Relaxion with Particle Production

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with A. Hook: 1607.01786


Perfect Fit
RELAXROLL®
The best is now
With small Higgs vev
Impulsiv Stimulation

Why is the Higgs mass small?

$$m_h^2 \sim \Lambda^2 \quad ?$$

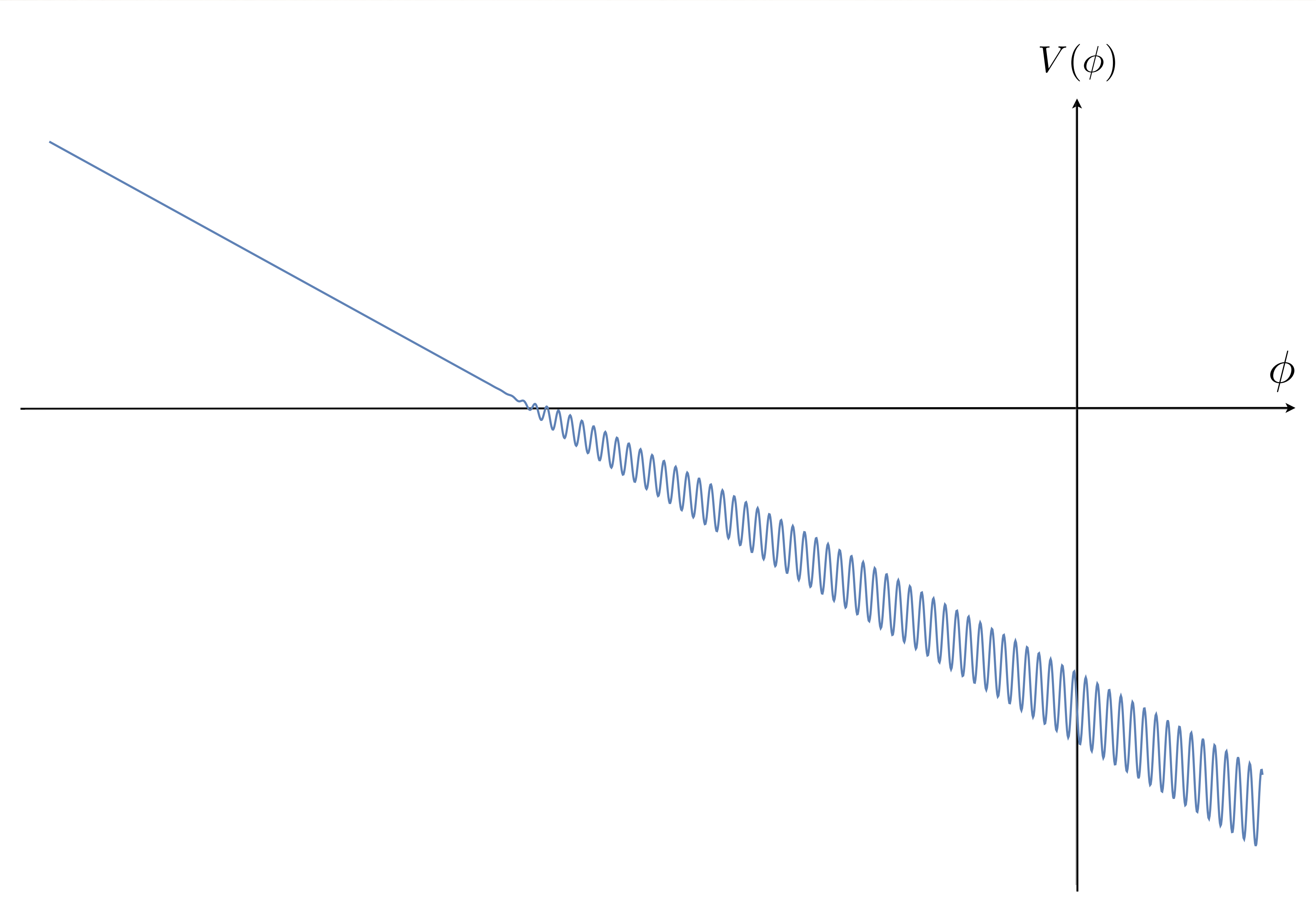
Why is the Higgs mass small?

$$m_h^2 \longrightarrow m_h^2(\phi)$$

Relaxion

P. W. Graham, D. E. Kaplan, and S. Rajendran, Phys. Rev. Lett. 115, 221801 (2015), 1504.07551

$$\mathcal{L} \supset -(\Lambda^2 - \epsilon\phi)|h|^2 - V(\epsilon\phi) - \Lambda_{\rm QCD}^3 \langle h \rangle \cos(\phi/f)$$



