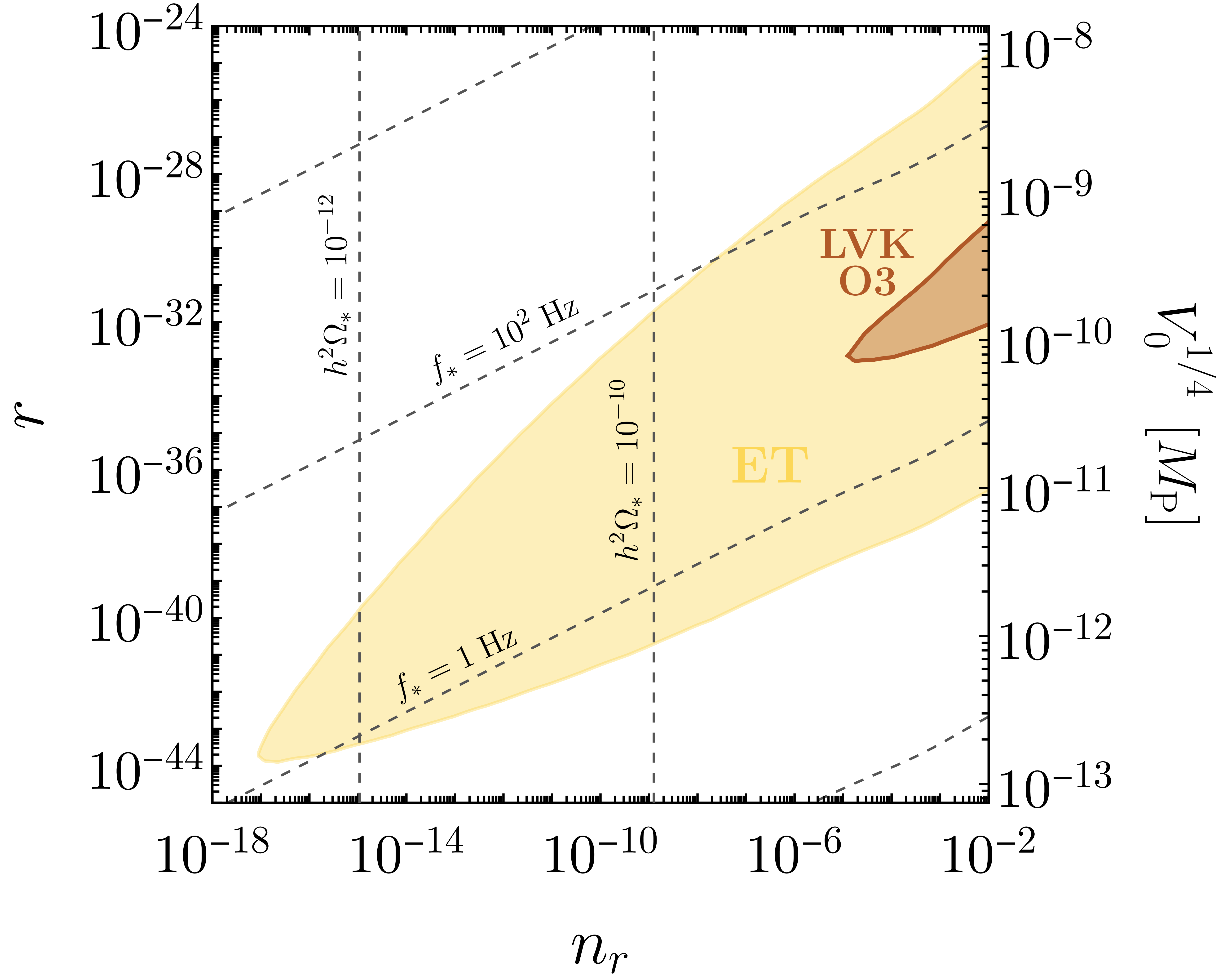
G. N. Felder et al. Phys. Rev. D 64, 123517 (2001)

Large "bubbly" inhomogeneities: $R_* \sim \dfrac{1}{k_*}$

$\Downarrow$

J. F. Dufaux et al.
Phys. Rev. D, vol. 76, p. 123517, 2007.

GWs: $$\begin{cases} f_* \simeq 4 \times 10^{10}\,\mathrm{Hz}\dfrac{k_*}{\rho_{\mathrm{inf}}^{1/4}} \\ h^2\Omega_* \simeq 10^{-6}\left(\dfrac{H_{\mathrm{inf}}}{k_*}\right)^2 \end{cases}$$



