PPP 2019, YITP, 29 Jul - 2 Aug 2019

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Fast-rolling relaxion

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1904.02545/hep-ph

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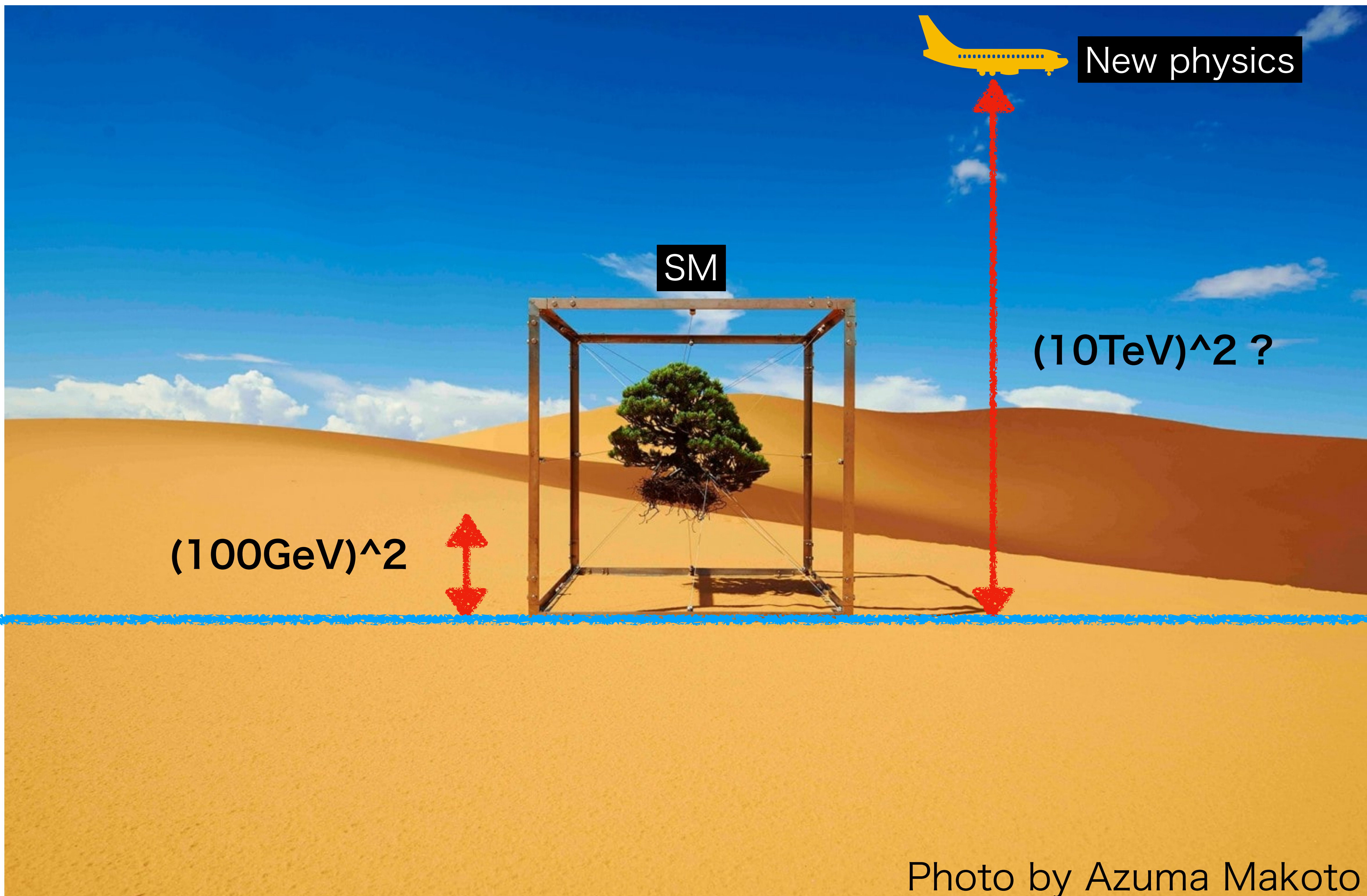
Introduction

Little Hierarchy



Dynamical solution

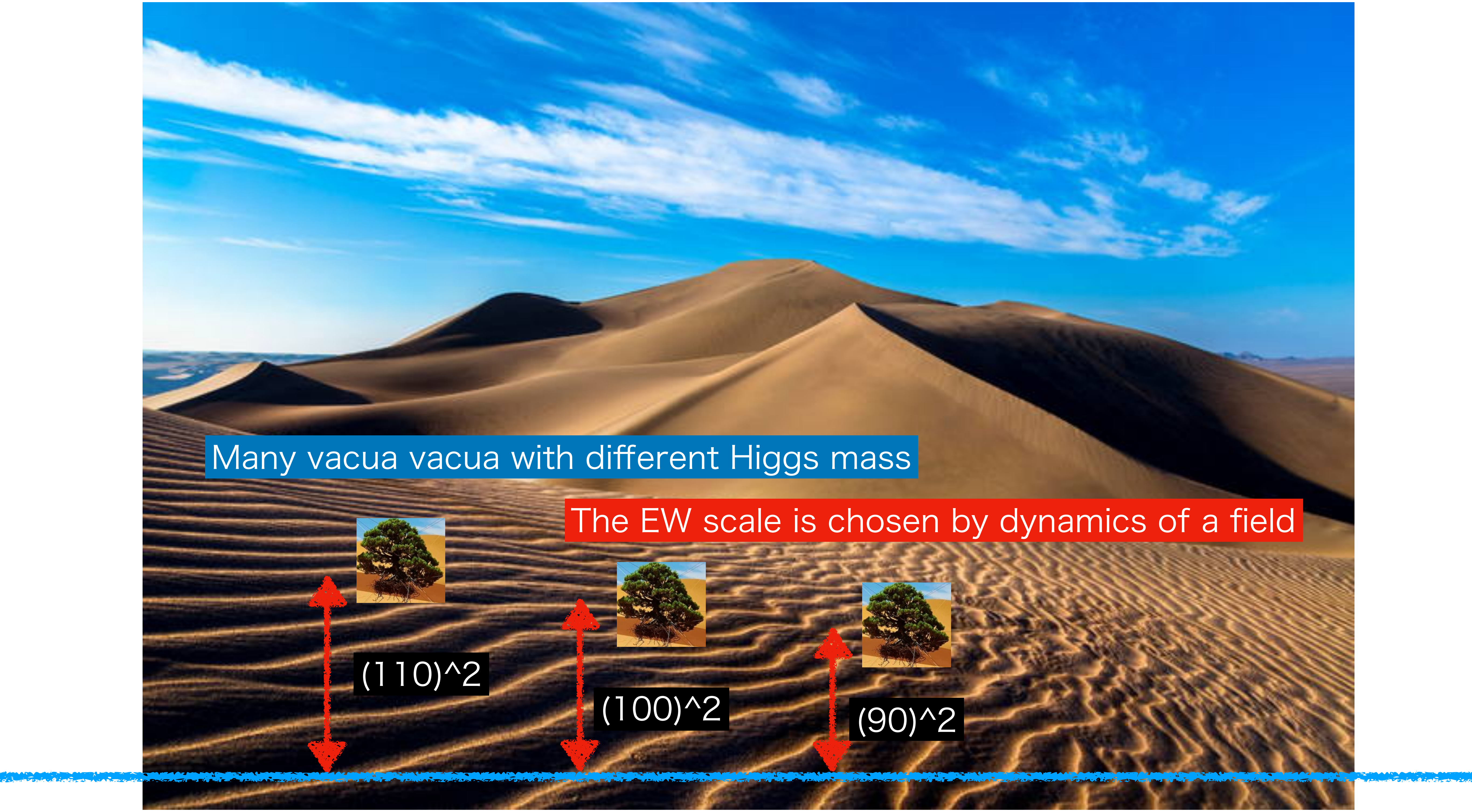
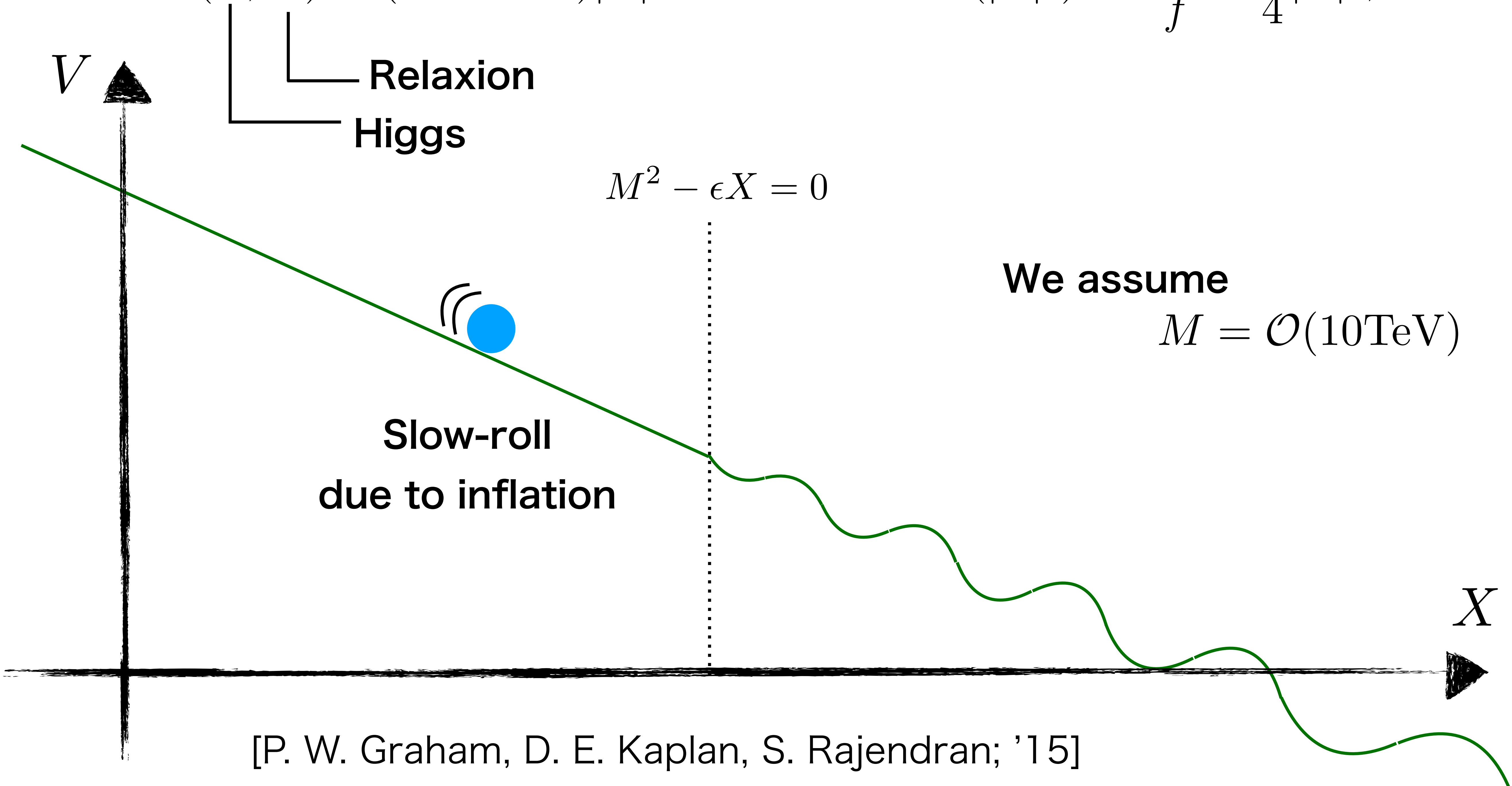