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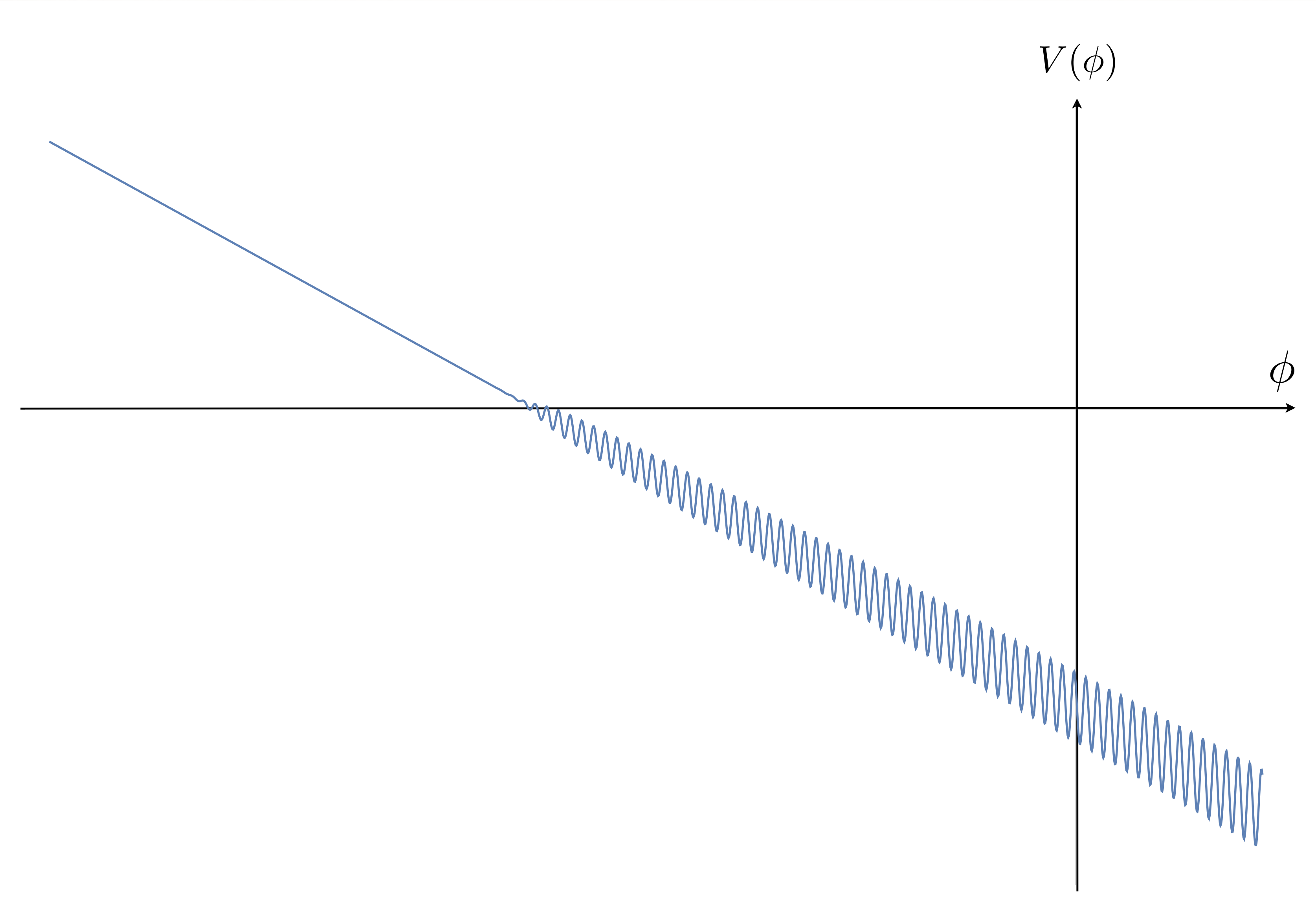
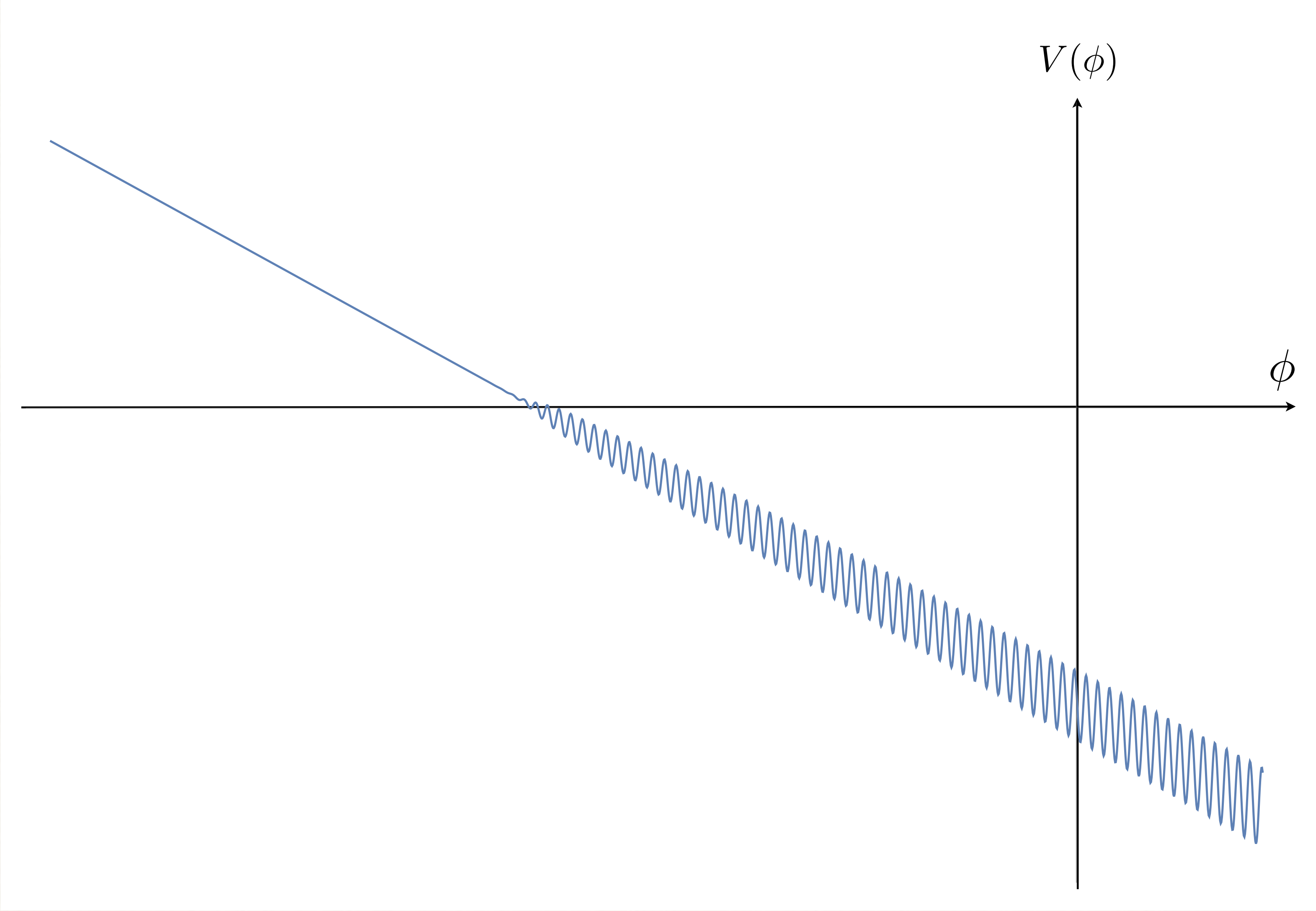


