Title: Relaxion from particle production

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Abstract: <p>Recently a new solution to the hierarchy problem was proposed which makes use of the cosmological evolution of a light scalar field, a scanner, instead of symmetry or anthropic arguments to select a small Higgs mass. In the original proposal this scanner field could be the QCD axion and thus such class of solution became known as ``relaxionâ€™â€™. Two central features required of the relaxion are a reason for why a small Higgs mass is special from the scannerâ€™s viewpoint and a mechanism fo the scanner to dissipate its energy in order to stop in a value associated with small Higgs mass. In this talk we propose a novel mechanism that achieves both goals and opens new possibilities for the relaxion. We show that particle production can create an effective friction force for the relaxion and show how it can be used to ``selectâ€™â€™ the TeV scale as a special energy scale from reasonable initial conditions. This allows for the scanning to happen much faster than in previous relaxion models, which usually require very large amounts of inflation, and also allows for the scanning to take place after inflation has ended.</p>

Relaxion with Particle Production

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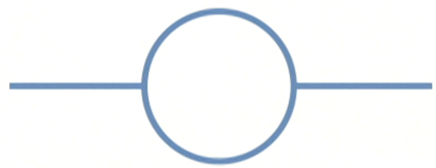
with A. Hook: 1607.01786

Why is the Higgs mass small?