Accidental Inflation

"Real" Model

$$\phi \sim \mathbf{5}\,, \quad \chi \sim \mathbf{3}$$

$$G = SO(3)_D \times \mathbb{Z}_2^{(\phi)}$$

$$V = -\frac{1}{2}\mu_\phi^2\phi^2 - \frac{1}{2}\mu_\chi^2\chi^2 + \frac{\lambda_\phi}{4}(\phi^2)^2 + \frac{\lambda_\chi}{4}(\chi^2)^2 + \frac{\varepsilon}{4}\phi^2\chi^2 + \frac{\zeta}{4}\,T^a_{AC}T^b_{CB}\phi_A\phi_B\chi^a\chi^b$$

No Topological Defect Production

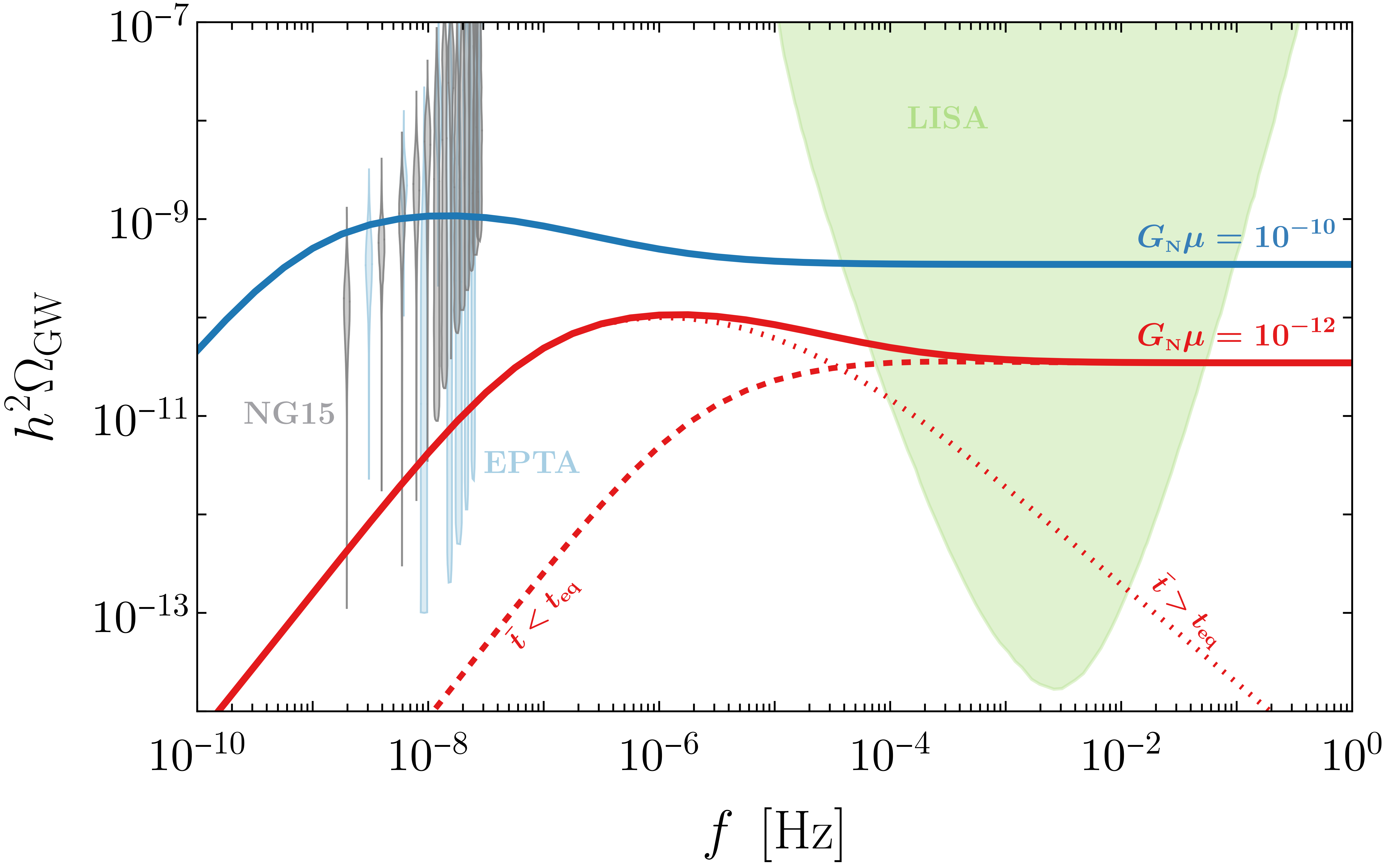
Cosmic Strings

Accidental $U(1)_\chi$ broken by $\begin{cases} \langle \phi \rangle = 0 \\ \langle \chi \rangle = v_\chi \end{cases} \Longrightarrow$ Stable Local Cosmic Strings