Photo by Naser Mizban

Relaxion mechanism

Higgs mass | Slope | Back reaction

$$V(\Phi, X) = (M^2 - \epsilon X)|\Phi|^2 - r\epsilon M^2 X + \Lambda^4(|\Phi|^2)\cos\frac{X}{f} + \frac{\lambda}{4}|\Phi|^4,$$

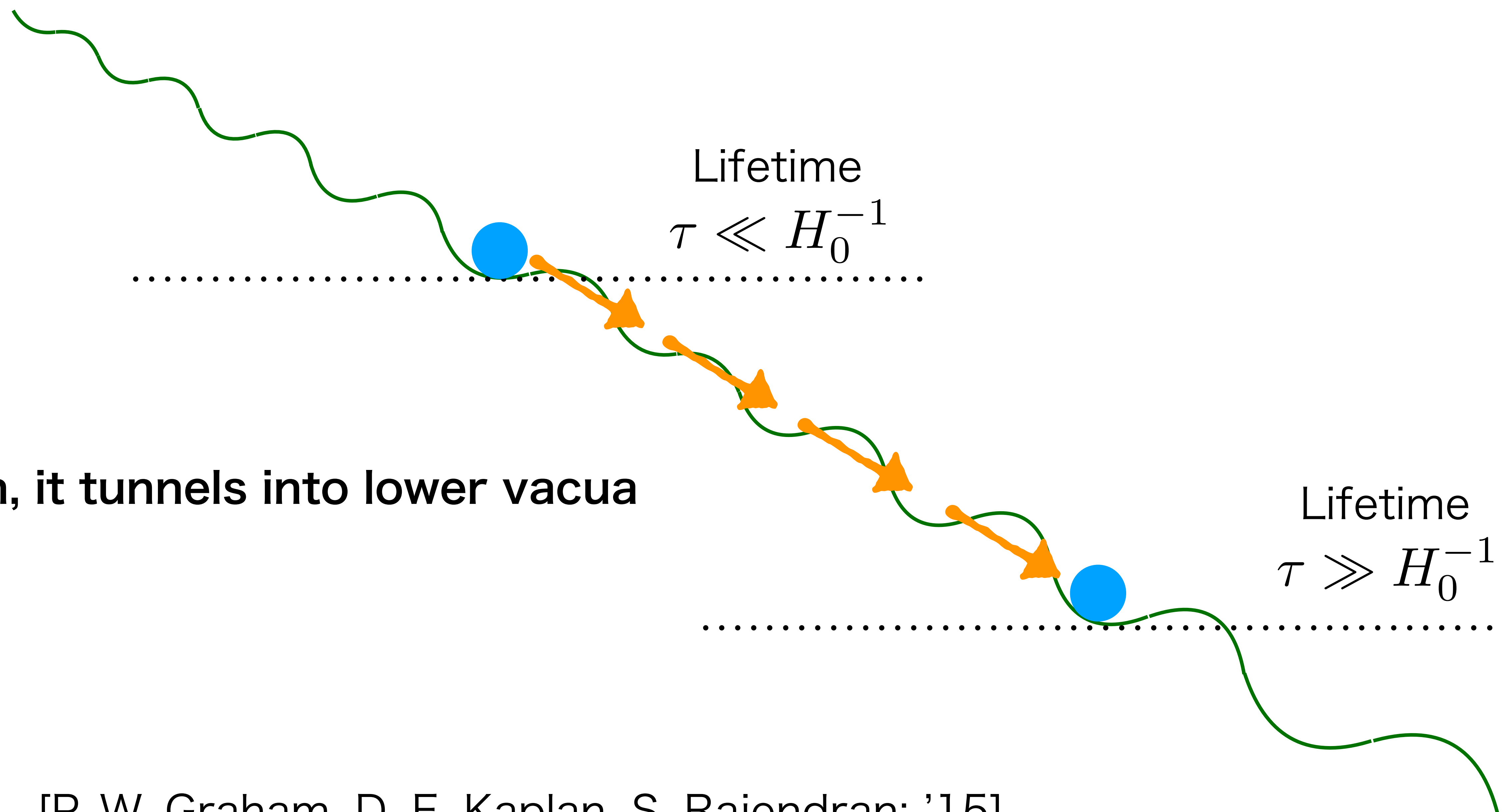


We assume
$M = \mathcal{O}(10\text{TeV})$

[P. W. Graham, D. E. Kaplan, S. Rajendran; ’15]

Quantum tunneling

The relaxion stops classically at $\dfrac{dV}{dX} = 0$



Then, it tunnels into lower vacua

[P. W. Graham, D. E. Kaplan, S. Rajendran; '15]

Timescale of tunneling

At the last tunneling, $\gamma \ll H_0^4$

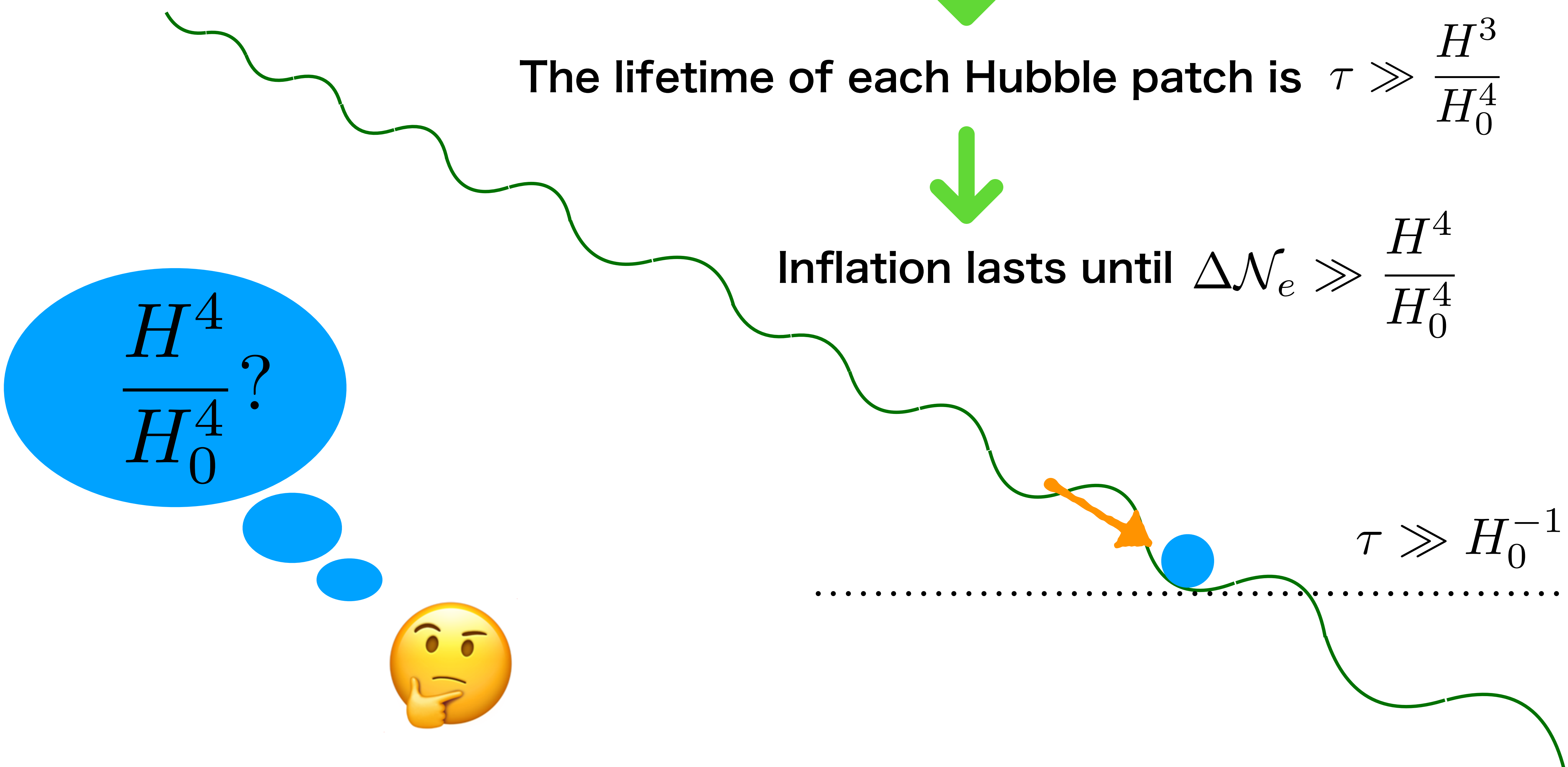
└ Bubble nucleation rate

↓

The lifetime of each Hubble patch is $\tau \gg \dfrac{H^3}{H_0^4}$

↓

Inflation lasts until $\Delta\mathcal{N}_e \gg \dfrac{H^4}{H_0^4}$



Too large e-folds

$$\mathcal{N}_e \gg \frac{H^4}{H_0^4} \simeq 10^{156} \left(\frac{H}{1\ \mathrm{MeV}} \right)^4$$

It is argued that a too large number of e-folds will cause problems in inflation sector

e.g.) [K. Choi, S. H. Im; ’16]

To avoid fine-tuning, we need $\mathcal{N}_e \lesssim 10^{24}$ for slow-roll inflation