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

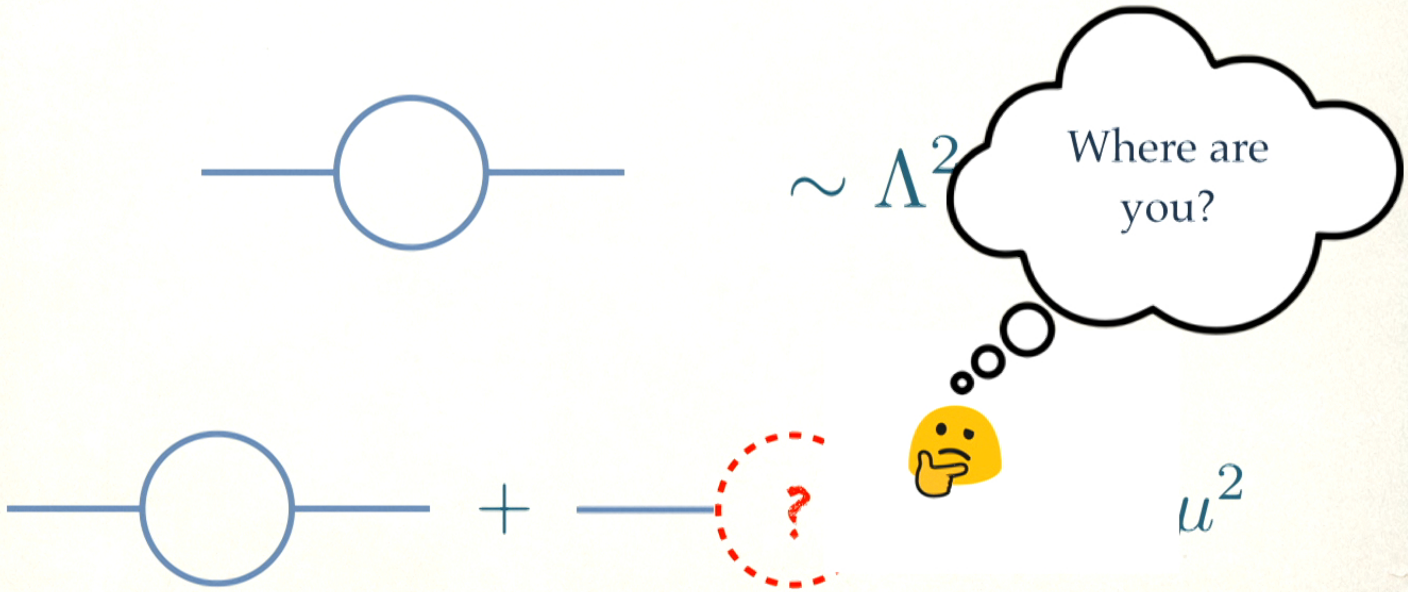
Symmetry



$$\sim \Lambda^2$$

$$\sim \mu^2$$

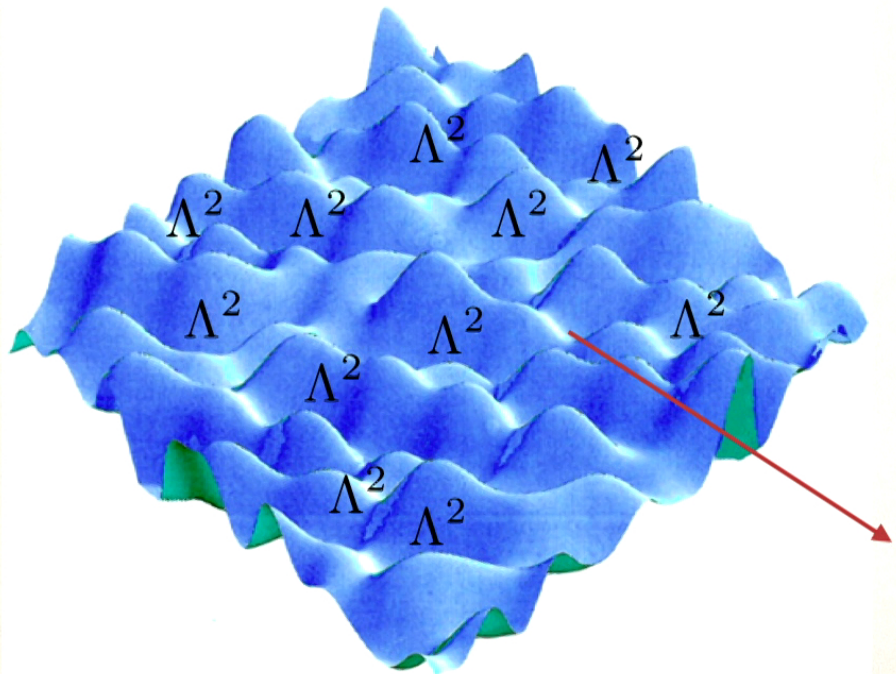
Symmetry



Why is the Higgs mass small?