$$\mu = 2\pi v_\chi^2$$

$$(G\mu)^{\text{CMB}} \lesssim 10^{-7} \Longrightarrow V_0^{1/4} \lesssim \text{few} \times 10^{14}\,\text{GeV}$$

Cosmic Strings



Domain walls

$$V = -\frac{1}{2}\mu_\phi^2\phi^2 + \frac{\lambda_\phi}{4}(\phi^2)^2 - \mu_\chi^2\chi^*\chi + \lambda_\chi\left(\chi^*\chi\right)^2 + \delta\chi^{*2}\chi^2 + \frac{1}{2}\left(\kappa\chi^2\chi^2 + \mathrm{h.c.}\right) + \frac{\varepsilon}{2}\phi^2\left(\chi^*\chi\right) + \frac{\zeta}{2}T^a_{AC}T^b_{CB}\phi_A\phi_B\chi^{a^*}\chi^b$$

$$f_p \simeq 1.6 \times 10^{-7}\ \mathrm{Hz}\left(\frac{g_*(T_{\mathrm{ann}})}{100}\right)^{1/6}\frac{T_{\mathrm{ann}}}{\mathrm{GeV}}$$

$$h^2\Omega_{\mathrm{GW}}\left(f_p\right) \simeq 1.6 \times 10^{-5}\left(\frac{100}{g_*(T_{\mathrm{ann}})}\right)^{1/3}\frac{3}{32\pi}\,\tilde{\epsilon}\,\alpha_{\mathrm{ann}}^2\,\mathcal{S}(f/f_p)$$

$$\alpha_{\mathrm{ann}} \equiv \frac{\rho_{\mathrm{DW}}(t_{\mathrm{ann}})}{\rho_r(t_{\mathrm{ann}})} \simeq \frac{4}{3}C_d\,\mathcal{A}^2\frac{\sigma^2}{M_P^2\,\Delta V}$$

$$T_{\mathrm{ann}} = \left[\frac{45}{2\pi^2}\,\frac{g_*(T_{\mathrm{ann}})^{-1}}{C_d^2\,\mathcal{A}^2}\,\frac{M_{\mathrm{P}}^2\Delta V^2}{\sigma^2}\right]^{1/4}$$

