Relaxion with Particle Production

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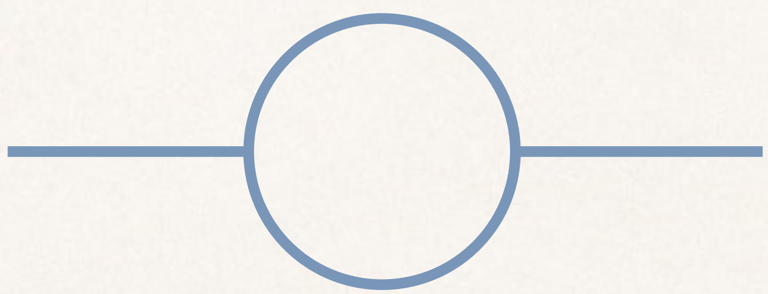
with A. Hook: 1607.01786

Why is the Higgs mass small?

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

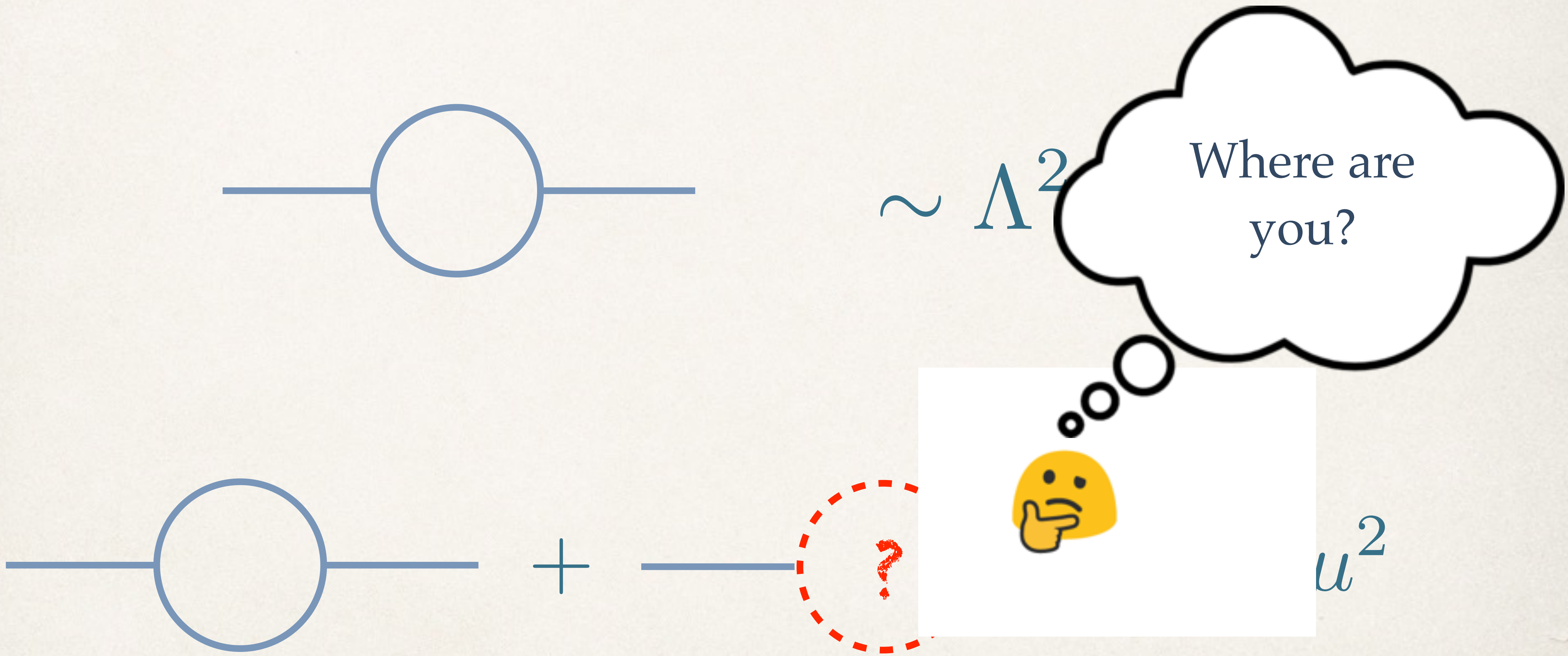
Symmetry



$\sim \Lambda^2$

$\sim \mu^2$