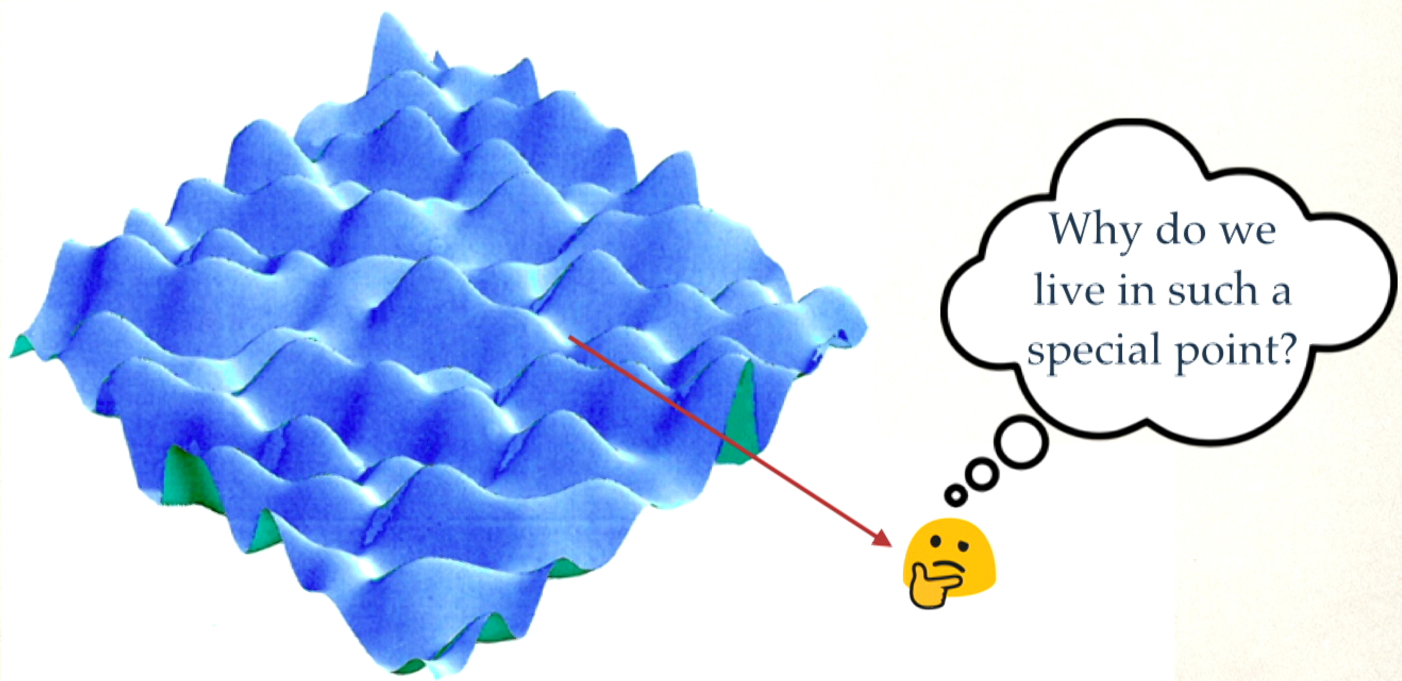
$$m_h^2 \longrightarrow m_h^2(\phi)$$

Multiverse



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

Multiverse



"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

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

Relaxion

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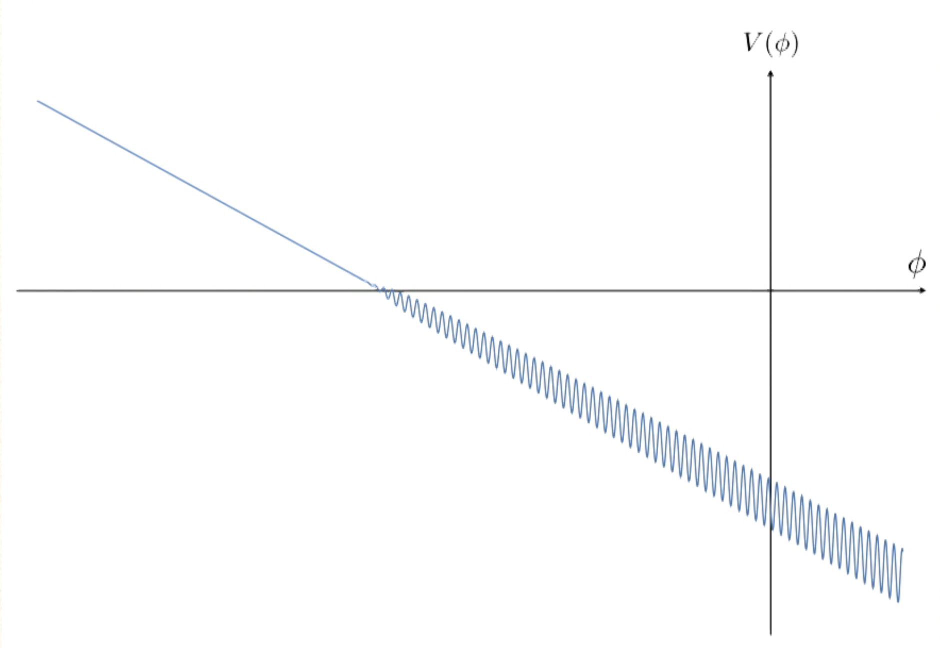