(in the context of scanning time)

[H. Matsui, F. Takahashi; ’18, K. Dimopoulos ’18,$\cdots$]

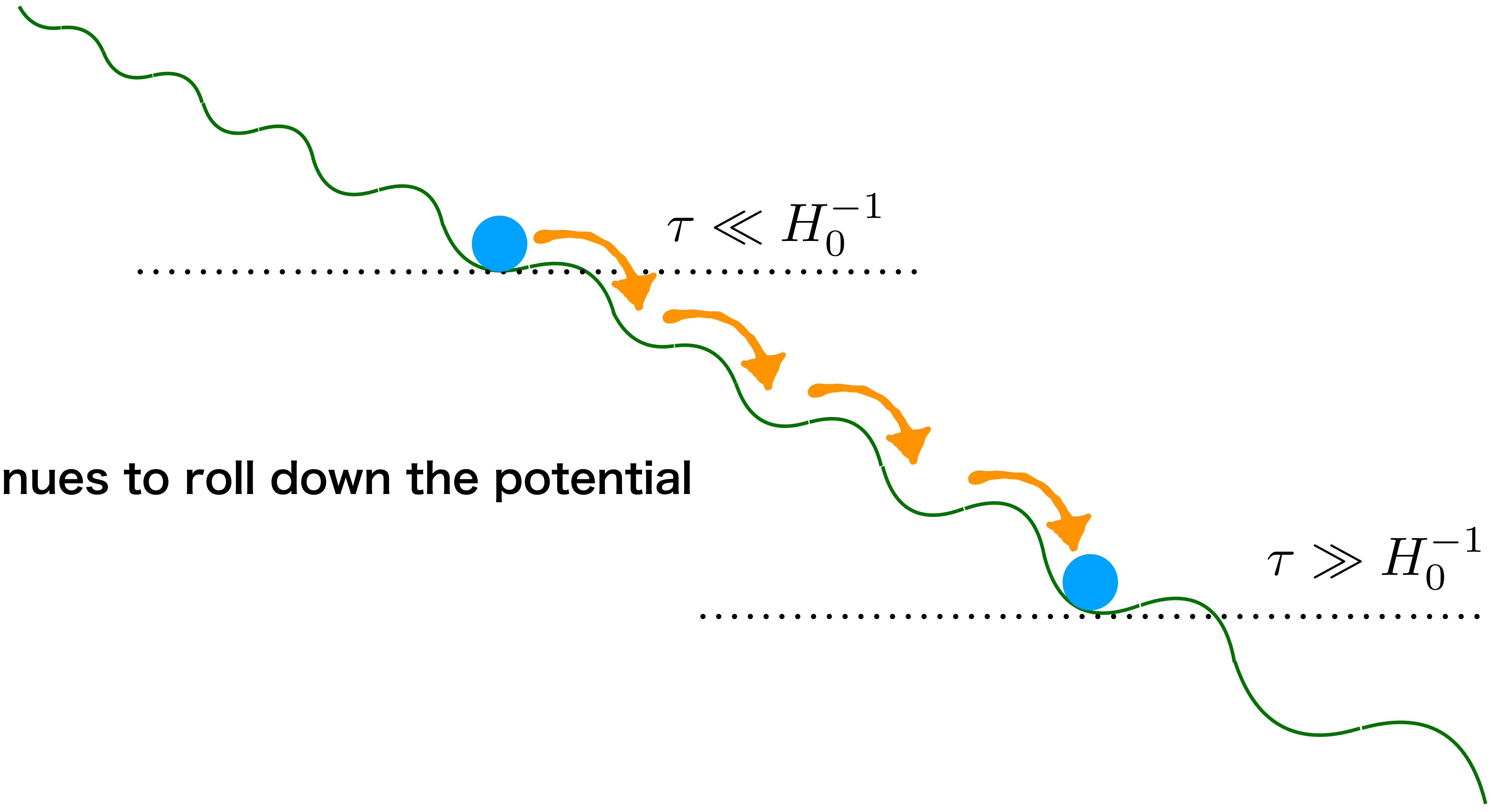
Eternal inflation is generically incompatible with the (refined) de Sitter swampland conjecture

+ Why not multiverse?

Fast-rolling relaxion

Fast-roll

The relaxion DOES NOT stop classically at $\dfrac{dV}{dX} = 0$



It continues to roll down the potential

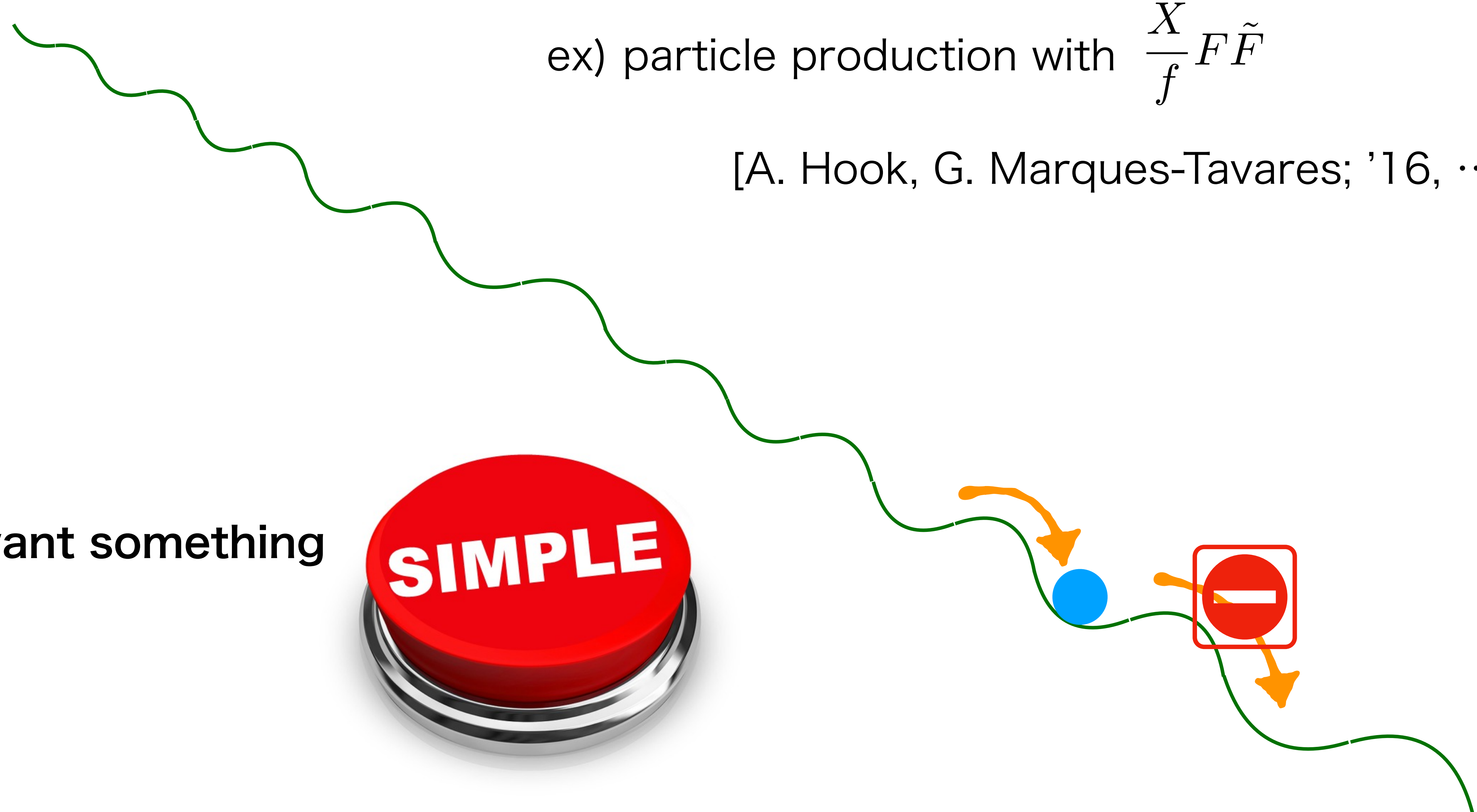
Stopping mechanism

We need another stopping mechanism

ex) particle production with $\frac{X}{f} F\tilde{F}$

[A. Hook, G. Marques-Tavares; '16, ⋯]