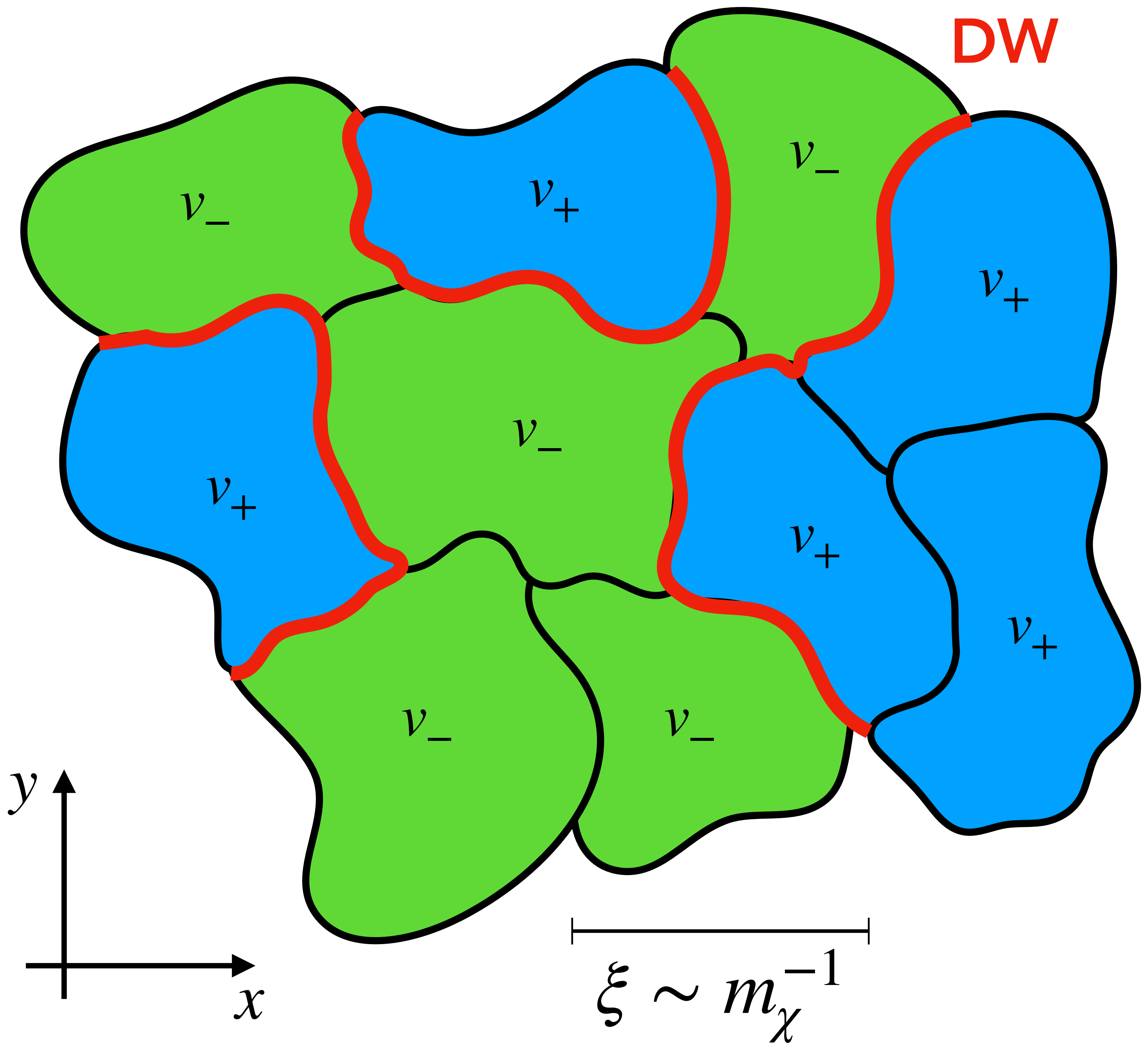
Domain walls

$\mathbb{Z}_4$- symmetric model