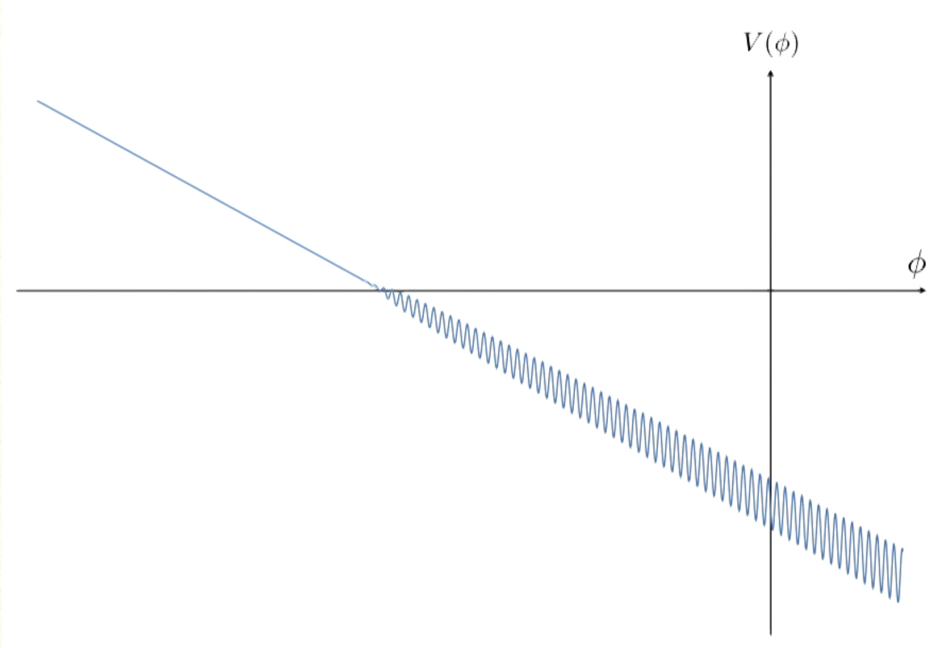
$$\phi \sim \Lambda^2/\epsilon$$

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

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

Relaxion

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

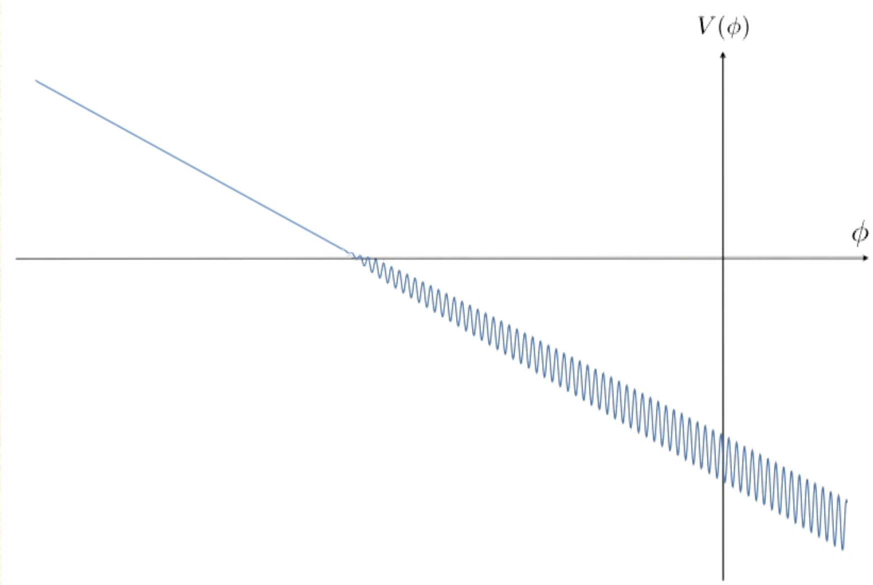


$$\phi \sim \Lambda^2/\epsilon$$

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

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

Relaxion



- Stopping mechanism
  cos() potential
- Dissipation
  Hubble friction

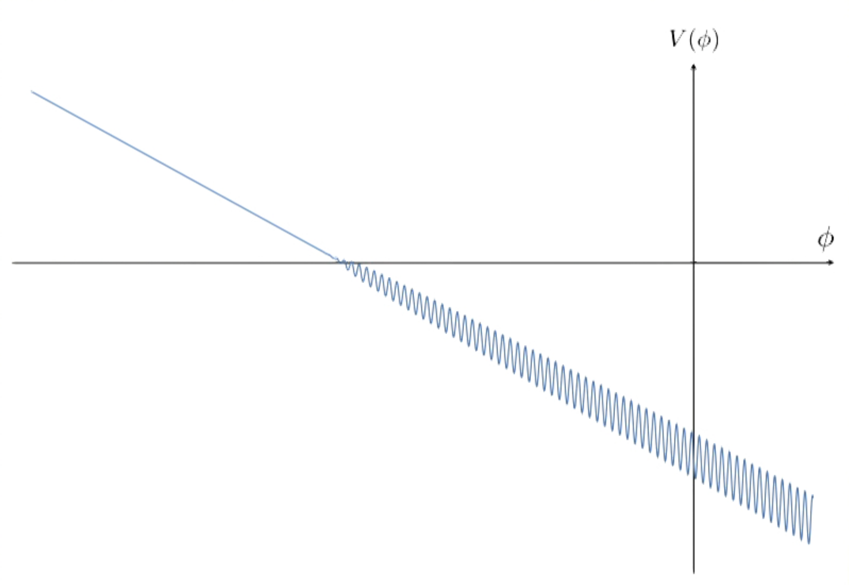
Relaxion: Slow roll regime

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