$$\phi \sim \Lambda^2/\epsilon$$

$$V(\epsilon\phi) \sim -\epsilon\Lambda^2\phi$$

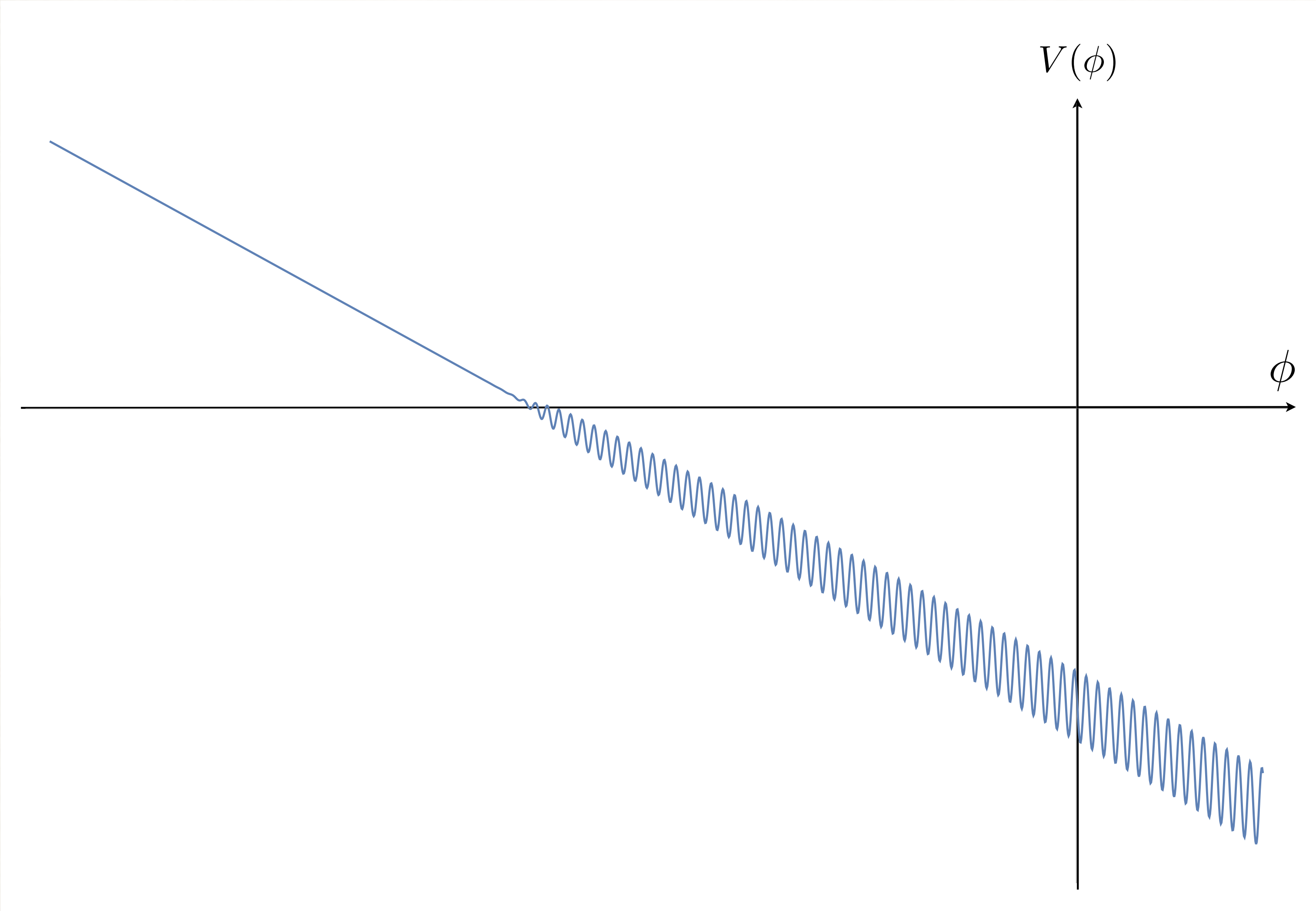
$$\langle h \rangle \sim \frac{\epsilon\Lambda^2 f}{\Lambda_{\rm QCD}^3}$$