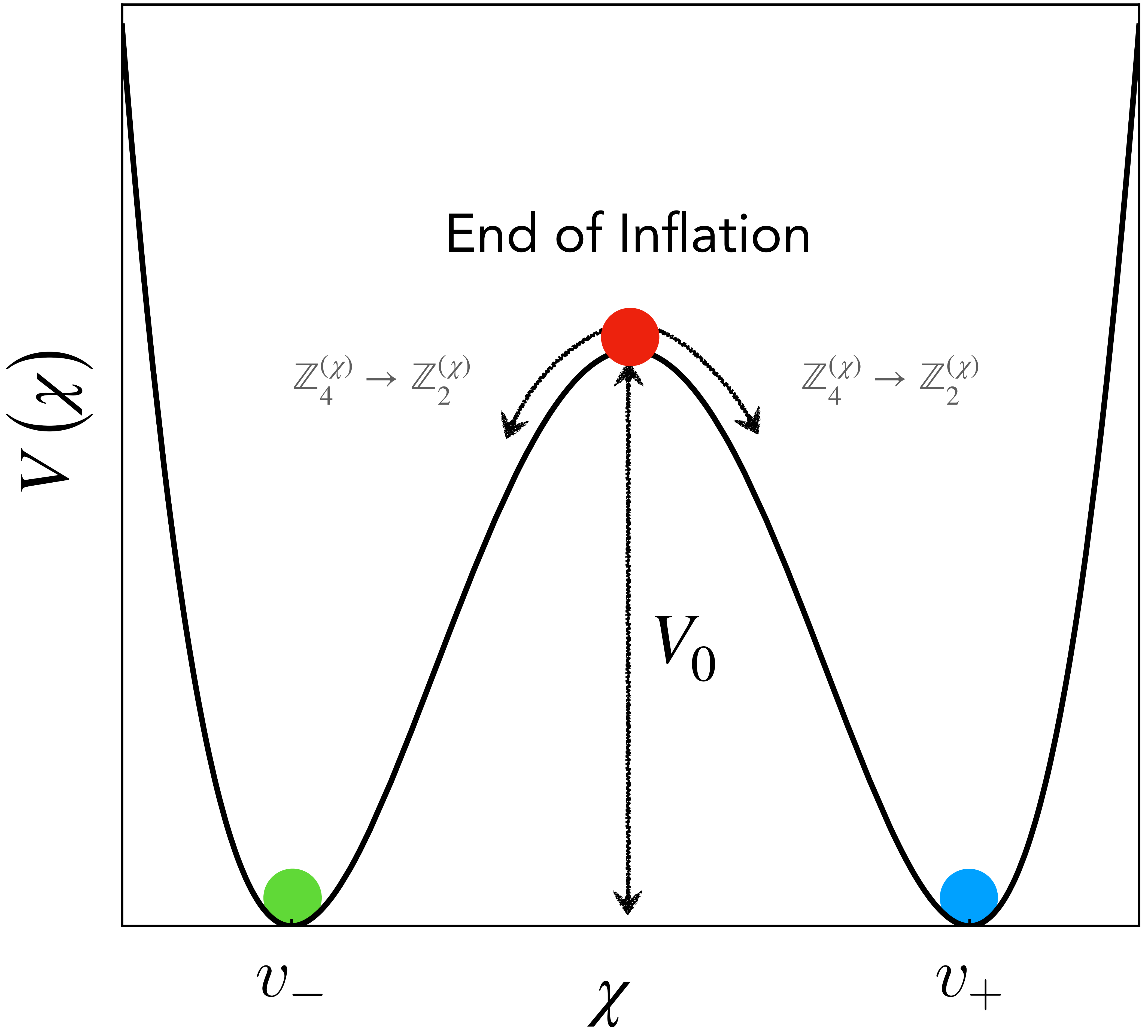
$\phi \sim \mathbf{5}, \chi \sim \mathbf{3}$