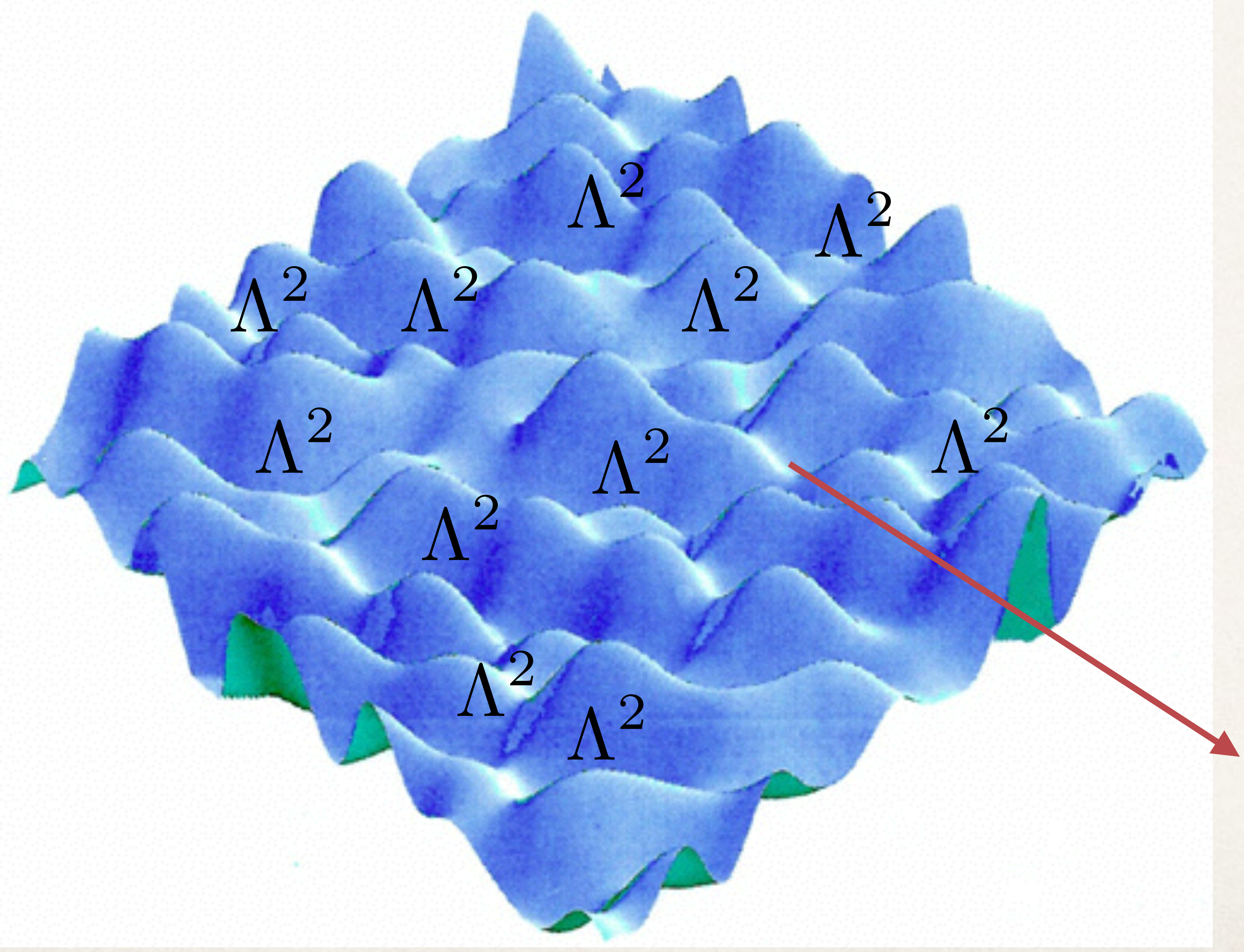
Symmetry



Why is the Higgs mass small?

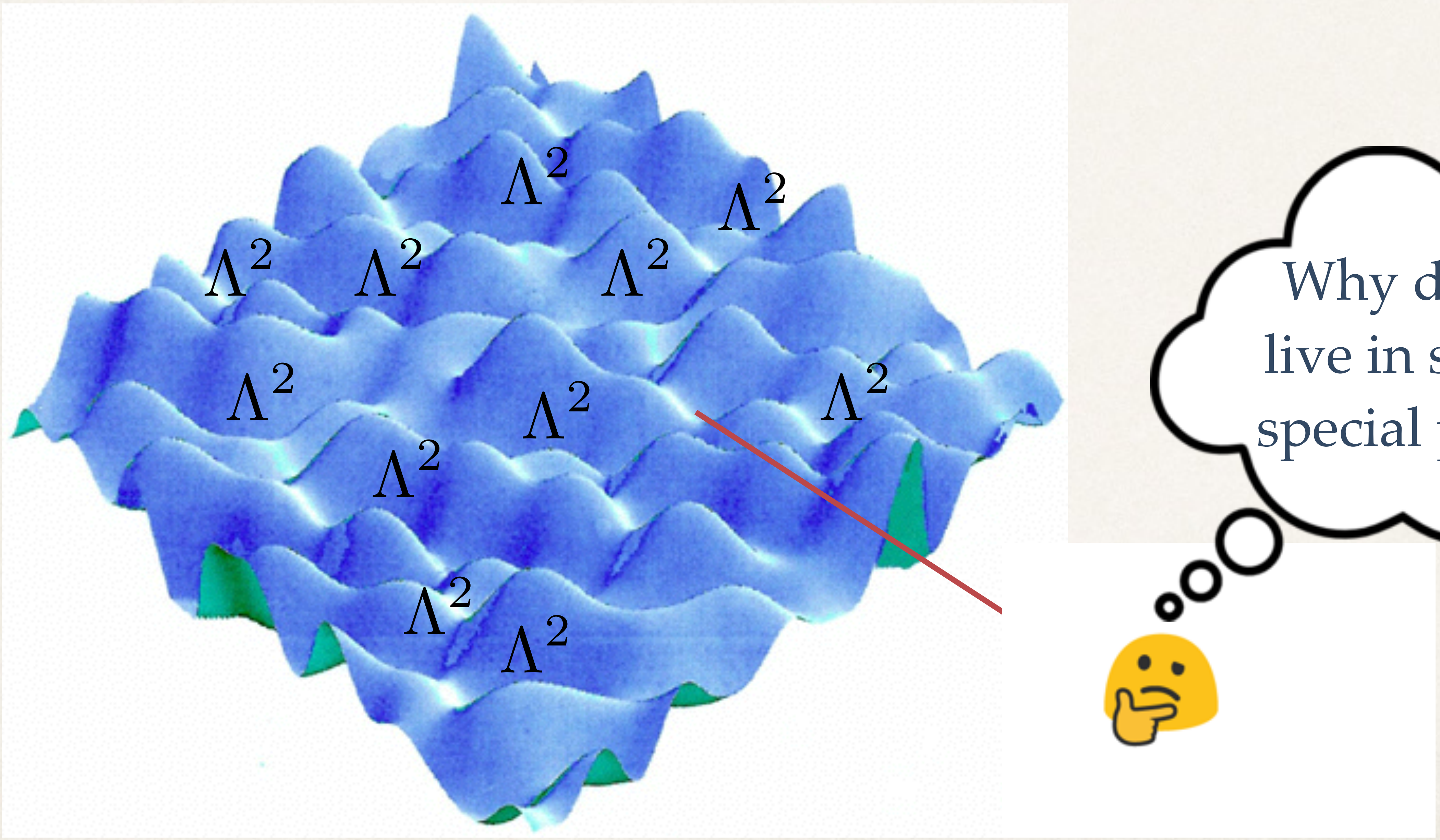
$$m_h^2 \longrightarrow m_h^2(\phi)$$

Landscape



$$m_h^2 \sim v^2$$

Landscape


Λ^2
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Λ^2
Why do we live in such a special point?

"Relaxion"