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

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

Relaxion: requires many e-foldings

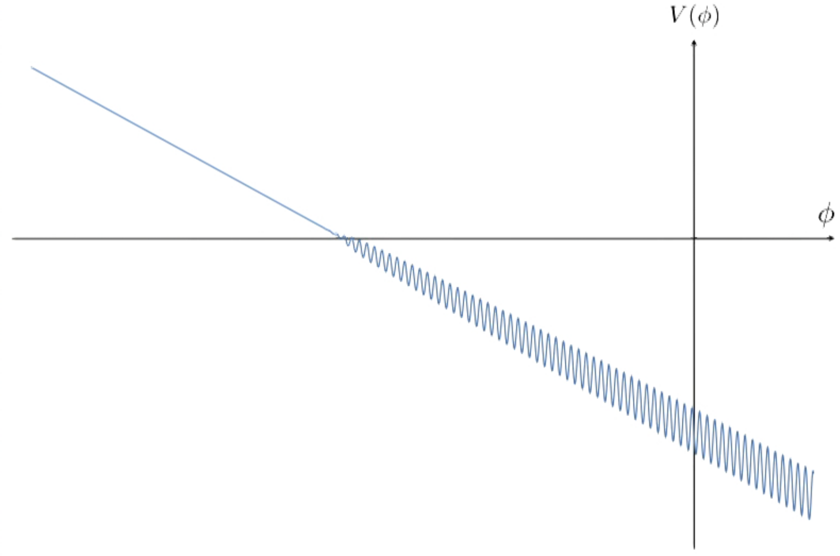


Slow Roll

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

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

Relaxion: requires many e-foldings



Slow Roll

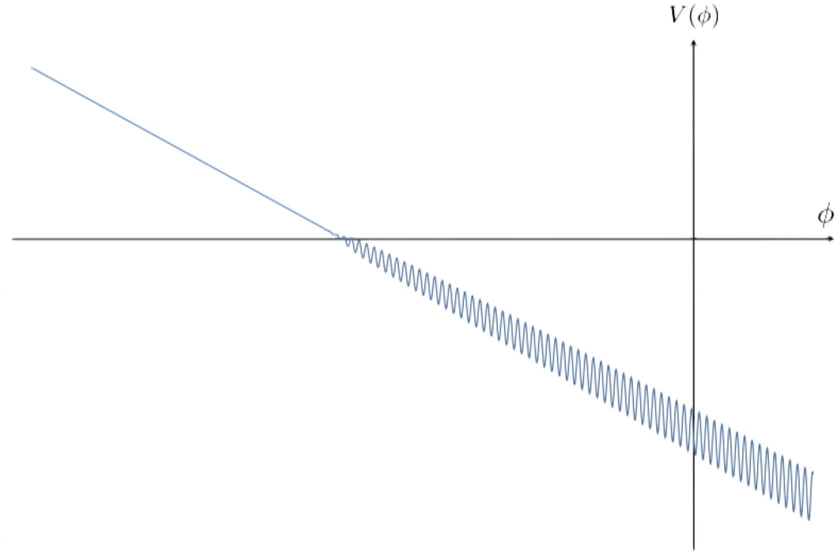
$$\dot{\phi} \sim \epsilon\Lambda^2/H$$

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

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

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

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

