Constraints on Relaxion Parameters

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(HU-IBS Summer Institute, Aug. 2016, Sapporo)

KC, S.H. Im, 1511.00132

KC, S.H. Im, work in preparation

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Outline

- Relaxion solution to the hierarchy problem
- Inflationary constraints on relaxion parameters
- Further constraints on relaxion parameters
- Conclusion

Relaxion solution to the hierarchy problem

* Gauge hierarchy problem of the Standard Model (SM)

$$\mathcal{L}_{\rm higgs} = D_\mu H^\dagger D^\mu H - m_H^2 |H|^2 - \frac{1}{4}\lambda |H|^4 + y_t H q_3 u_3^c + \ldots$$

$$\Rightarrow \quad \delta m_H^2 = \left[-3y_t^2 + 3\lambda + \frac{9g_2^2 + 3g_1^2}{8} + \ldots\right] \frac{\Lambda_{\rm SM}^2}{16\pi^2}$$

This requires a fine tuning if the SM cutoff scale $\Lambda_{\rm SM}$ >> weak scale.

* Possible solutions:

- New physics to regulate the quadratic divergence near the weak scale

  SUSY, composite Higgs, extra dim, …

- Anthropic selection with multiverse

- **Cosmological relaxation**

- Neutral Naturalness, N-naturalness, …

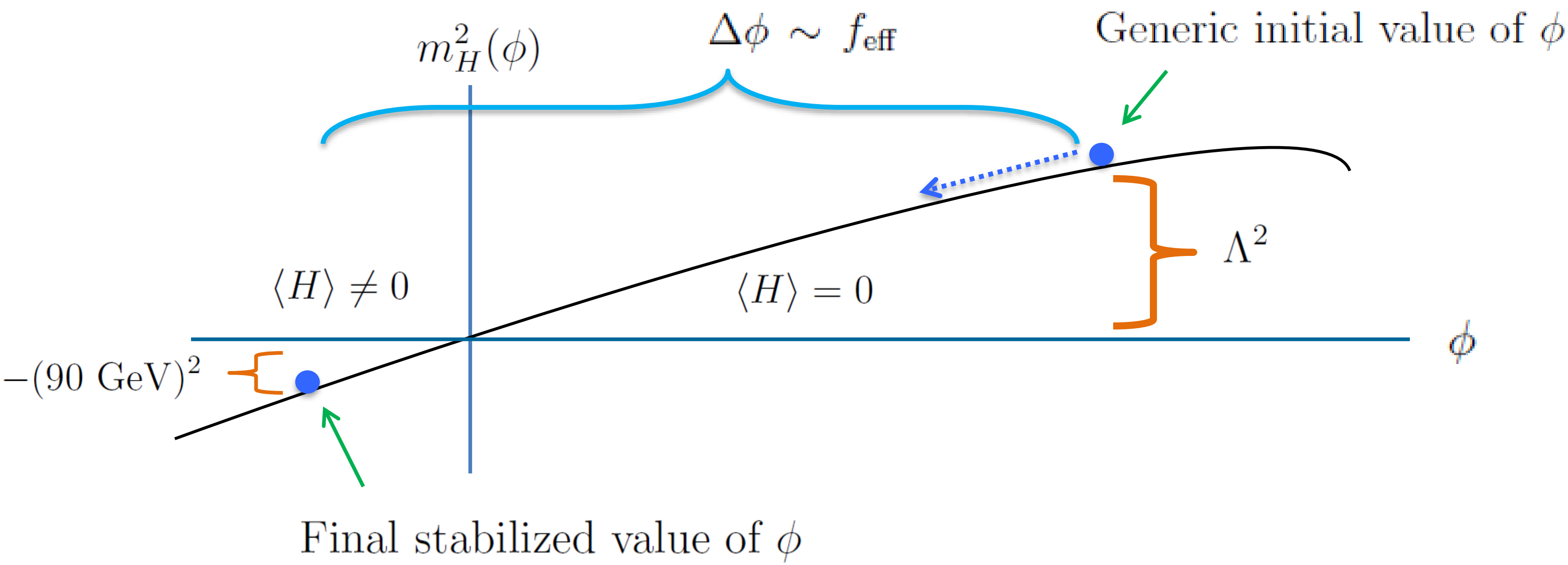
Cosmological relaxation of the hierarchy problem Graham, Kaplan, Rajendran '15

A pseudo-Nambu-Goldstone boson (= **relaxion**) ϕ scans the Higgs mass[2]

from $m_H^2(\phi_i) \sim \Lambda^2$ to $m_H^2(\phi_f) \sim -(90\,\mathrm{GeV})^2$:

$$\boxed{\Lambda^2\left(c_1 + c_2\cos\left(\frac{\phi}{f_{\rm eff}} + \delta_1\right) + \ldots\right)|H|^2}$$

$$m_H^2(\phi)|H|^2 = \Lambda^2\left(c_1 + c_2\frac{\phi}{f_{\rm eff}} + \ldots\right)|H|^2$$