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

Relaxion

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

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

Relaxion

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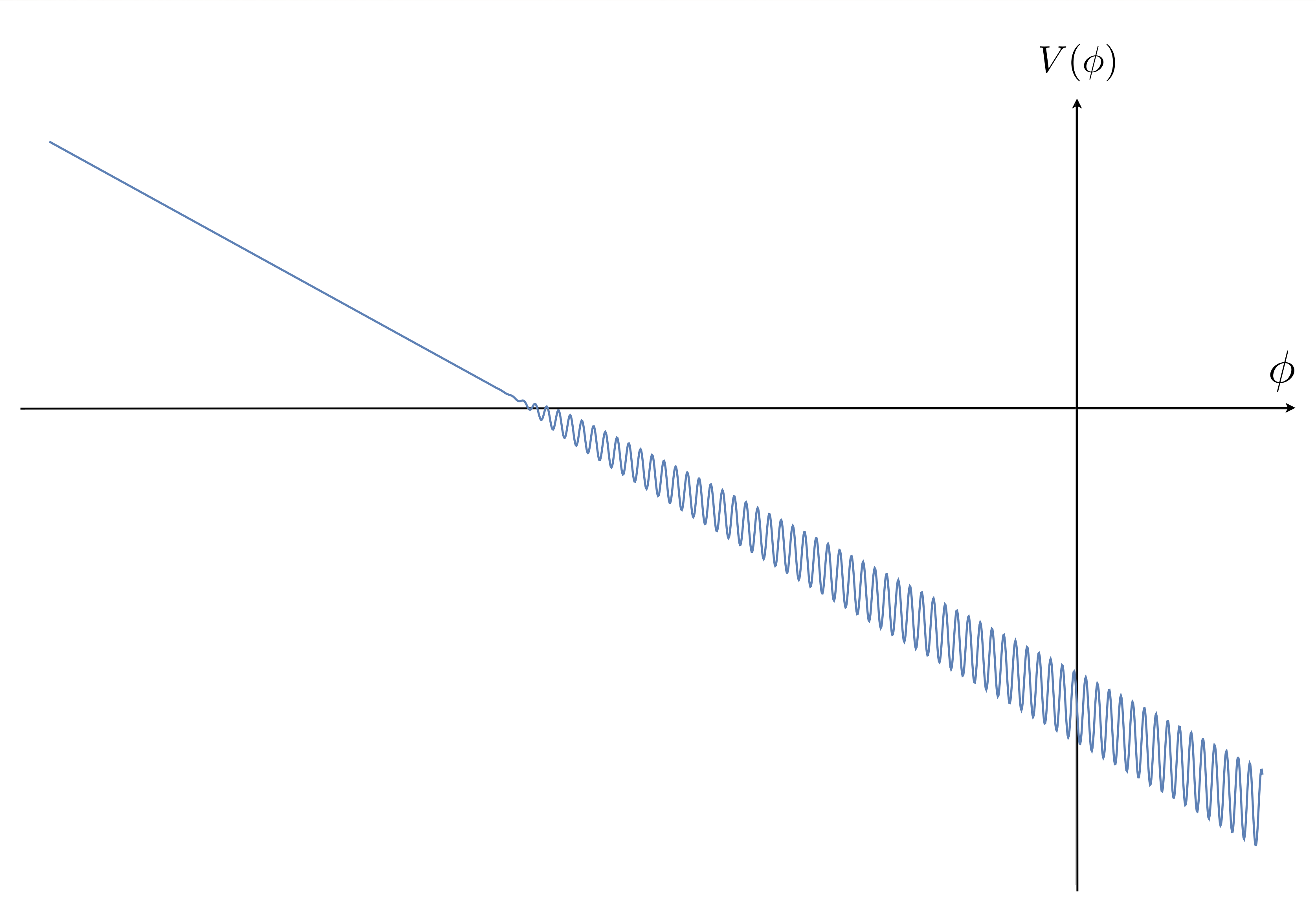