Keep me honest slide

Relaxion models

- The good
  - Technically natural (hope for natural UV)
  - Non-anthropic "multiverse" type solution
  - Relatively unexplored idea

- The bad
  - Introduces new small numbers
  - Tall order for inflationary models
  - Aesthetics
  - ...

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

⬇

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

Basic Mechanism

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

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

- 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

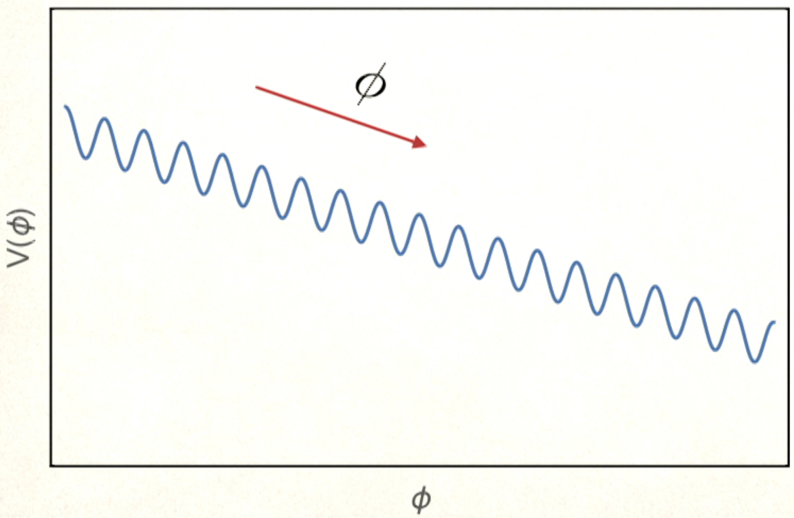
$$\omega^2 = k^2 + m_A^2 - \frac{k\dot{\phi}}{f}$$