Relaxion



- Stopping mechanism
- Dissipation

Relaxion: requires many e-foldings

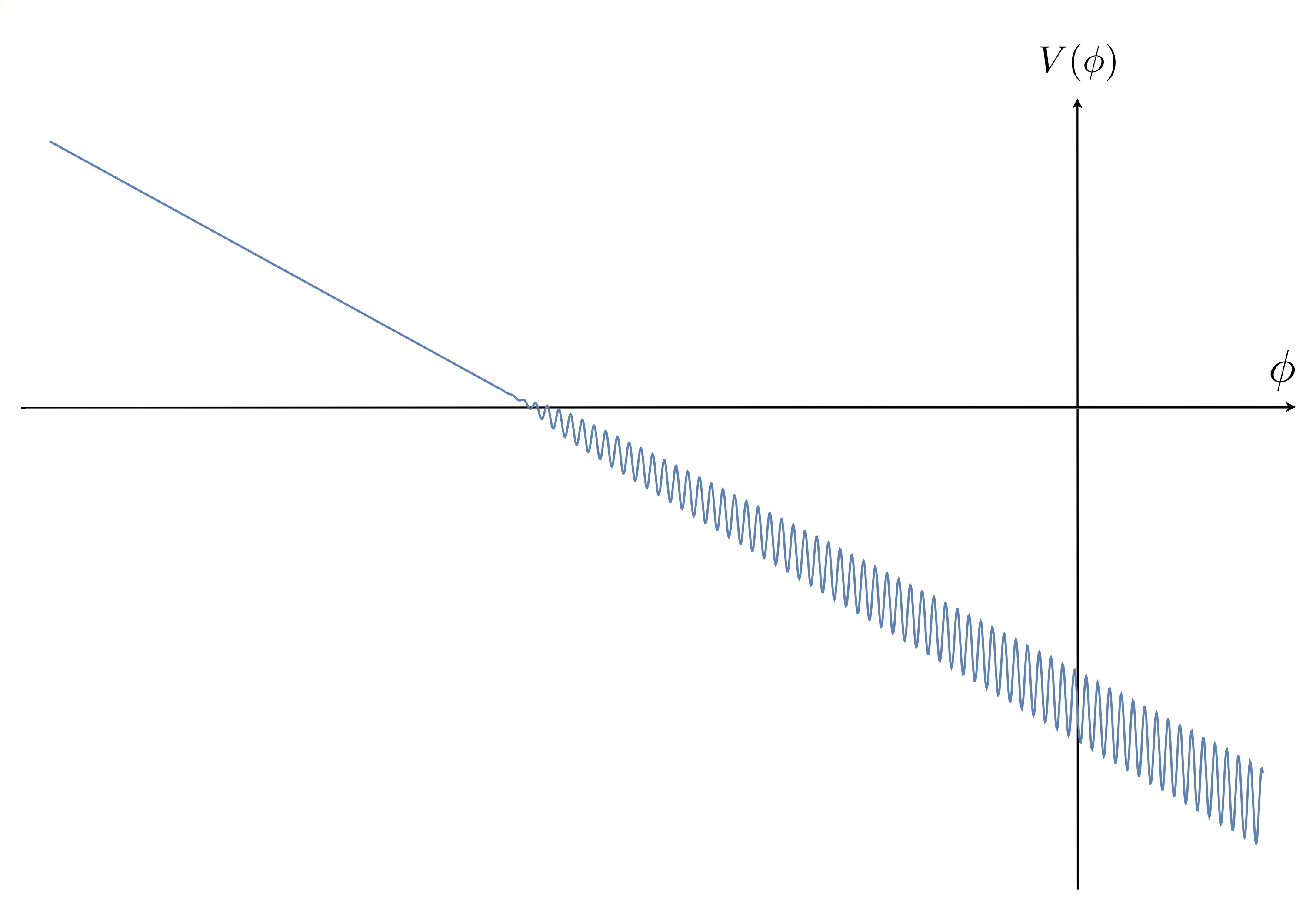


$$\dot{\phi} \sim \epsilon\Lambda^2/H$$

$$\Delta\phi|_{1 \text{ e-fold}} \sim \epsilon\Lambda^2/H^2$$

$$\Delta N_e = H^2/\epsilon^2$$

Relaxion: requires many e-foldings



$$\Delta N_e = H^2/\epsilon^2$$

To actually stop:

$$\epsilon\Lambda^2/H \lesssim \Lambda_b^2$$

$$\Delta N_e \gtrsim \Lambda^4/\Lambda_b^4$$

Relaxion

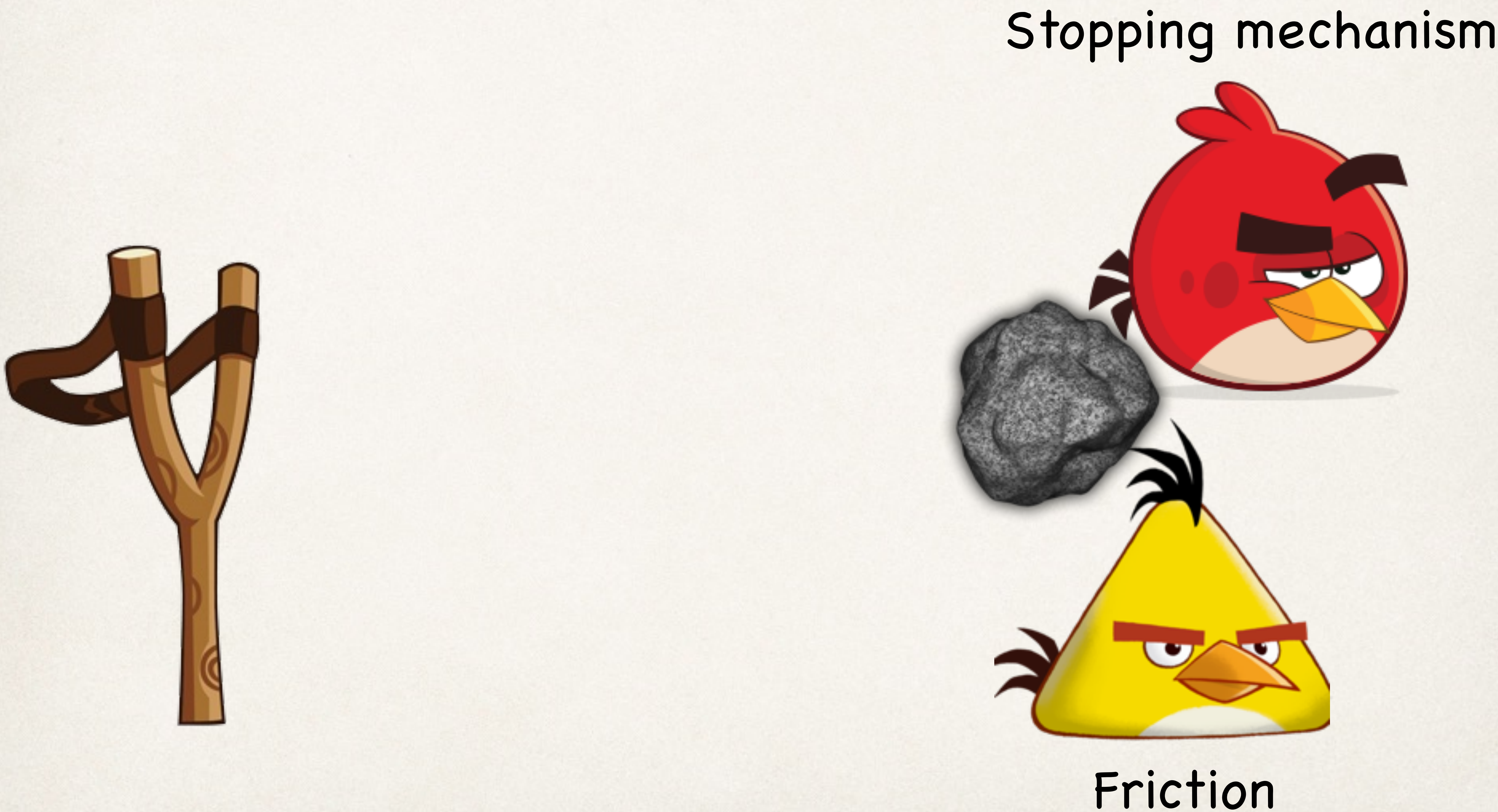
- Stopping mechanism: barrier depends on Higgs vev
  - Tension with strong CP problem
  - Non-trivial to have barrier height larger than v