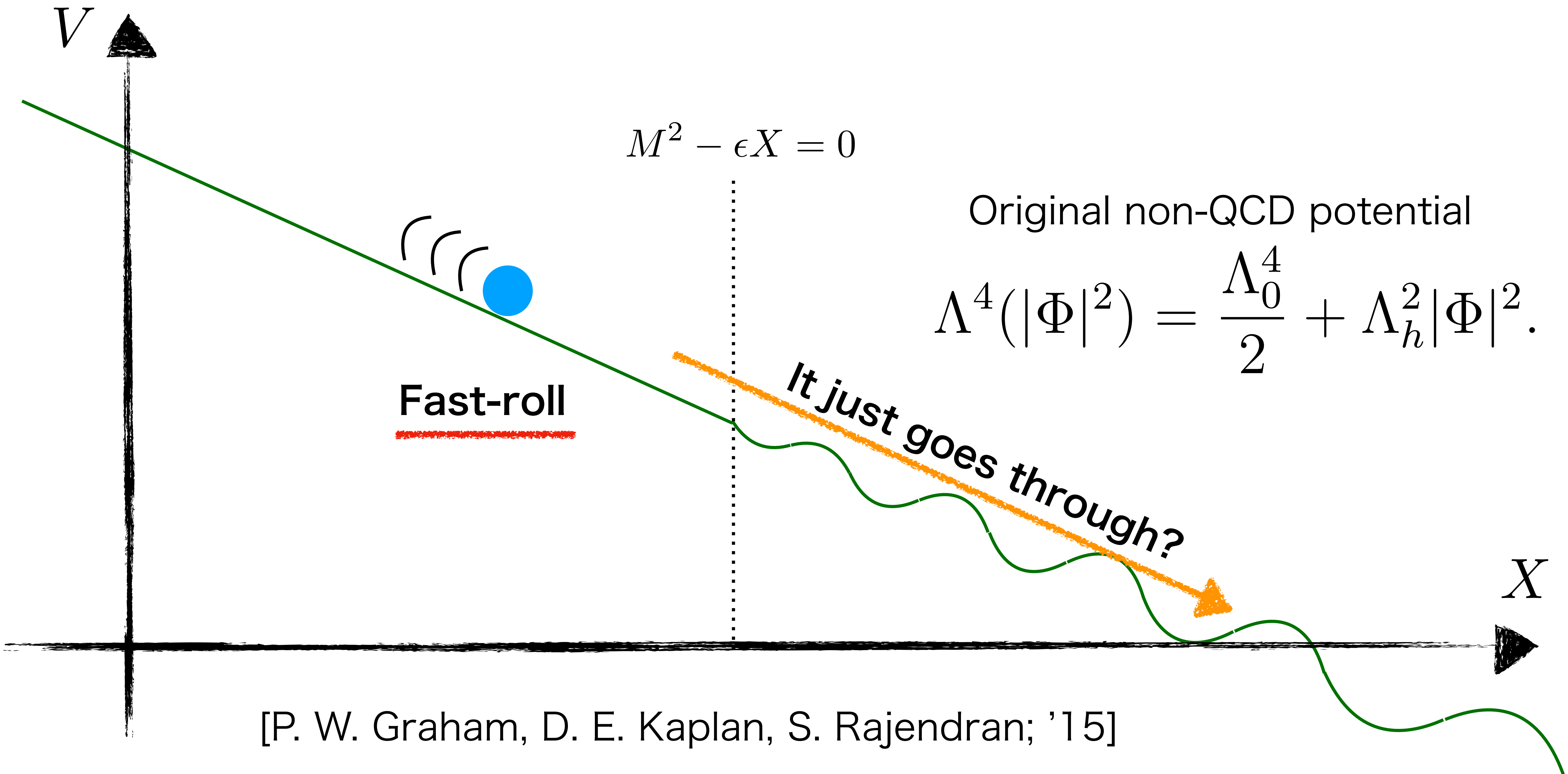
But, we want something



Model

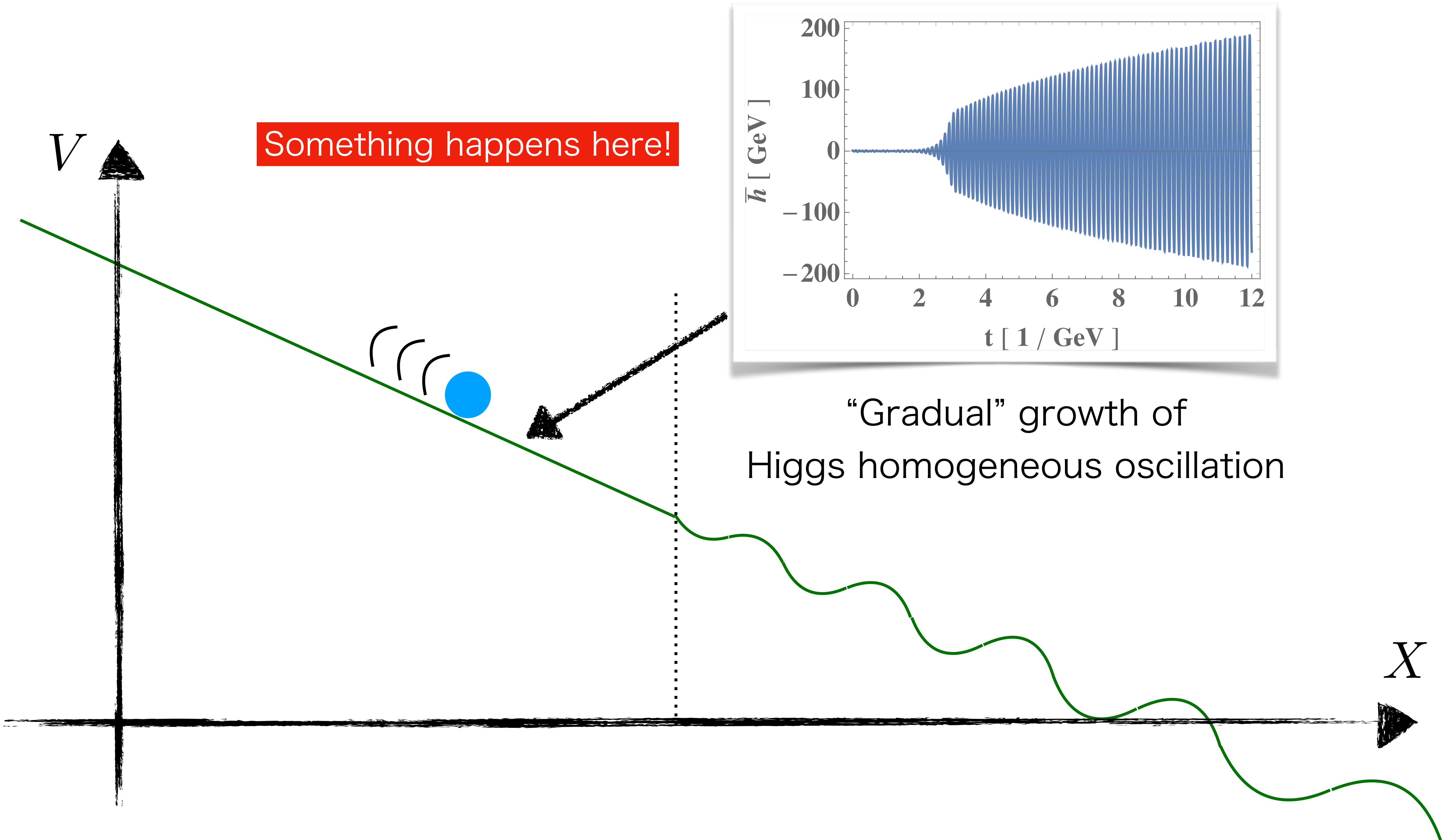
No extension!

$$V(\Phi, X) = (M^2 - \epsilon X)|\Phi|^2 - r\epsilon M^2 X + \Lambda^4(|\Phi|^2)\cos\frac{X}{f} + \frac{\lambda}{4}|\Phi|^4,$$



[P. W. Graham, D. E. Kaplan, S. Rajendran; '15]

Higgs homogeneous oscillation



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Edge solution

Equations of motion

$$\ddot{\bar{X}} + 3H\dot{\bar{X}} = \epsilon\left(rM^2 + \frac{\bar{h}^2}{2}\right) + \frac{\cancel{\Lambda_0^4} + \Lambda_h^2\bar{h}^2}{2f}\sin\frac{\bar{X}}{f} \,,$$

$$\ddot{\bar{h}} + 3H\dot{\bar{h}} = -(M^2 - \epsilon\bar{X})\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2\bar{h}\cos\frac{\bar{X}}{f} \,,$$

Terminal velocity

$$\dot{\bar{X}} \simeq \frac{\epsilon r M^2}{3H}$$

$$\ddot{\bar{h}} + 3H\dot{\bar{h}} \simeq -(m^2 - \delta m^2 t)\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2 h\cos\omega t$$

$$\delta m^2 = f\omega = \frac{\epsilon r M^2}{3H}$$

$$m^2 = M^2 - \epsilon\bar{X}(0)$$

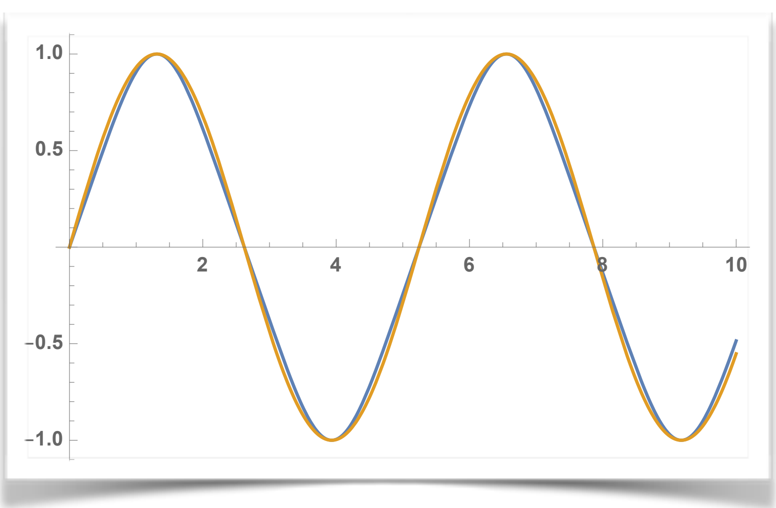
$\bar{X}$: Relaxion homogeneous mode

$\bar{h}$: Higgs homogeneous mode

Oscillatory solution

$$\ddot{\bar{h}} + \cancel{3H\dot{\bar{h}}} \simeq -(m^2 - \cancel{\delta m^2 t})\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \cancel{\Lambda_h^2 \bar{h}\cos\omega t}$$

$$\bar{h}(t) = \mathcal{A}\,\mathrm{sn}\left(\sqrt{m^2 + \frac{\lambda}{8}\mathcal{A}^2}t, -\frac{\mathcal{A}^2\lambda}{8m^2 + \mathcal{A}^2\lambda}\right)$$



$$\simeq \mathcal{A}\sin(\overline{m}(\mathcal{A})t) \ ,$$

$\mathcal{A}$: Amplitude of oscillation

Effective mass

$$\overline{m}^2(\mathcal{A}) = \frac{\pi^2(8m^2 + \mathcal{A}^2\lambda)}{32\left[K\left(-\frac{\mathcal{A}^2\lambda}{8m^2+\mathcal{A}^2\lambda}\right)\right]^2} \simeq m^2 + \frac{3}{16}\lambda\mathcal{A}^2$$