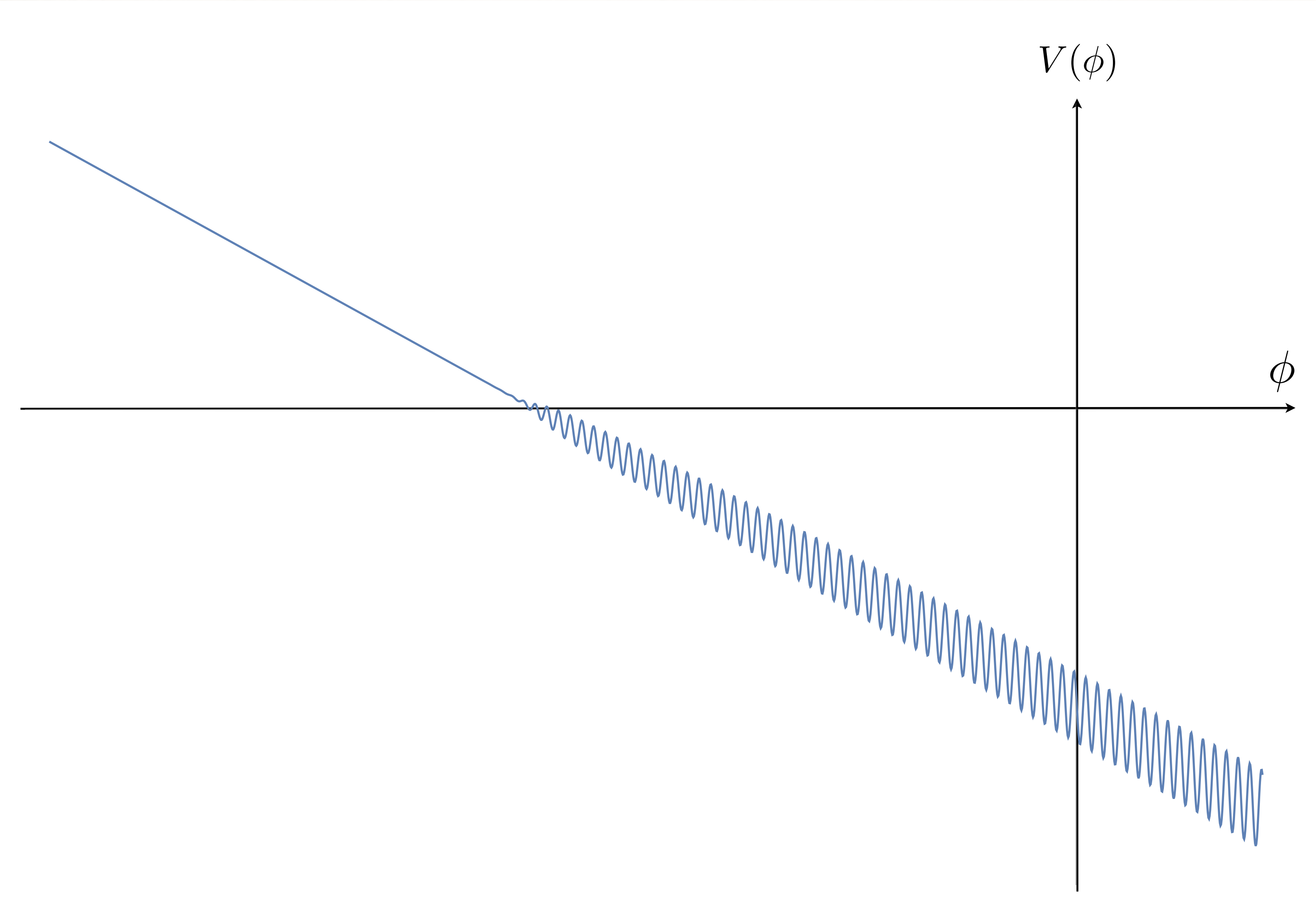
$$\phi \sim \Lambda^2/\epsilon$$

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

$$V'(\phi) = 0 \quad ?$$

Relaxion

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

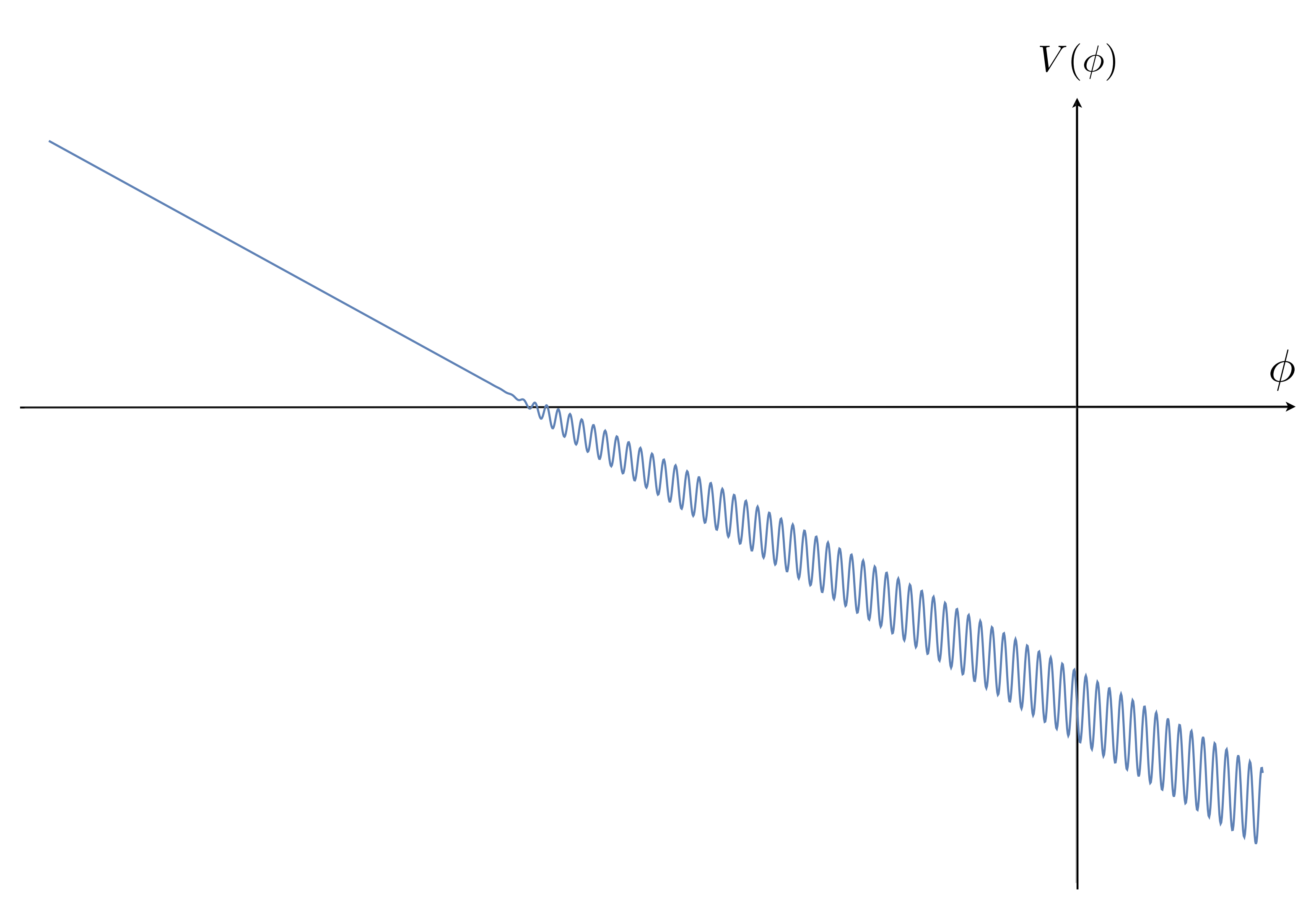


$$\phi \sim \Lambda^2/\epsilon$$

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

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

Relaxion



- Stopping mechanism
  cos() potential
- Dissipation
  Hubble friction

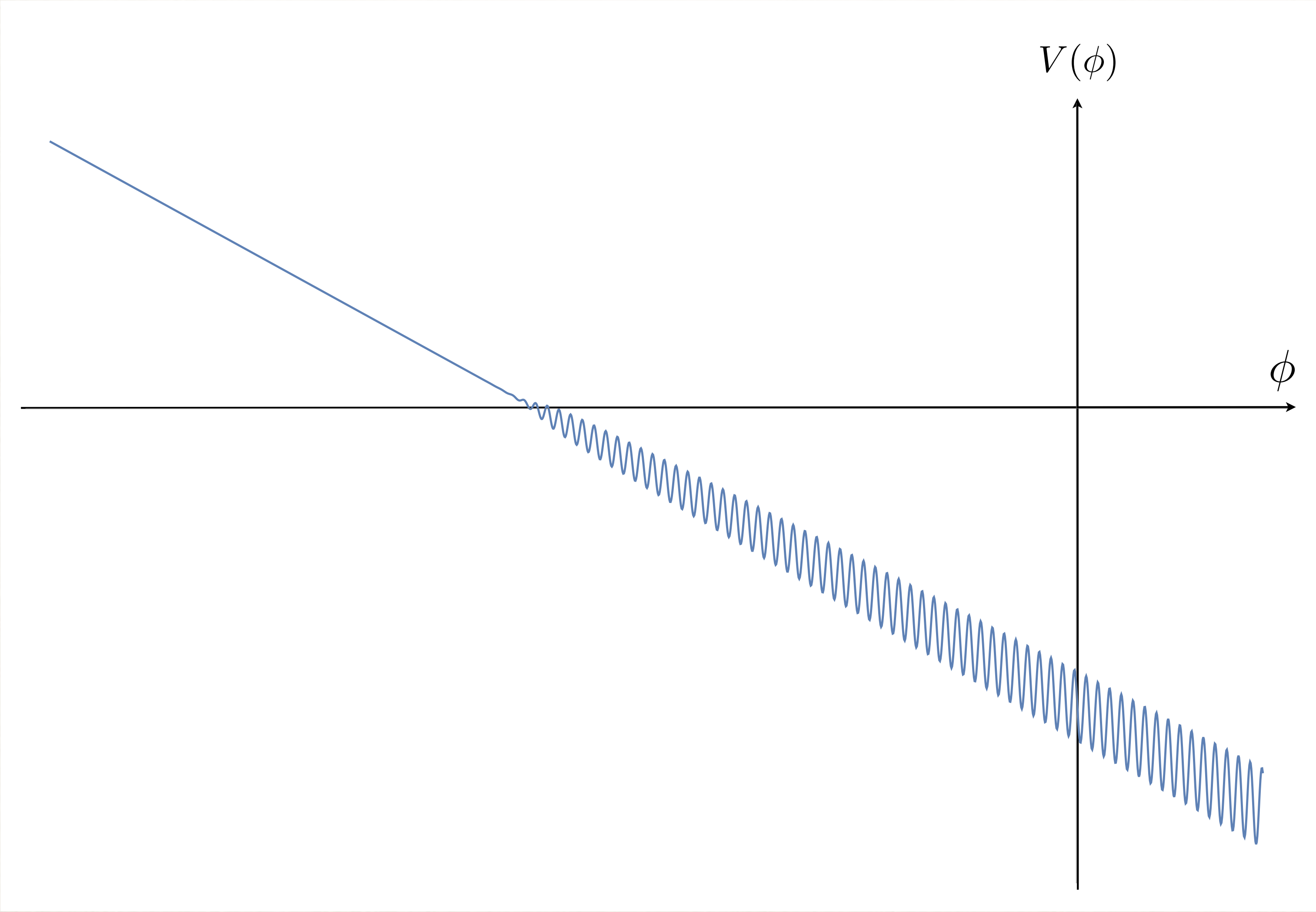
Relaxion: Slow roll regime

$$V'' \ll H^2$$

$$\ddot{\phi} + 3H\dot{\phi} = -V'$$

$$\dot{\phi} \approx -\frac{V'}{3H} \sim \frac{\epsilon\Lambda^2}{H}$$

Relaxion: requires many e-foldings

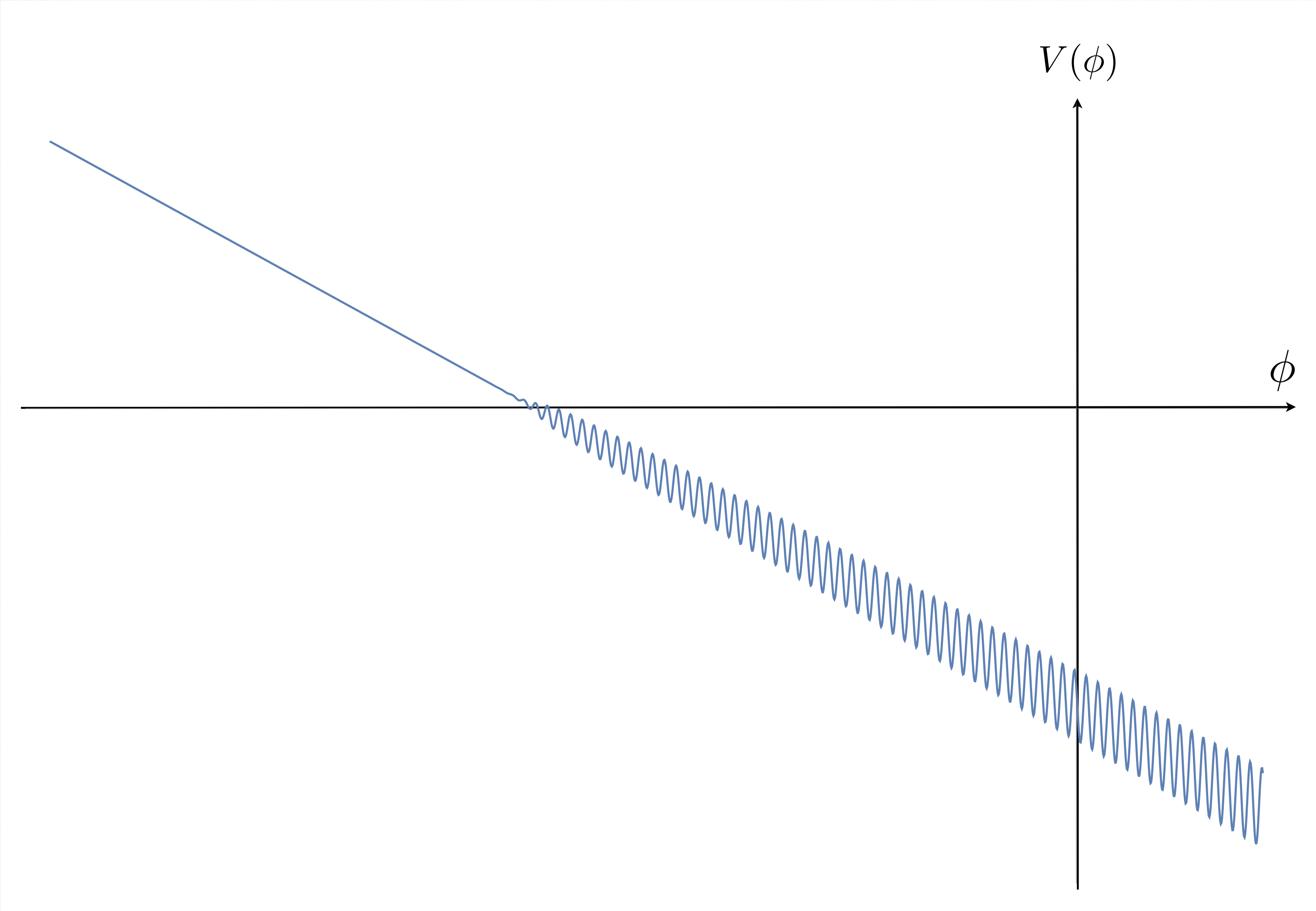


Slow Roll

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