*(both solved)**

- Dissipation mechanism: Hubble
  - Super Planckian field excursions
  - Requires many e-foldings
  - Scanning must happen during inflation

* J. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolas and G. Servant, Phys.Rev.Lett. 115 (2015) no.25, 251803, arxiv:1506.09217

Particle production: kill 2 birds with 1 stone



Basic Mechanism

- Toy Model: Abelian Higgs + relaxion (static universe)

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)|h|^2 + (\epsilon\Lambda^2\phi + \ldots) - \mu_s^4 \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f} F\tilde{F}$$

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- EOM for gauge fields

$$\ddot{A}_\pm + \left(k^2 + m_A^2 \mp k\frac{\dot{\phi}}{f}\right)A_\pm = 0$$

Basic Mechanism

$$\ddot{A}_\pm + \left(k^2 + m_A^2 \mp k\frac{\dot{\phi}}{f}\right) A_\pm = 0 \Rightarrow \omega^2 = k^2 + m^2 - \frac{k\dot{\phi}}{f}$$

- Tachyonic modes for: $\frac{\dot{\phi}}{f} \gtrsim m_A$

$$A(t) \sim e^{\frac{\dot{\phi}}{f}t}$$

Basic Mechanism

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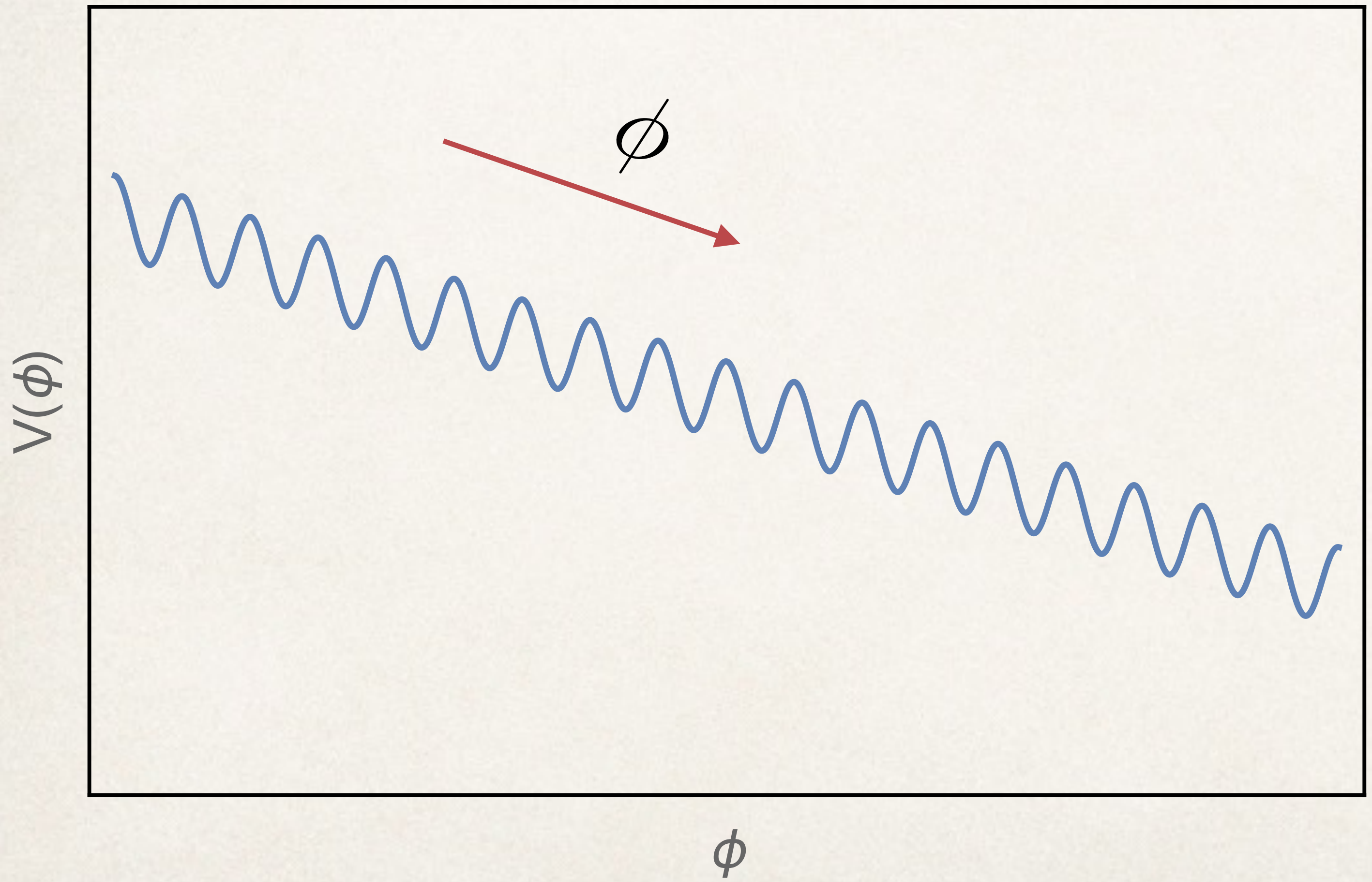