Parametric resonance

$$\ddot{\bar{h}} + 3H\dot{\bar{h}} \simeq -(m^2 - \delta m^2 t)\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2 h \cos\omega t$$

$$\overline{m}^2(\mathcal{A})\bar{h}$$

Mathieu equation

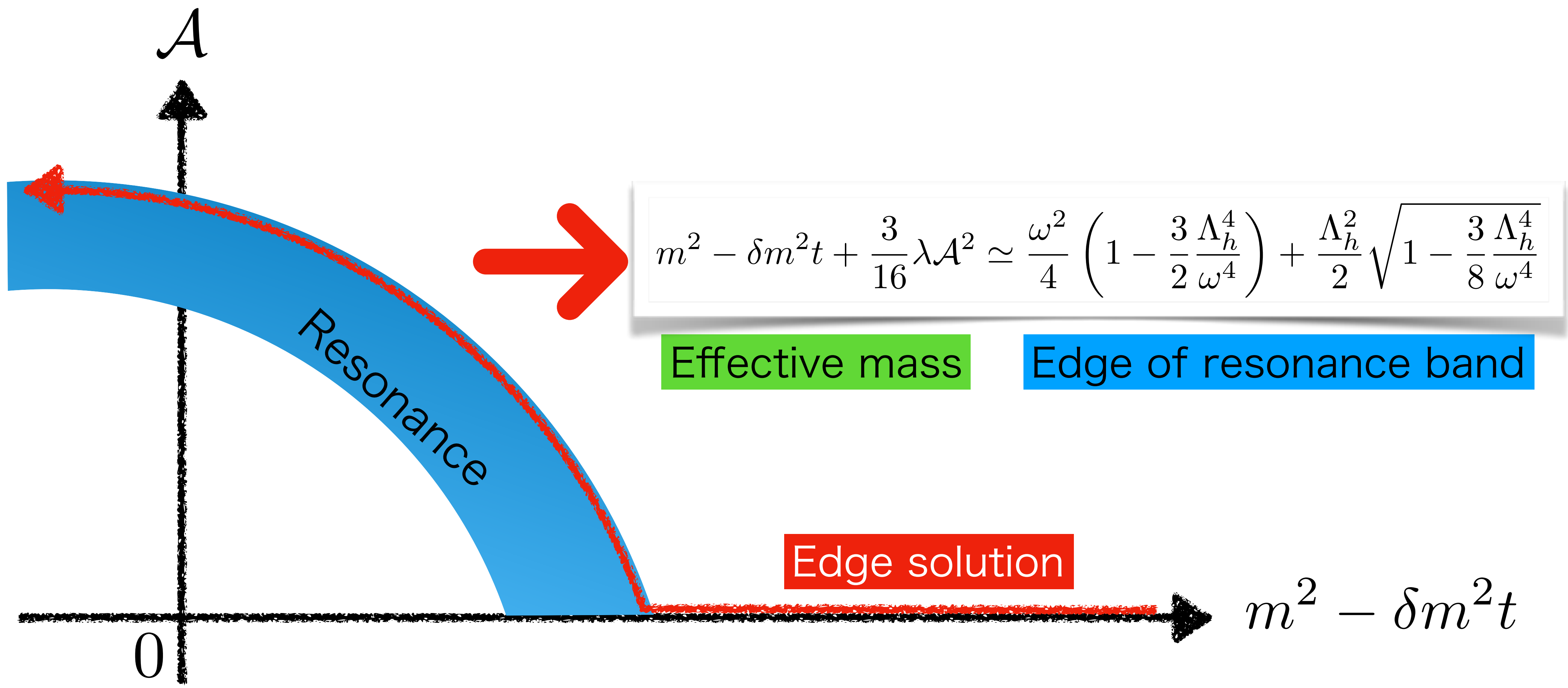
$$\ddot{\bar{h}} \simeq -\overline{m}^2(\mathcal{A})\bar{h} - \Lambda_h^2 h \cos\omega t$$

Exponential growth of the amplitude occurs when

$$\frac{\omega^2}{4}\left(1 - \frac{3}{2}\frac{\Lambda_h^4}{\omega^4}\right) - \frac{\Lambda_h^2}{2}\sqrt{1 - \frac{3}{8}\frac{\Lambda_h^4}{\omega^4}} \lesssim \overline{m}^2(\mathcal{A}) \lesssim \frac{\omega^2}{4}\left(1 - \frac{3}{2}\frac{\Lambda_h^4}{\omega^4}\right) + \frac{\Lambda_h^2}{2}\sqrt{1 - \frac{3}{8}\frac{\Lambda_h^4}{\omega^4}}$$

Edge solution

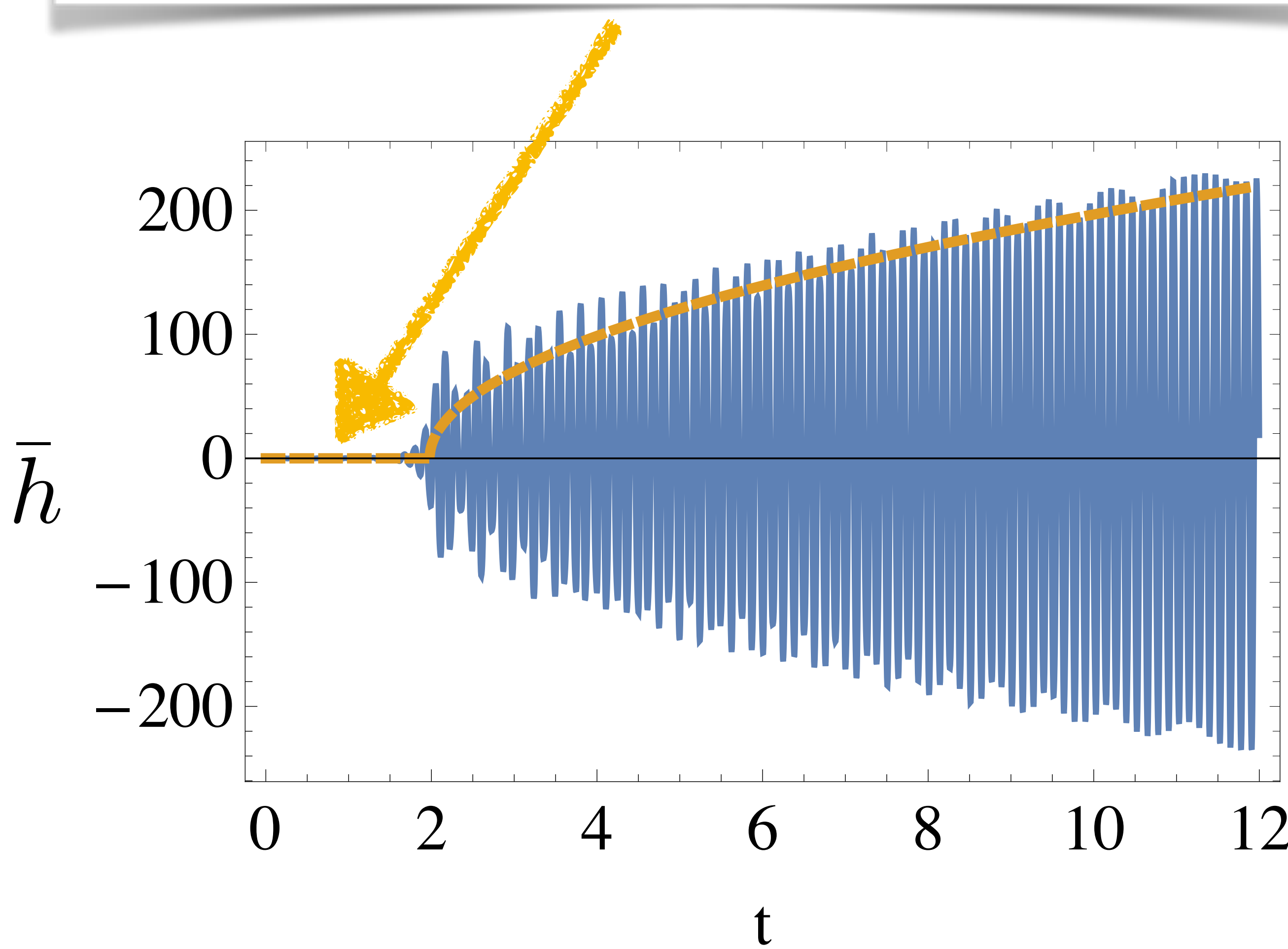
$$\ddot{\bar{h}} + \cancel{3H\dot{\bar{h}}} \simeq -(m^2 - \underline{\delta m^2 t})\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2 h \cos\omega t$$



Numerical check

$$\ddot{\bar{h}} + \cancel{3H\dot{\bar{h}}} \simeq -(m^2 - \delta m^2 t)\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2 h \cos\omega t$$

$$m^2 - \delta m^2 t + \frac{3}{16}\lambda \mathcal{A}^2 \simeq \frac{\omega^2}{4}\left(1 - \frac{3}{2}\frac{\Lambda_h^4}{\omega^4}\right) + \frac{\Lambda_h^2}{2}\sqrt{1 - \frac{3}{8}\frac{\Lambda_h^4}{\omega^4}}$$

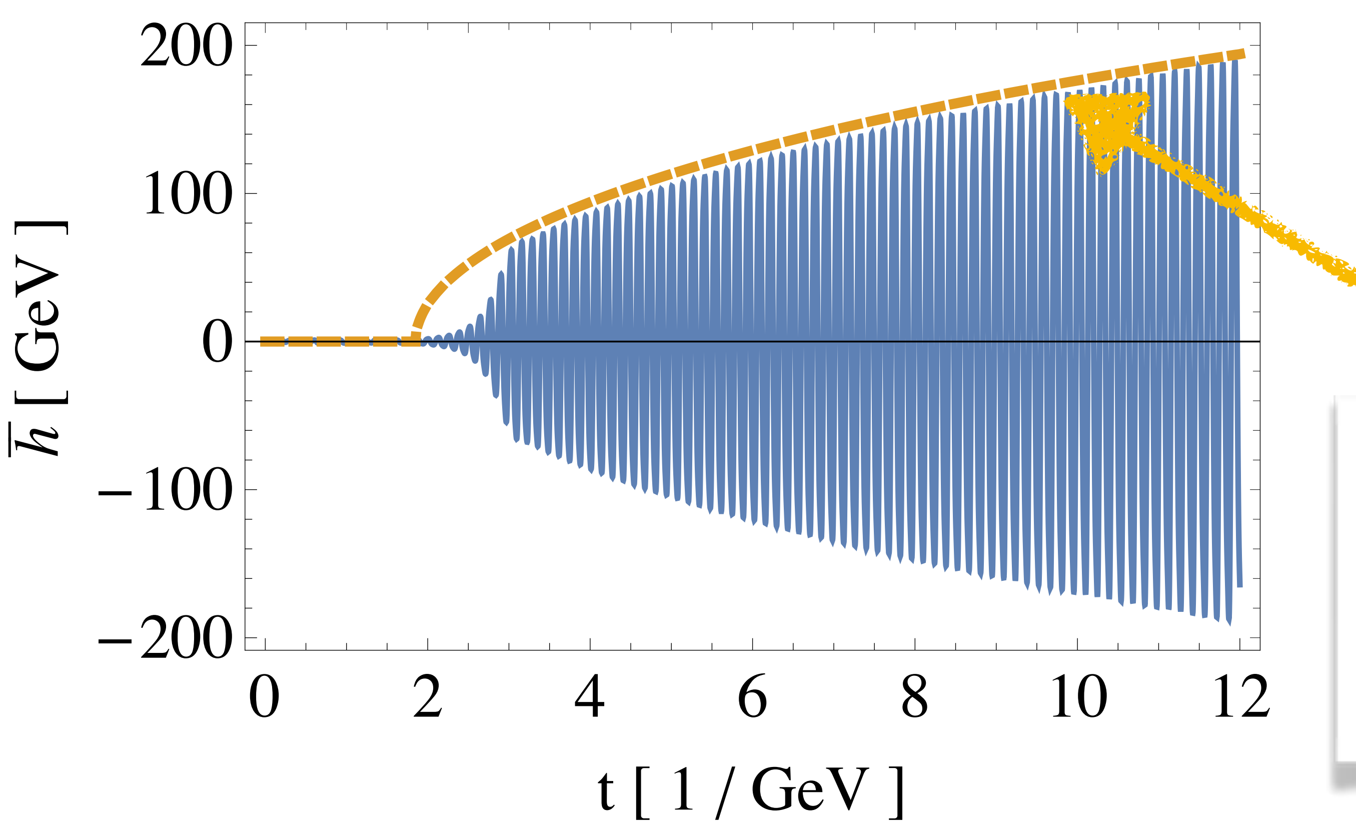


Edge solution (full)