$\mathrm{SO}(3) \times \mathbb{Z}_4^{(\chi)} : \chi \to i\chi$

Physical space



$\longleftrightarrow$



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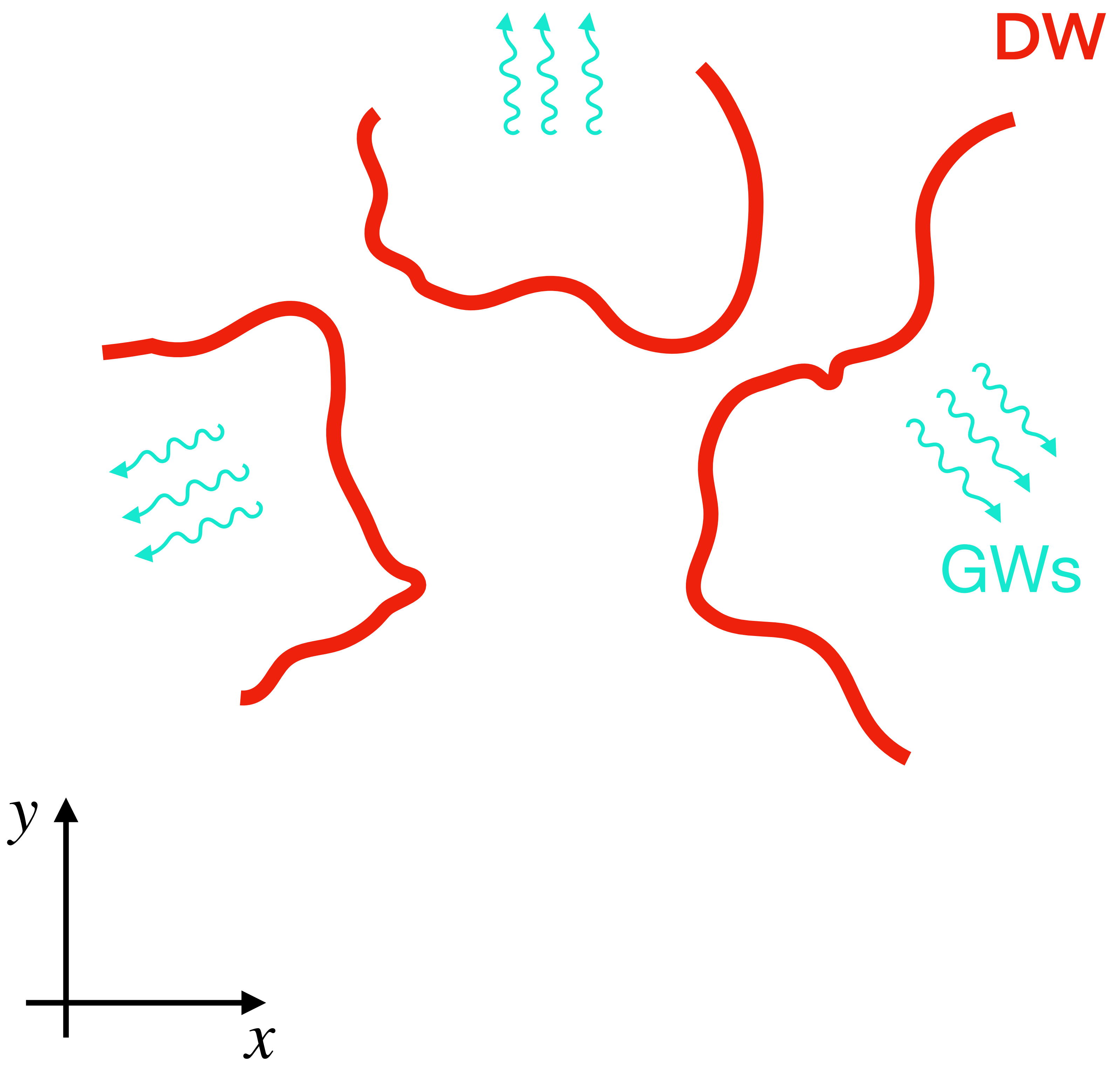