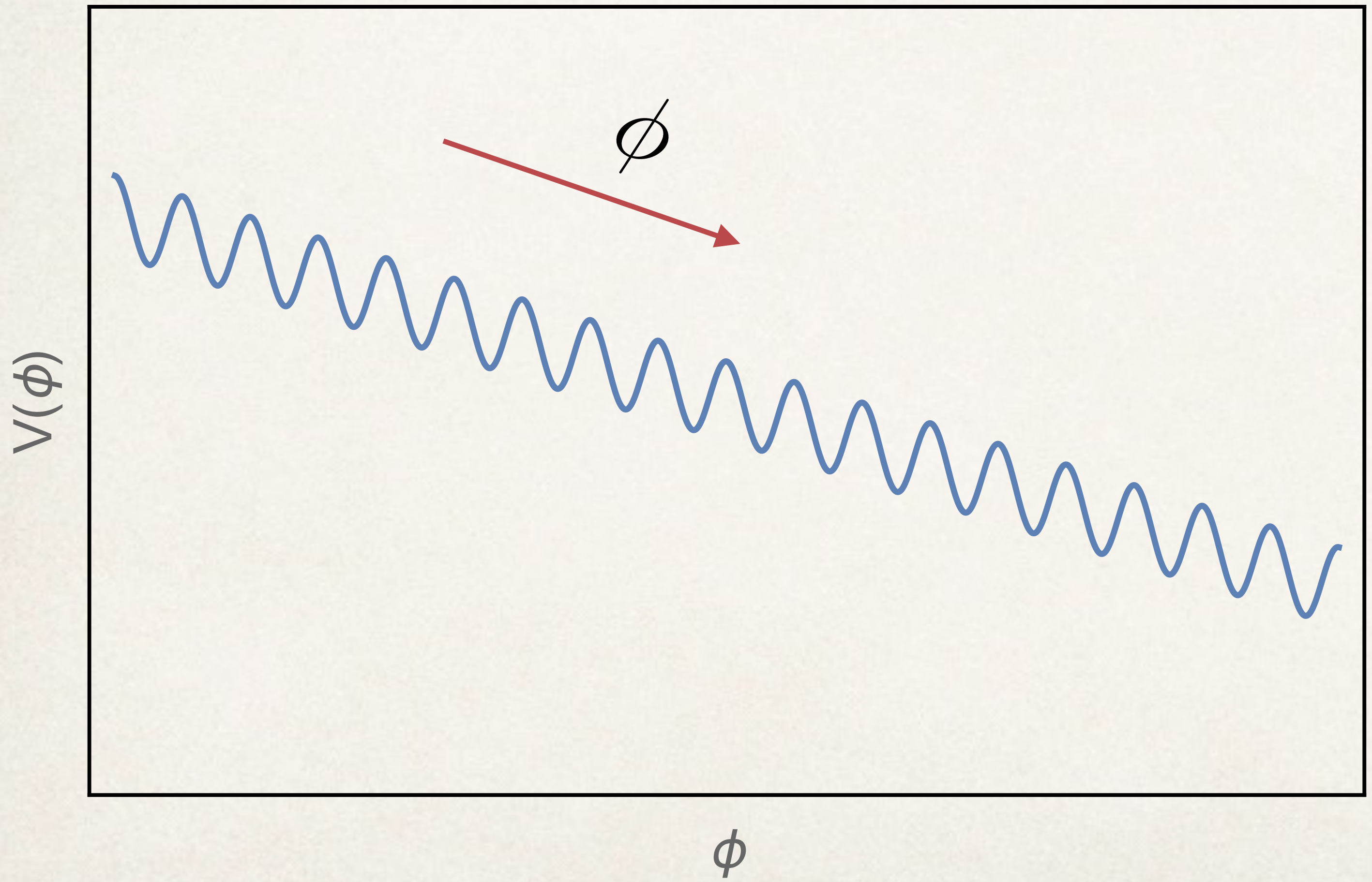
$$\dot{\phi} > \mu_s^2$$

$$m_H^2 \sim -\Lambda^2$$

$$m_A \sim \langle h \rangle \sim \Lambda$$

Basic Mechanism

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)|h|^2 + (\epsilon\Lambda^2\phi + ...) - \mu_s^4 \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f} F\tilde{F}$$



- Scans until

$$\langle h \rangle \ll \Lambda$$

- When

$$\frac{\dot{\phi}}{f} \gtrsim \langle h \rangle \sim \mathcal{O}(100\,\mathrm{GeV})$$

Finite Temperature

Relaxion kinetic energy transferred to gauge fields

$$T \sim \sqrt{\dot{\phi}}$$

- Gauge symmetry restoration

$$m_A \sim 0$$

- Plasma effects (screening)

$$m_D \sim T$$

Finite Temperature

$$\omega^2 - k^2 \pm \frac{k\dot{\phi}}{f} = \Pi_t(\omega, k) = m_D^2 F(\omega/k)$$

We are interested in the regime

$$\omega = i\Omega, \qquad |\Omega| \ll k \ll m_D$$

Finite Temperature

$$\omega^2 - k^2 \pm \frac{k\dot{\phi}}{f} = \Pi_t(\omega, k) = m_D^2 F(\omega/k)$$

We are interested in the regime

$$\omega = i\Omega, \qquad |\Omega| \ll k \ll m_D$$

$$-\Omega^2 - k^2 \pm \frac{k\dot{\phi}}{f} \approx \frac{m_D^2 |\Omega| \pi}{4k}$$

$$\Omega \sim \frac{(\dot{\phi}/f)^3}{m_D^2}$$

Quick Summary

- $\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)|h|^2 + (\epsilon\Lambda^2\phi + \ldots) - \mu_s^4 \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f} F\tilde{F}$

- Tachyonic mode for A: $\Omega \sim \dot{\phi}/f$

- Temperature dilutes tachyon time-scale:

$$\Omega \sim \frac{(\dot{\phi}/f)^3}{T^2}$$

Particle Production relaxion in SM

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)|h|^2 + (\epsilon\phi\Lambda^2 + \ldots) - \mu_s^4 \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f}\left(\alpha_Y B\tilde{B} - \alpha_W W\tilde{W}\right)$$