Hubble friction, Back reactions, ⋯

$$\ddot{\bar{X}} + 3H\dot{\bar{X}} = \epsilon\left(rM^2 + \frac{\bar{h}^2}{2}\right) + \frac{\Lambda_0^4 + \Lambda_h^2\bar{h}^2}{2f}\sin\frac{\bar{X}}{f} \; ,$$

$$\ddot{\bar{h}} + 3H\dot{\bar{h}} = -(M^2 - \epsilon\bar{X})\bar{h} - \frac{\lambda}{4}\bar{h}^3 - \Lambda_h^2\bar{h}\cos\frac{\bar{X}}{f} \; ,$$



Analytic expression

$$m_\Phi^2 + \frac{3\lambda}{16}\mathcal{A}_h^2 \simeq \frac{\omega_X^2}{4} + \frac{\Lambda_h^2}{2} - \frac{\Lambda_h^2(32\Lambda_0^4 + 17\Lambda_h^2\mathcal{A}_h^2)}{128f^2\omega_X^2} - \frac{(8\Lambda_h^2 - 3\lambda\mathcal{A}_h^2)(8\Lambda_h^2 - \lambda\mathcal{A}_h^2)}{512\omega_X^2} - \frac{9\omega_X^2}{4\Lambda_h^2}H^2 \; ,$$

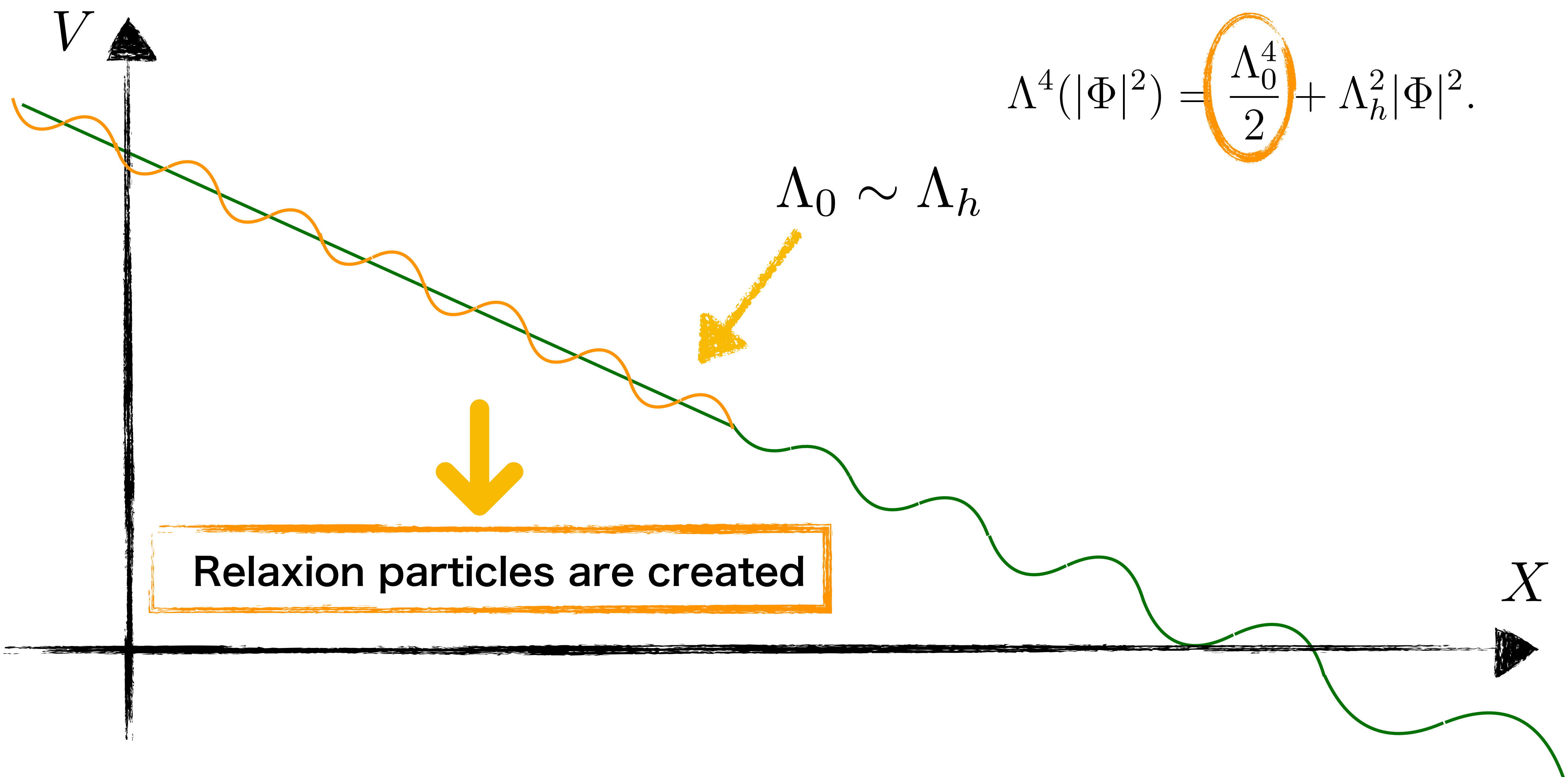
$$\omega_X \simeq \frac{r\epsilon M^2}{3Hf} - \frac{\mathcal{A}_h^2\omega_X}{8f^2} - \frac{\lambda\mathcal{A}_h^4}{128f^2\omega_X} + \frac{3\mathcal{A}_h^2\omega_X^3}{16f^2\Lambda_h^4}H^2 \; ,$$

Inhomogeneous modes

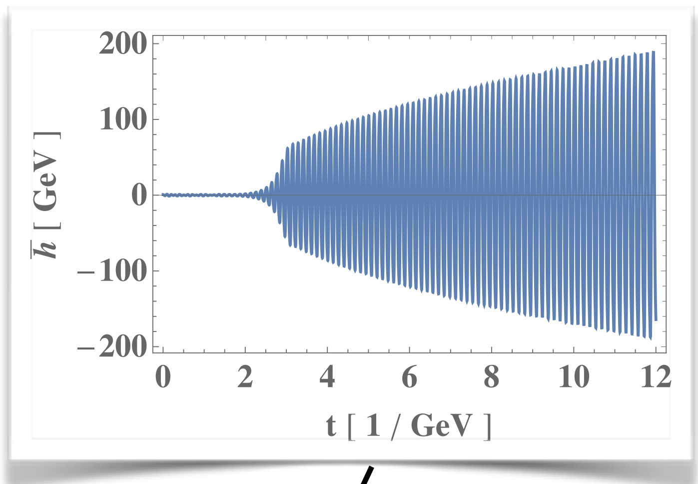
Particle production

$$V(\Phi, X) = (M^2 - \epsilon X)|\Phi|^2 - r\epsilon M^2 X + \Lambda^4(|\Phi|^2)\cos\frac{X}{f} + \frac{\lambda}{4}|\Phi|^4,$$

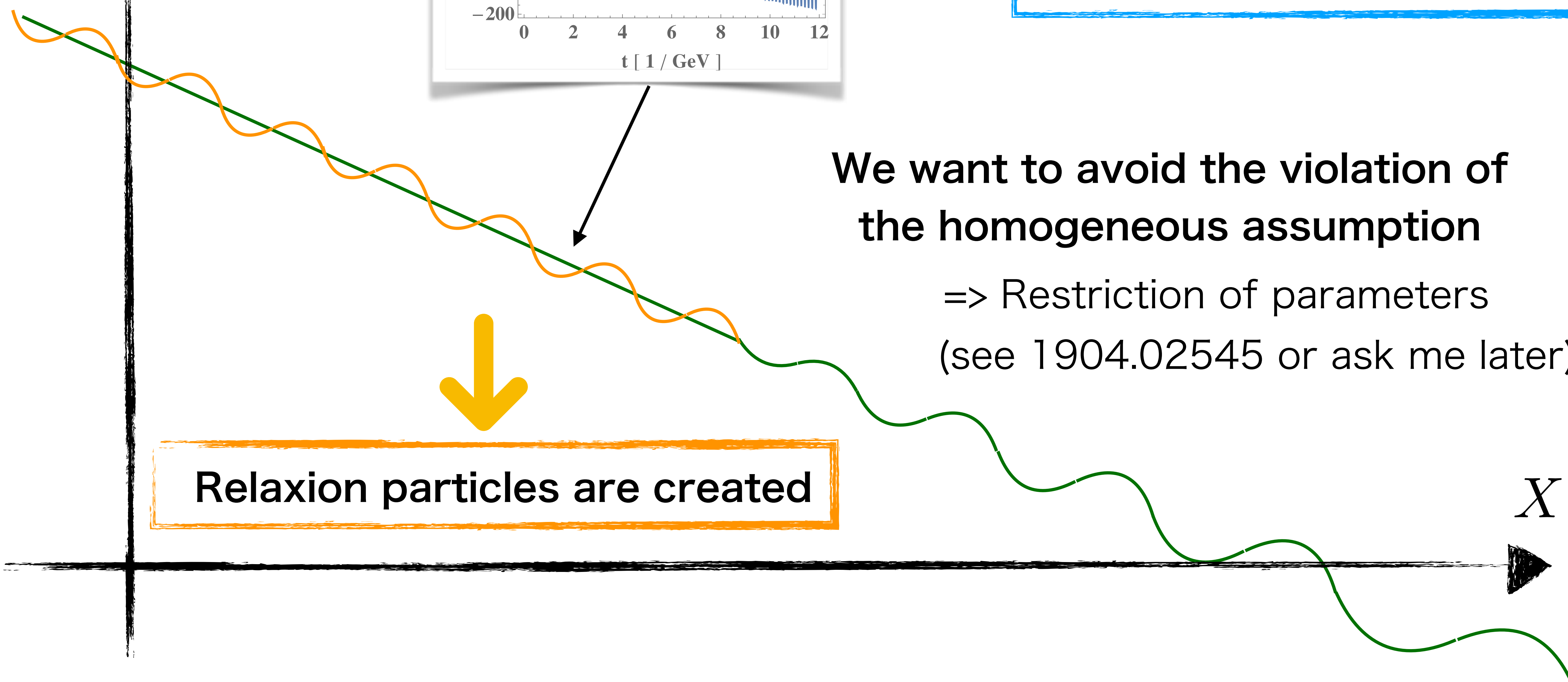
$$\Lambda^4(|\Phi|^2) = \frac{\Lambda_0^4}{2} + \Lambda_h^2|\Phi|^2.$$