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

Relaxion: requires many e-foldings



Slow Roll

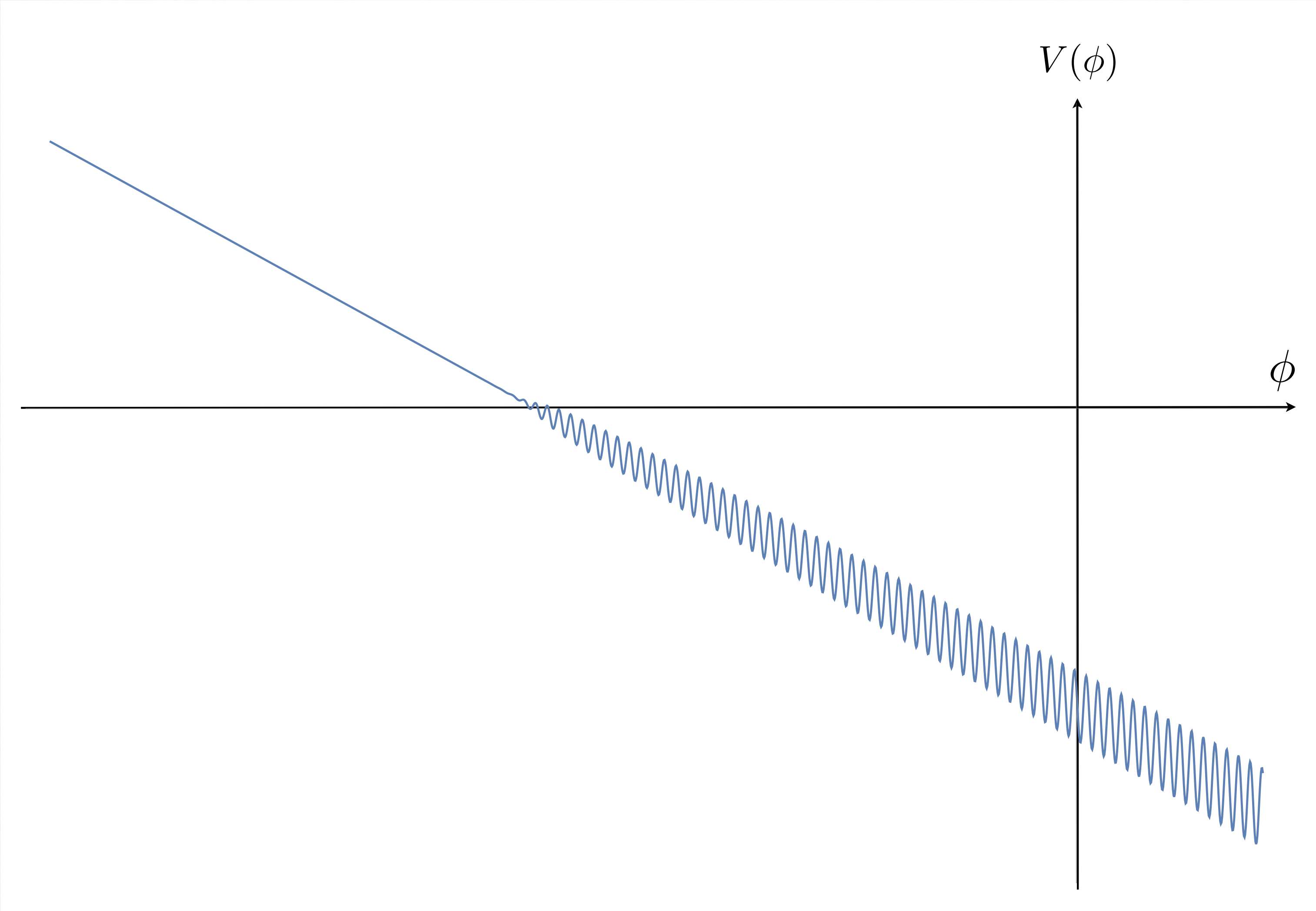
$$\dot{\phi} \sim \epsilon\Lambda^2/H$$

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

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

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

Relaxion: requires many e-foldings



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

To actually stop:

$$\dot{\phi}^2 \sim (\epsilon\Lambda^2/H)^2 \lesssim \Lambda_b^4$$

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

Relaxion

- Stopping mechanism: barrier depends on Higgs vev
  - Tension with strong CP problem
  - Non-trivial to have barrier height larger than v
- Dissipation mechanism: Hubble
  - Super Planckian field excursions
  - Requires many e-foldings