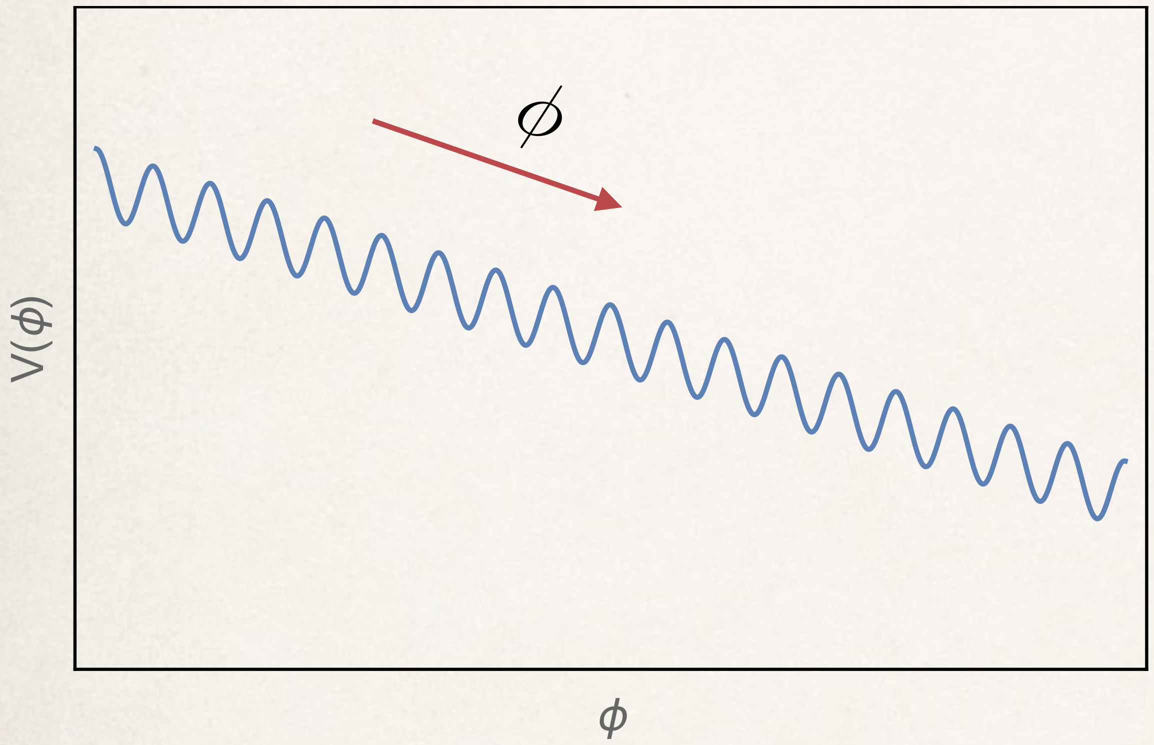
- Relaxion does not couple to the photon!

Relaxion setup

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)|h|^2 + (\epsilon\phi + \ldots) - \mu_s^4 \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f}\left(\alpha_Y B\tilde{B} - \alpha_W W\tilde{W}\right)$$

- Sub planckian: $\epsilon > \Lambda^2/M_P$
- Many minima: $\mu_s^4 > \epsilon\Lambda^2 f'$
- Fine scanning: $\epsilon f' < v^2$

Relaxion setup



$$\dot{\phi} \sim \text{const} > \mu_s^2$$

- "Self-tune" to Weak Scale

$$\dot{\phi}/f \sim v = 246 \text{ GeV}$$

- Need to ensure energy loss is efficient

Energy Loss

- Not overshooting v

$$\delta m_H^2 = \epsilon \delta \phi$$

$$\delta m_H \sim \frac{\epsilon \dot{\phi}}{v} \delta t \sim \frac{\epsilon T^2 f^3}{v \dot{\phi}^2} < v$$

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$$\epsilon < \frac{v^5 \mu_s^4}{T^8}$$