Particle production



Decay into
relaxion, Higgs, gauge, ⋯



Relaxion particles are created

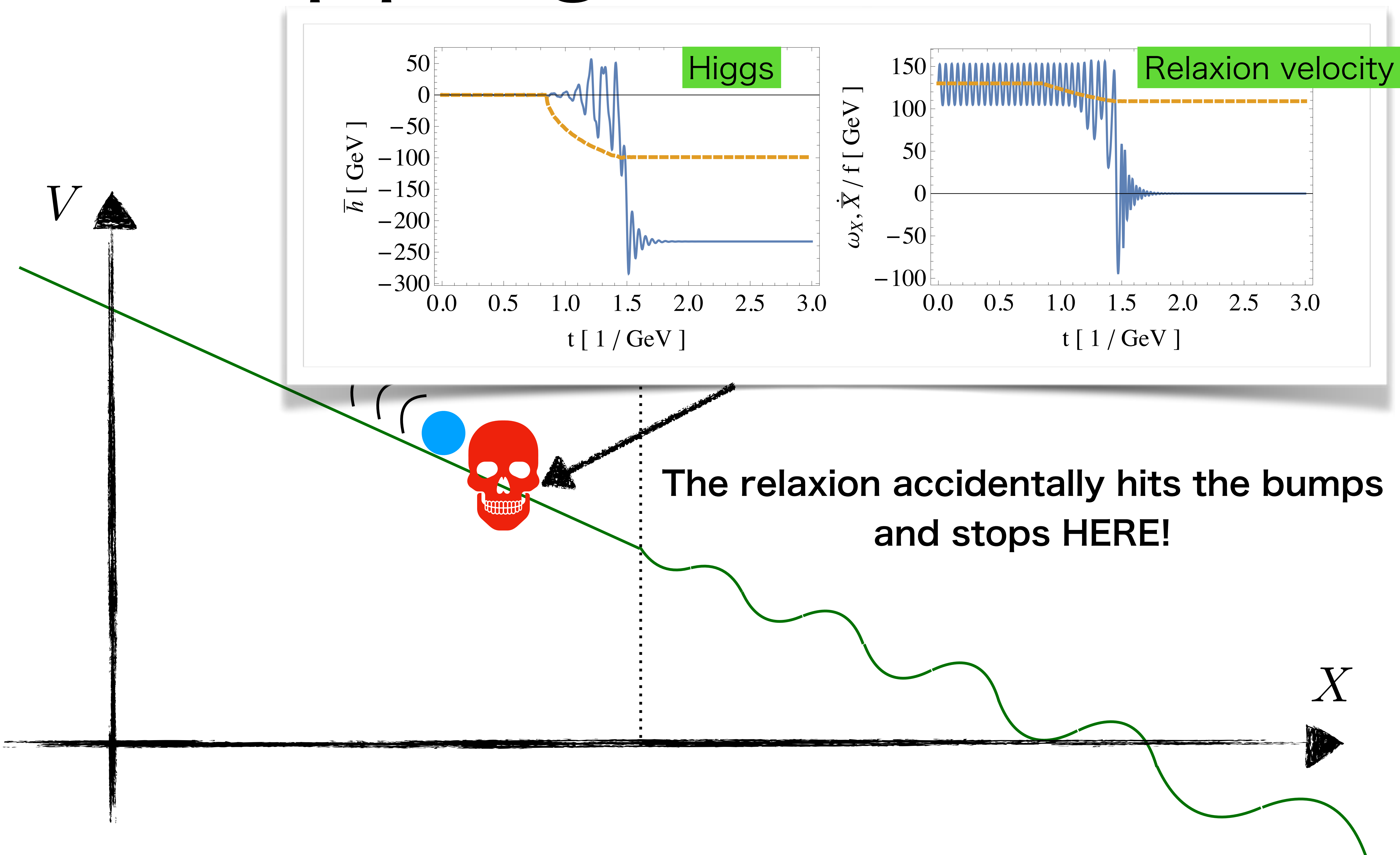
We want to avoid the violation of the homogeneous assumption

=> Restriction of parameters

(see 1904.02545 or ask me later)

Stopping mechanism

Stopping mechanism



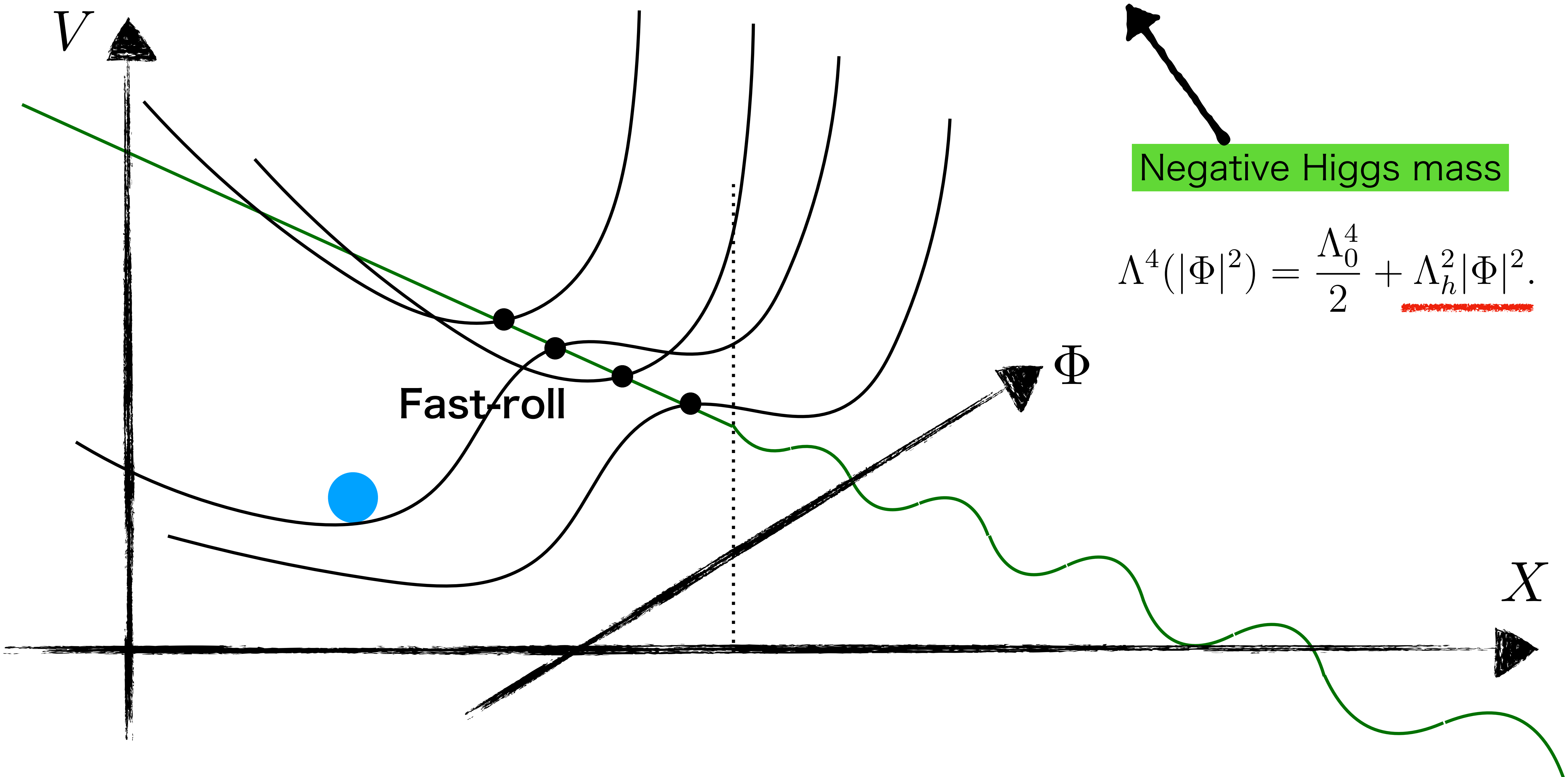
Negative Higgs mass

Positive but small

$$V(\Phi, X) = (M^2 - \epsilon X)|\Phi|^2 - r\epsilon M^2 X + \Lambda^4(|\Phi|^2)\cos\frac{X}{f} + \frac{\lambda}{4}|\Phi|^4,$$