  - Scanning must happen during inflation

Particle production: kill 2 birds with 1 stone

Stopping mechanism

Friction

Outline

- Basic mechanism
- Implementing particle production relaxion in the SM
- Relaxing with particle production:
  - During inflation
  - After inflation

Basic Mechanism

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

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

Basic Mechanism

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$$m_h^2 = -(\Lambda^2 - \epsilon\phi) < 0$$

$$\Downarrow$$

$$m_A \sim g\Lambda \sim \Lambda$$

Basic Mechanism

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

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

- 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

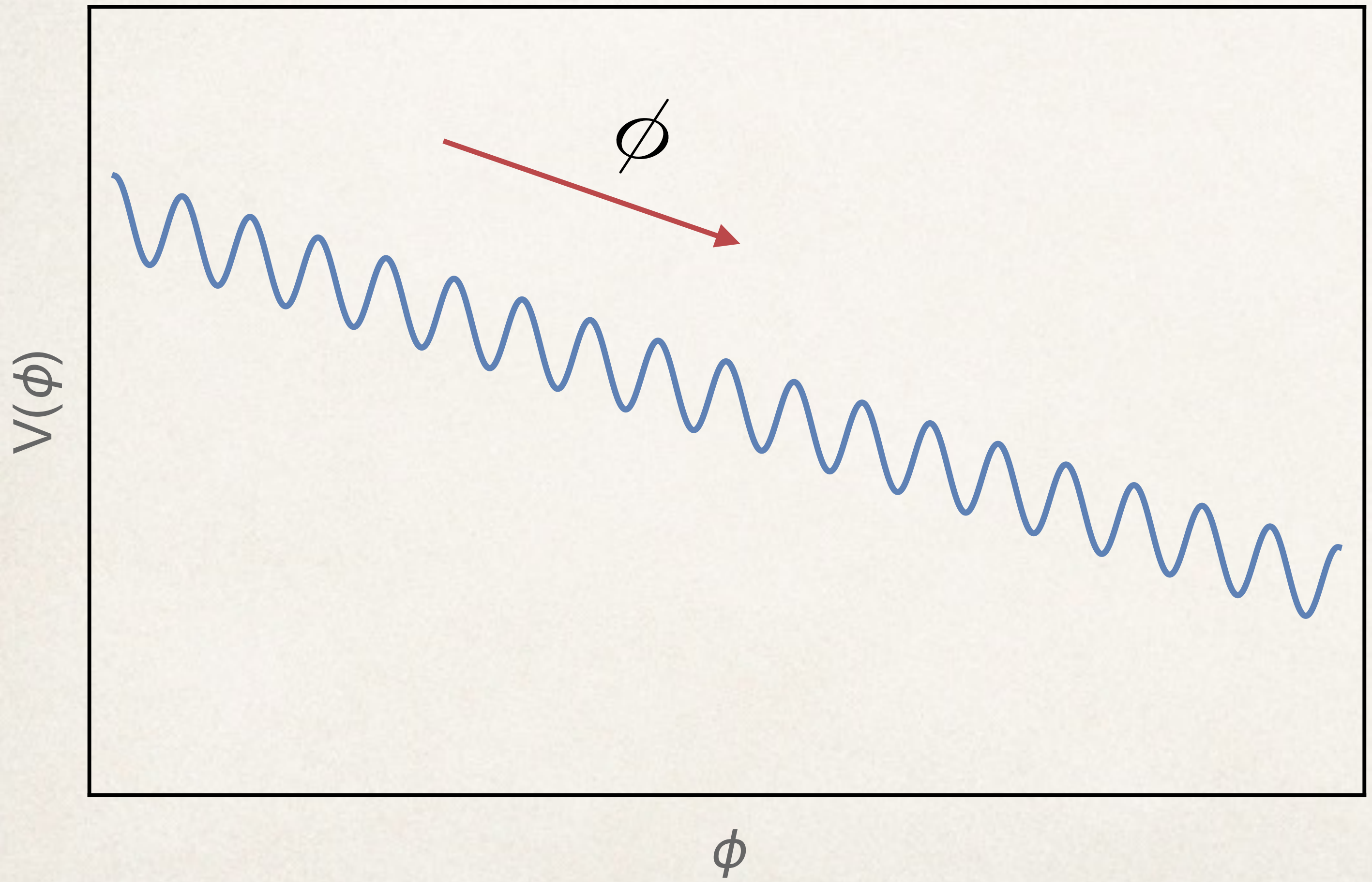
$$\omega^2 = k^2 + m_A^2 - \frac{k\dot{\phi}}{f}$$