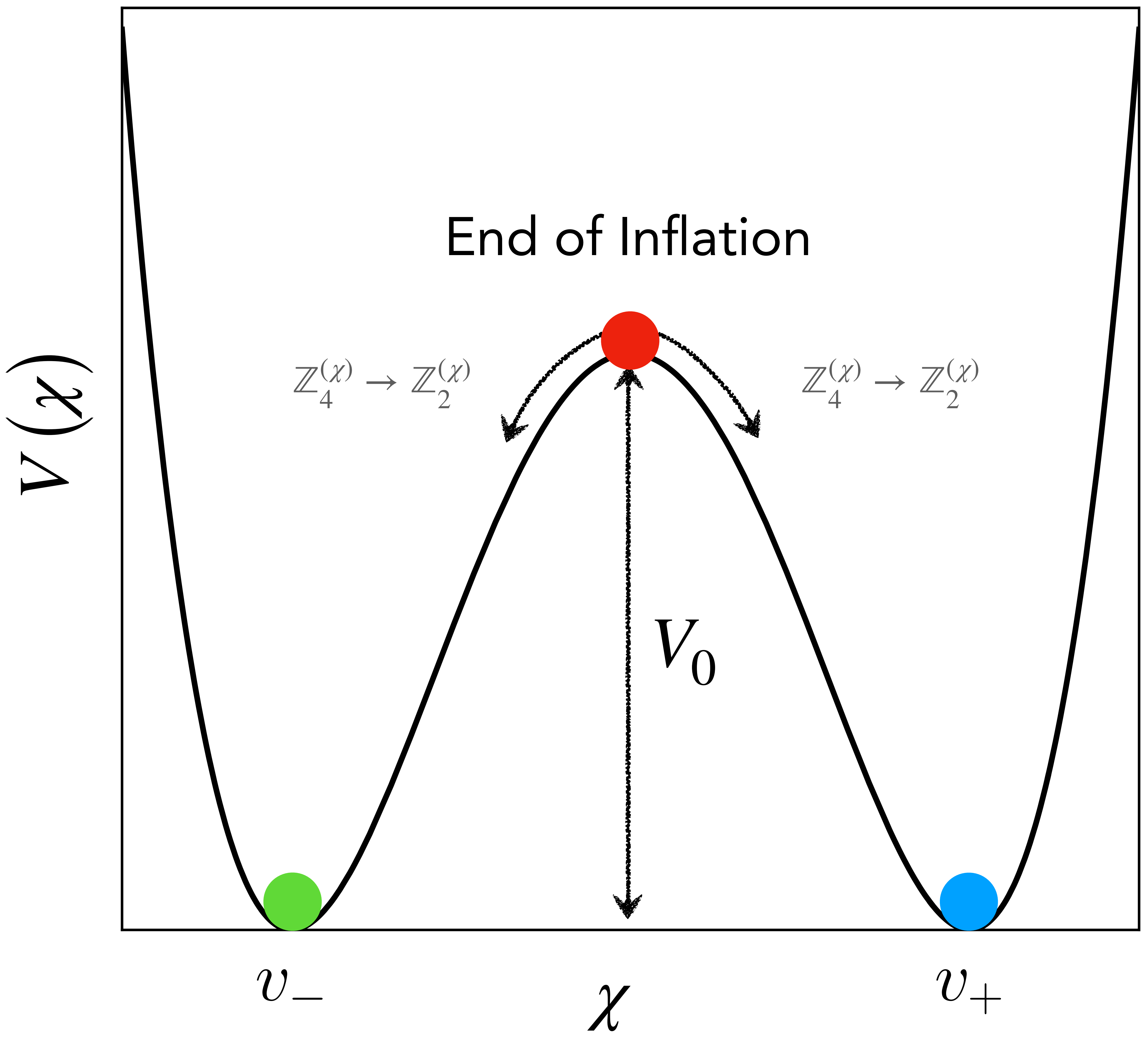

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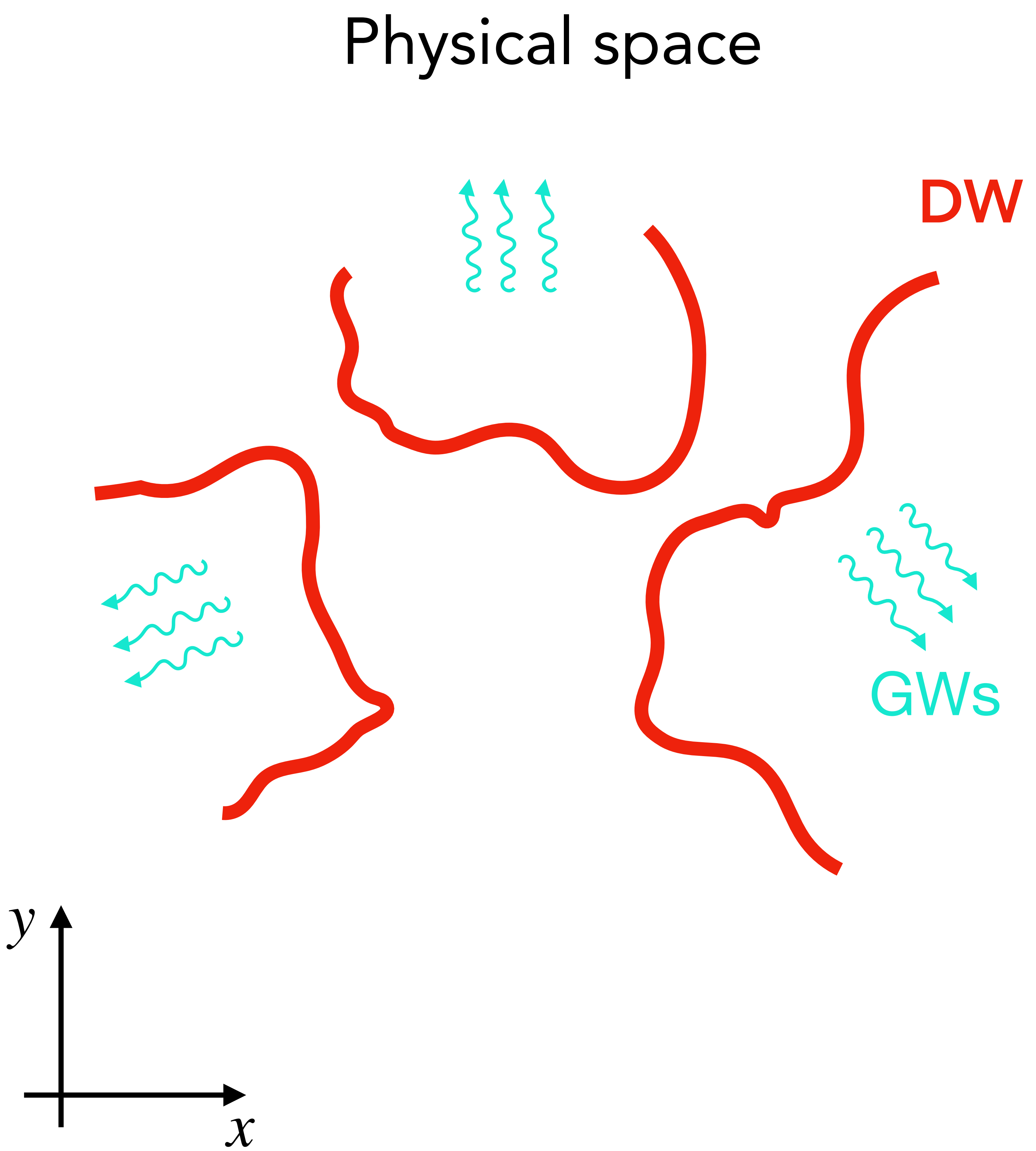