Negative Higgs mass

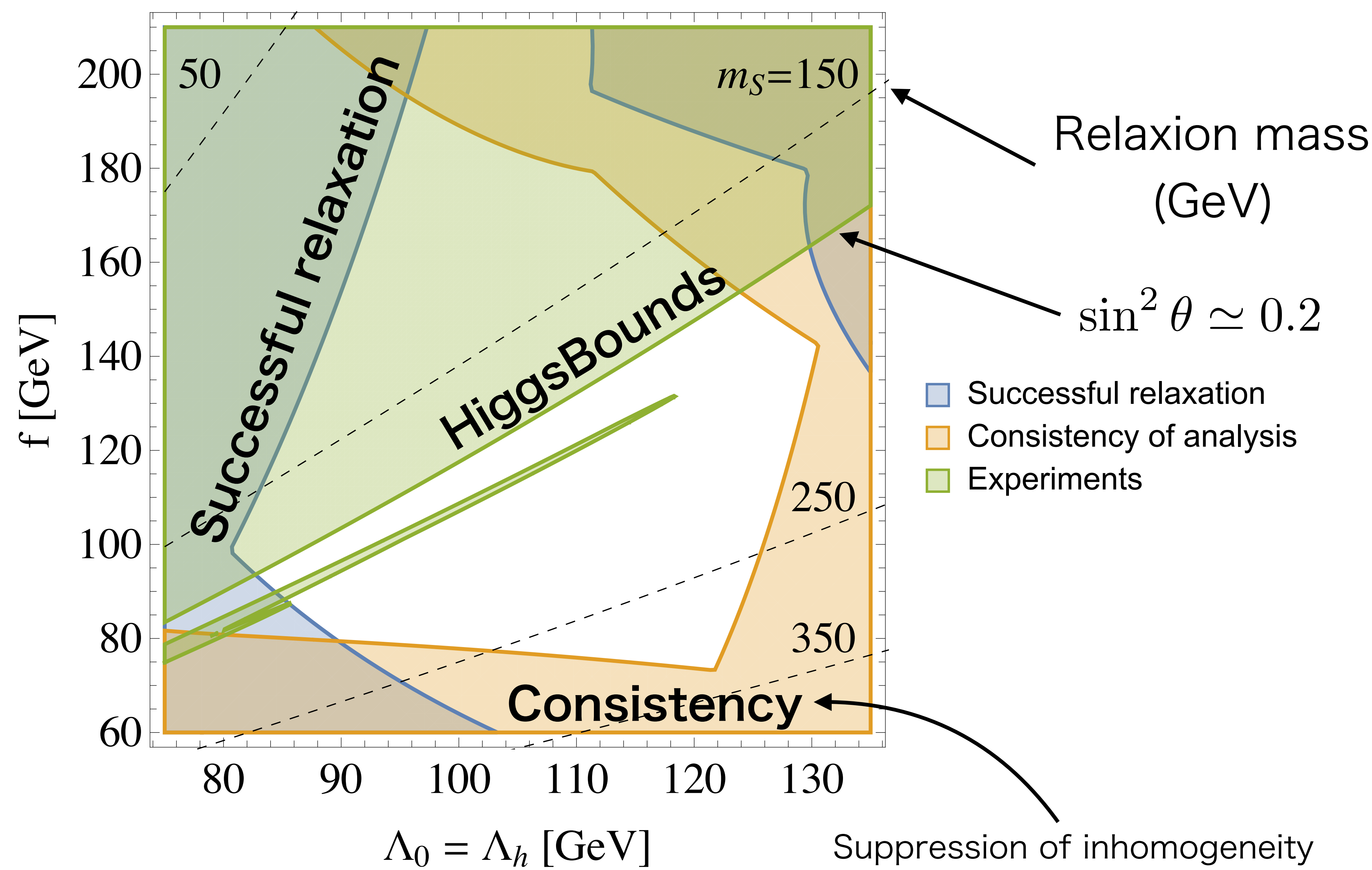
$$\Lambda^4(|\Phi|^2) = \frac{\Lambda_0^4}{2} + \Lambda_h^2|\Phi|^2.$$



Parameter space

Parameter space

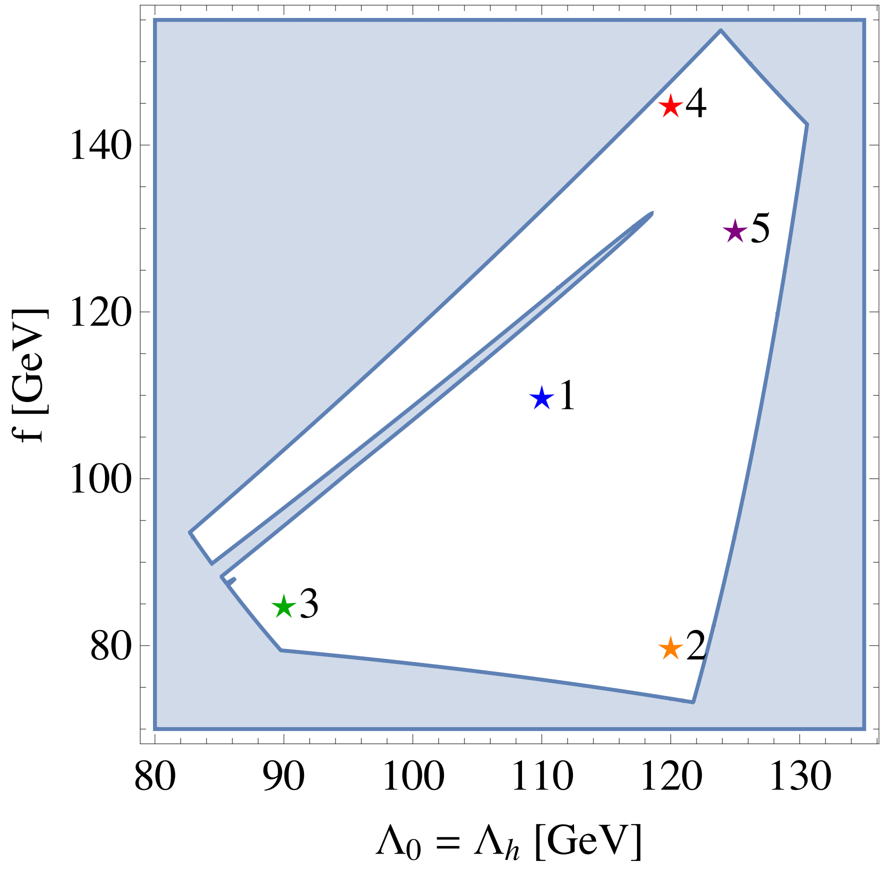
$$H = 10 \text{ GeV}, \ \epsilon = 0.8 \text{ GeV}, \ r = 0.002, \ M = 20 \text{ TeV}.$$

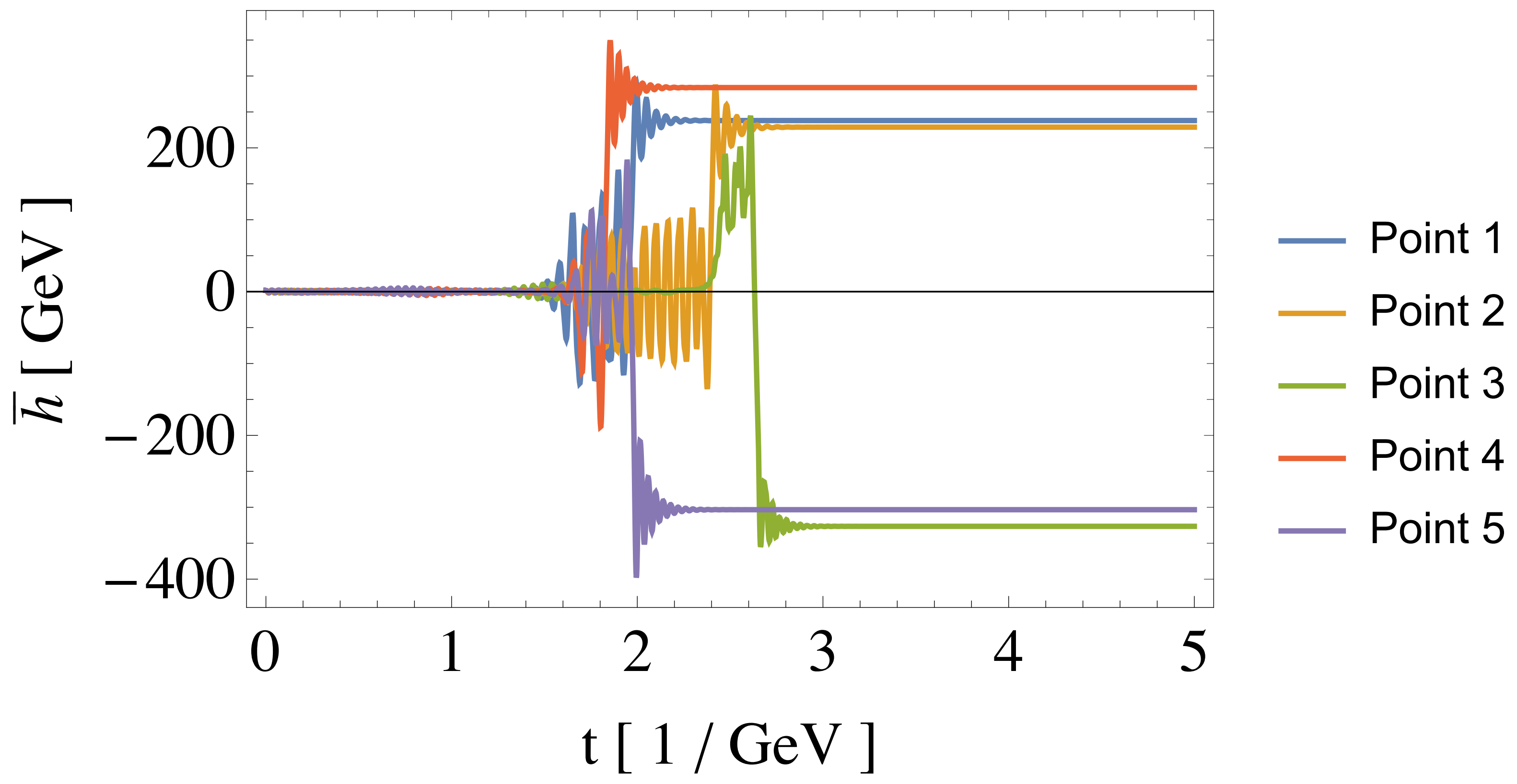


The lifetime of each vacuum is much longer than the age of the universe

It stops!

$$H = 10\ \text{GeV},\ \epsilon = 0.8\ \text{GeV},\ r = 0.002,\ M = 20\ \text{TeV}.$$





Summary

- In the original relaxion model, the tunneling phase requires an unacceptably large number of e-folds.
- The fast-roll relaxion can easily solve this problem, but we can not use the original stopping mechanism.
- We propose a mechanism to stop the relaxion without extending the original model.
- The mechanism predicts a relaxion that has a mass of O(100) GeV and mixes with the Higgs boson. It improves the testability of our mechanism.