Possible realization

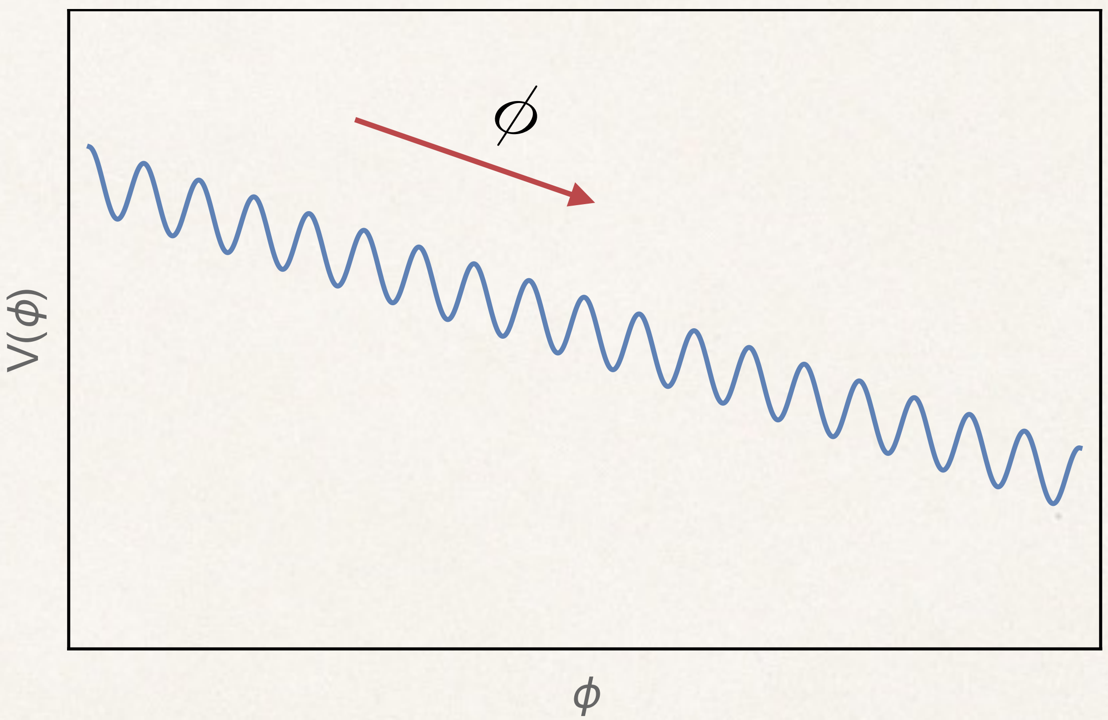
Initial Conditions

- Take this inflationary initial conditions

$$H > \frac{\Lambda^2}{M_P}$$

$$\dot{\phi} > \mu_s^2$$

$$T \ll \Lambda$$



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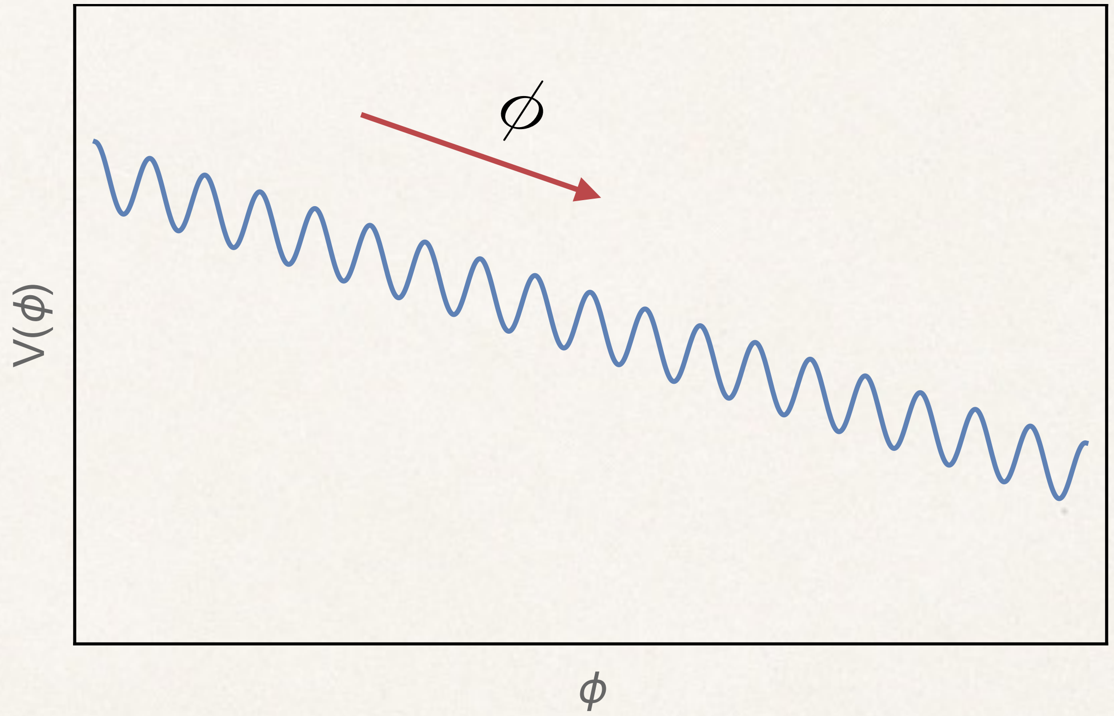

$$\frac{\epsilon\Lambda^2}{H} \gtrsim \mu_s^2 \quad \Rightarrow \quad \dot{\phi} \sim \frac{\epsilon\Lambda^2}{H} + \delta(t)$$

Relaxing during inflation

$$T \sim \sqrt{\dot{\phi}} \sim \sqrt{\frac{\epsilon \Lambda^2}{H}} \qquad \Delta N_e \sim \left(\frac{H}{\epsilon}\right)^2$$

$$\frac{\Lambda^2}{M_P} < \epsilon < \frac{v^5 \mu_s^4}{T^8}$$

$$\Lambda^6 < v^5 M_P \Delta N_e$$

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$\Delta N_e \sim 100$ →

$$\Lambda \lesssim 10^5 \text{ GeV}$$

Inflation too brief

$$\left(\frac{H}{\epsilon}\right)^2 > N_e$$

- Can the scanning continue after inflation ends?

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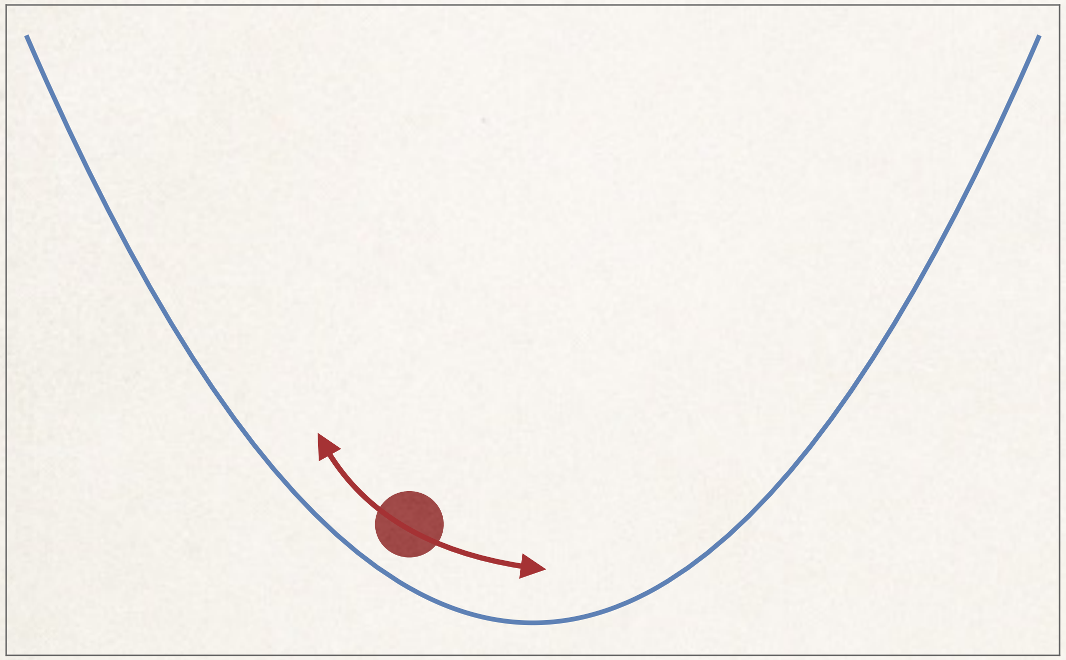
- Can the scanning continue after inflation ends?

Yes!

Scanning after inflation



$$H \propto a^{-3/2}$$

$$T_{SM} < v$$

- Scanning very fast once: $H \lesssim \epsilon$

$$\dot{\phi} \sim \Lambda^2$$

Scanning after inflation

$$\frac{\Lambda^2}{M_P} < \epsilon < \frac{v^5 \mu_s^4}{T^8} \qquad \& \qquad \dot{\phi} \sim \Lambda^2$$

$$\Lambda^{10} \lesssim v^5 \mu_s^4 M_P$$

$$\Lambda \sim \mu_s \qquad \Lambda < 40 \text{ TeV}$$

Conlusions

- Particle production is an efficient mechanism to both dissipate energy and to select small Higgs mass
- Qualitatively new approach to relaxion
- It can work without super planckian field excursions and with normal amounts of inflation
- The scanning can happen after inflation