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

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

Basic Mechanism

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



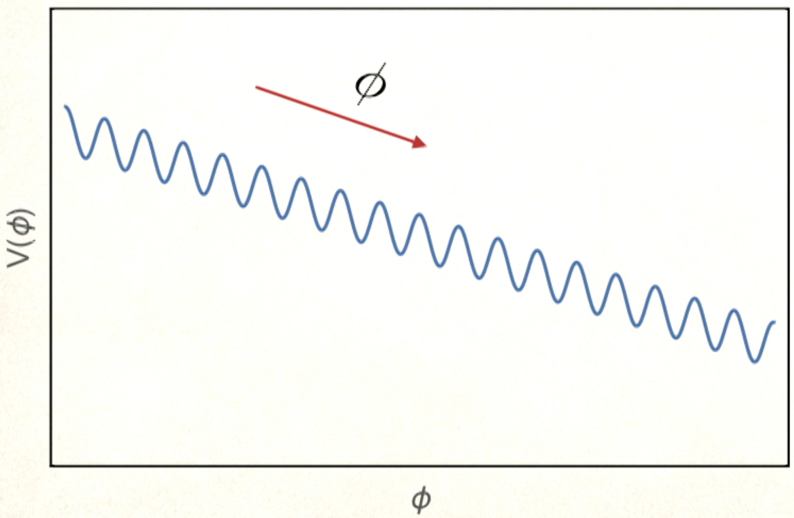
$$\dot{\phi} > \mu_s^2$$

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

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

Basic Mechanism

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



- Scans until

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

- When

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

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

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

Particle Production relaxion in SM

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

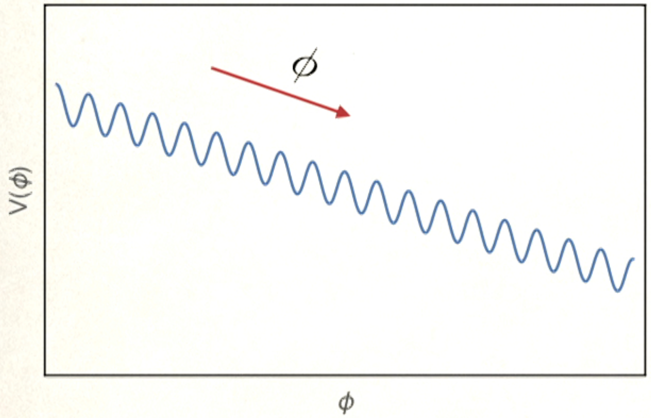
- Relaxion does not couple to the photon!

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

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

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

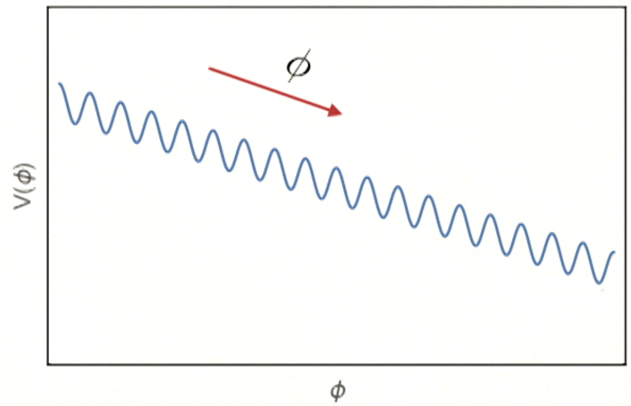
$$\epsilon < \frac{v^5 \mu_s^4}{T^8}$$

Initial Conditions

- Take this inflationary initial conditions

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

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

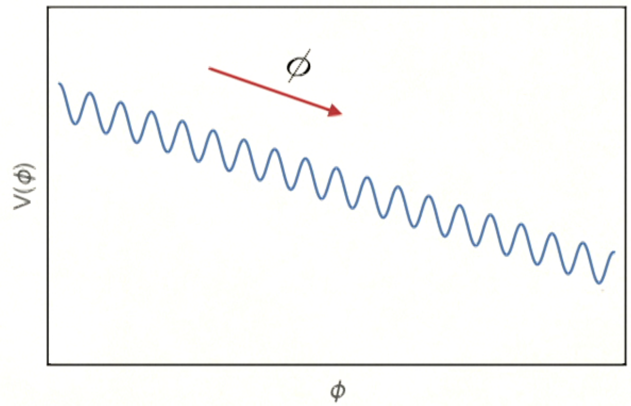


Initial Conditions

- Take this inflationary initial conditions

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

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



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

Relaxing during inflation

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

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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

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

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

$$\Lambda^6 < v^5 M_P \Delta N_e \xrightarrow{\Delta N_e \sim 100} \Lambda \lesssim 10^5 \text{ GeV}$$

	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