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

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

Basic Mechanism

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



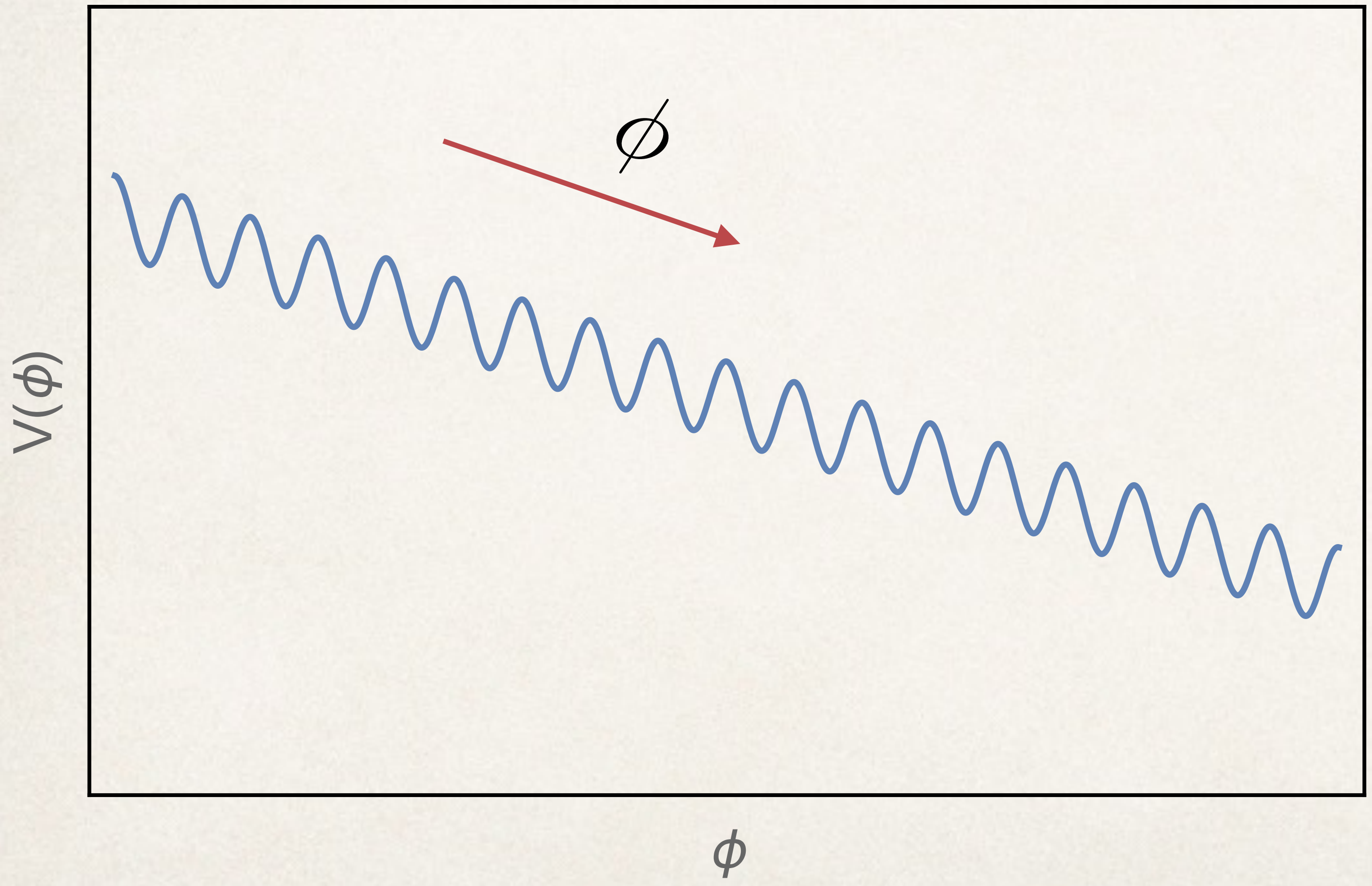
$$\dot{\phi} > \mu_s^2$$

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

$$\frac{\dot{\phi}}{f} < \Lambda$$

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

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

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

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

Quick Summary

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

- Tachyonic mode for A: $\Omega \sim \dot{\phi}/f$
  - → selects v
  - → creates friction

- Temperature dilutes tachyon time-scale:

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

Can it work in the real world?

Particle Production relaxion in SM

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

Particle Production relaxion in SM

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

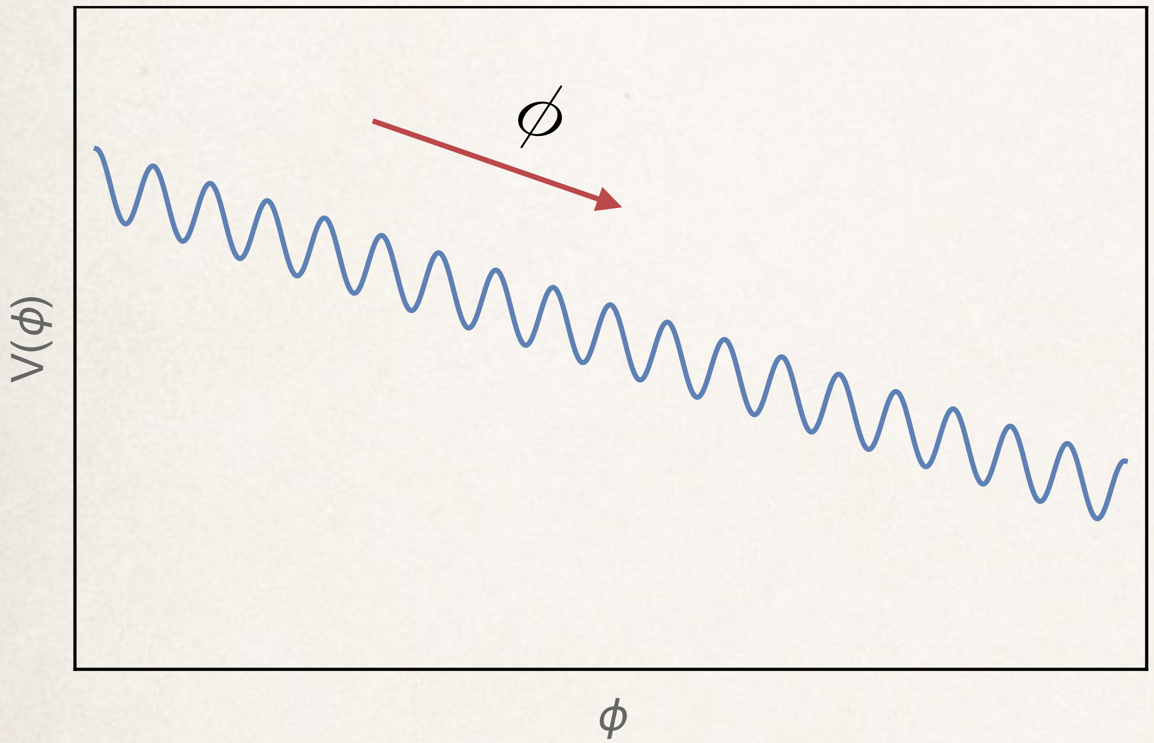
- Relaxion does not couple to the photon!