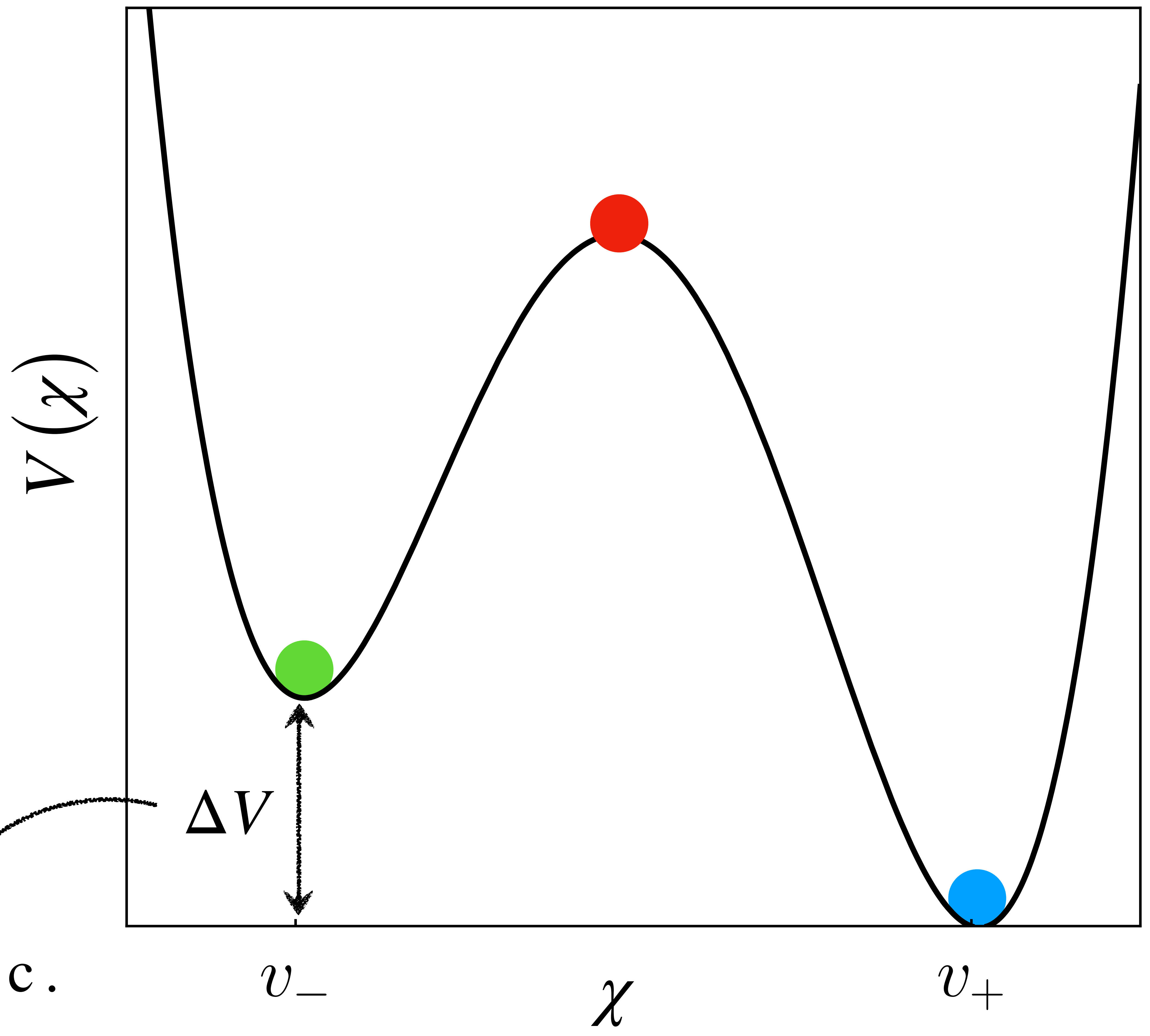

$i\, m_\chi^2 \chi\chi + \mathrm{h.c.}$

DWs emit GWs and annihilate!

Domain walls

Gravitational waves