Relaxion setup

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

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

Relaxion setup



$$\mu_s^2 < \dot{\phi} \sim \text{const} \lesssim \Lambda^2$$

- "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

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

$$\delta m_H \sim \frac{\epsilon\dot{\phi}}{v}\delta t$$

$$\delta t \sim \Omega^{-1} \sim \frac{f}{\dot{\phi}}\left(\frac{\dot{\phi}/f}{T}\right)^{-2}$$

Energy Loss

- Not overshooting v

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

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

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

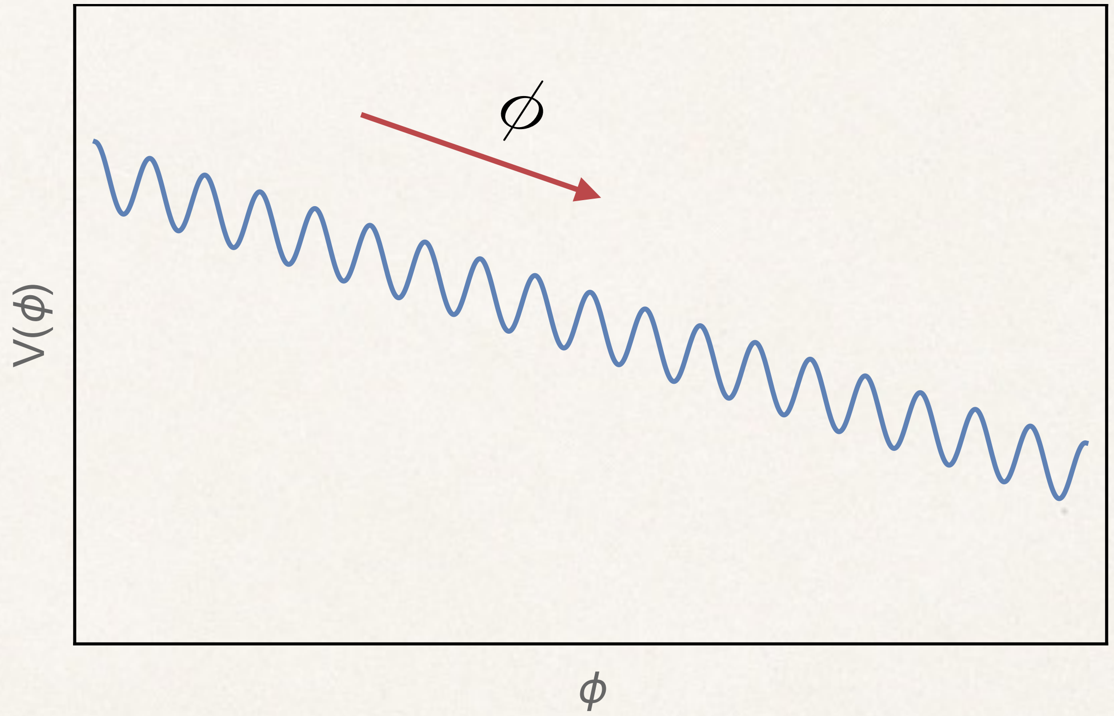
Possible realization

Initial Conditions

- Take this inflationary initial conditions

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

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



Initial Conditions

- Take this inflationary initial conditions

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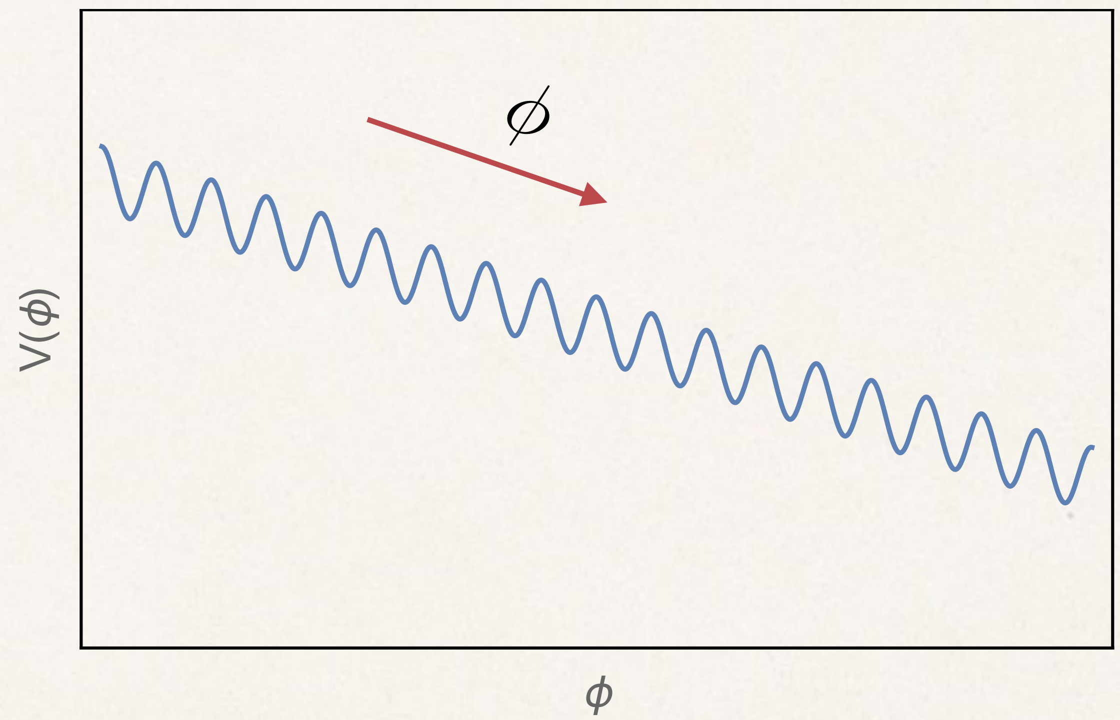
$$\dot{\phi} > \mu_s^2$$



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

Relaxing during inflation

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

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

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

Relaxing during inflation

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

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

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

$\Delta N_e \sim 100$ →

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

	Λ	H	ϵ	N_e	f	f'	Λ_c
Values in GeV	10^5	10^{-5}	10^{-6}	10^2	3×10^6	10^9	1.5×10^4

Inflation too brief

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

- Can the scanning continue after inflation ends?

Inflation too brief

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

- Can the scanning continue after inflation ends?

Yes!

*but before SM reheats

Scanning after inflation

Hubble decreases → $\dot{\phi}$ increases

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

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

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

Scanning after inflation

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

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

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

	Λ	ϵ	f	f'	Λ_c
Values in GeV	10^4	10^{-10}	10^6	10^{14}	10^3

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