To stop the rolling relaxion at the right position, we need a periodic barrier potential whose height depends on the Higgs VEV:

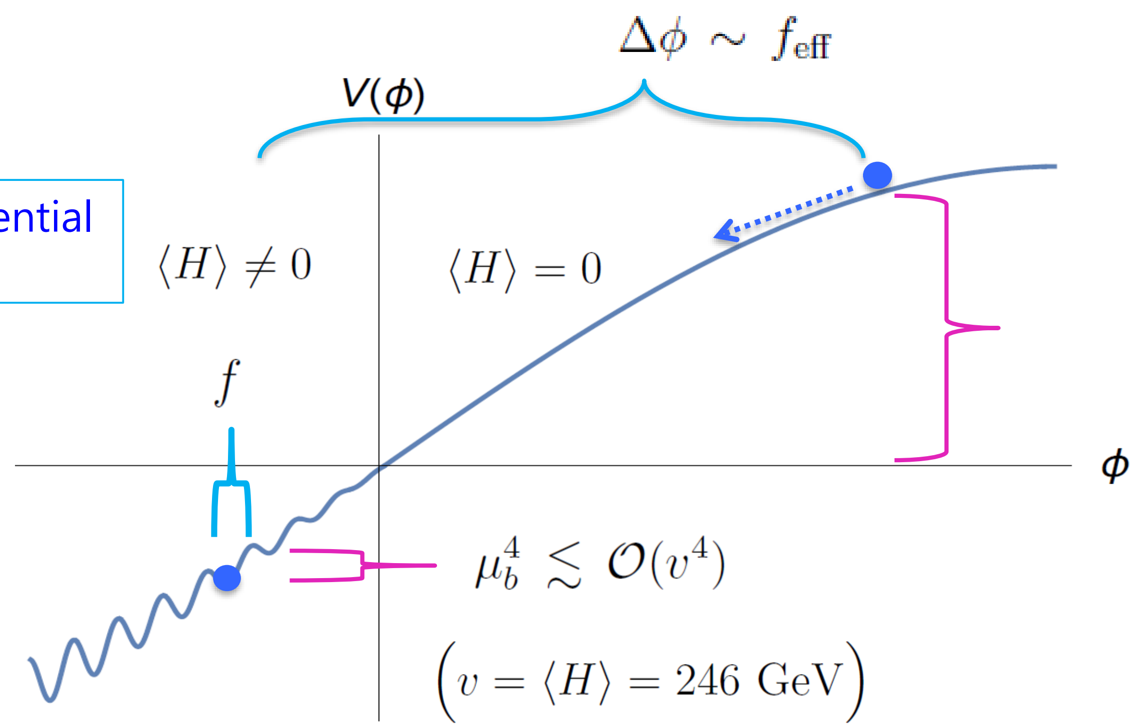
$$V = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right) + \Lambda^4\left(c_3 + c_4\frac{\phi}{f_{\rm eff}} + \ldots\right)$$

$$\left(\mu_b^4(H) = \mu^{4-n}|H|^n\right)$$

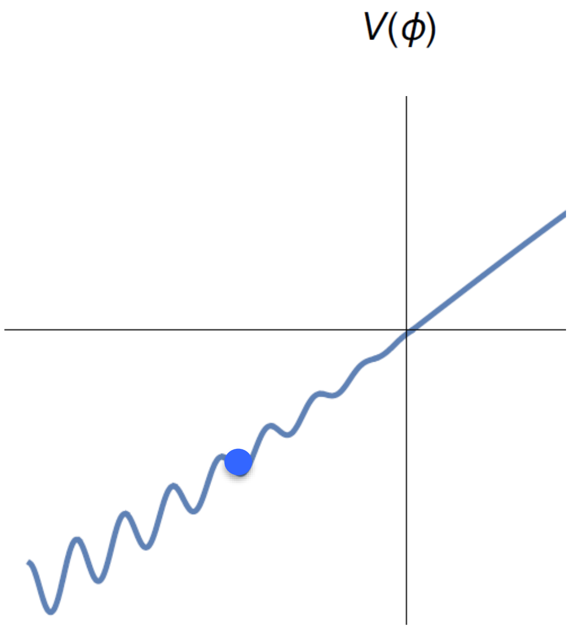
Sliding potential

$$\Lambda^4\left(c_3 + c_4\cos\left(\frac{\phi}{f_{\rm eff}} + \delta_2\right) + \ldots\right)$$

Periodic barrier potential to stop the relaxion



Possible origin of the barrier potential:



$$V_{\rm barrier} = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right)$$

$$\left(\mu_b^4(H) = \mu^{4-n}|H|^n\right)$$

* $SU(2)\times U(1)$-breaking QCD condensation:

$$\frac{1}{32\pi^2}\frac{\phi}{f}\left(G\tilde{G}\right)_{\rm QCD}$$

$$\rightarrow \quad \mu_b^4(H=v) \sim m_u\Lambda_{\rm QCD}^3 \sim \left(0.1 \text{ GeV}\right)^4$$

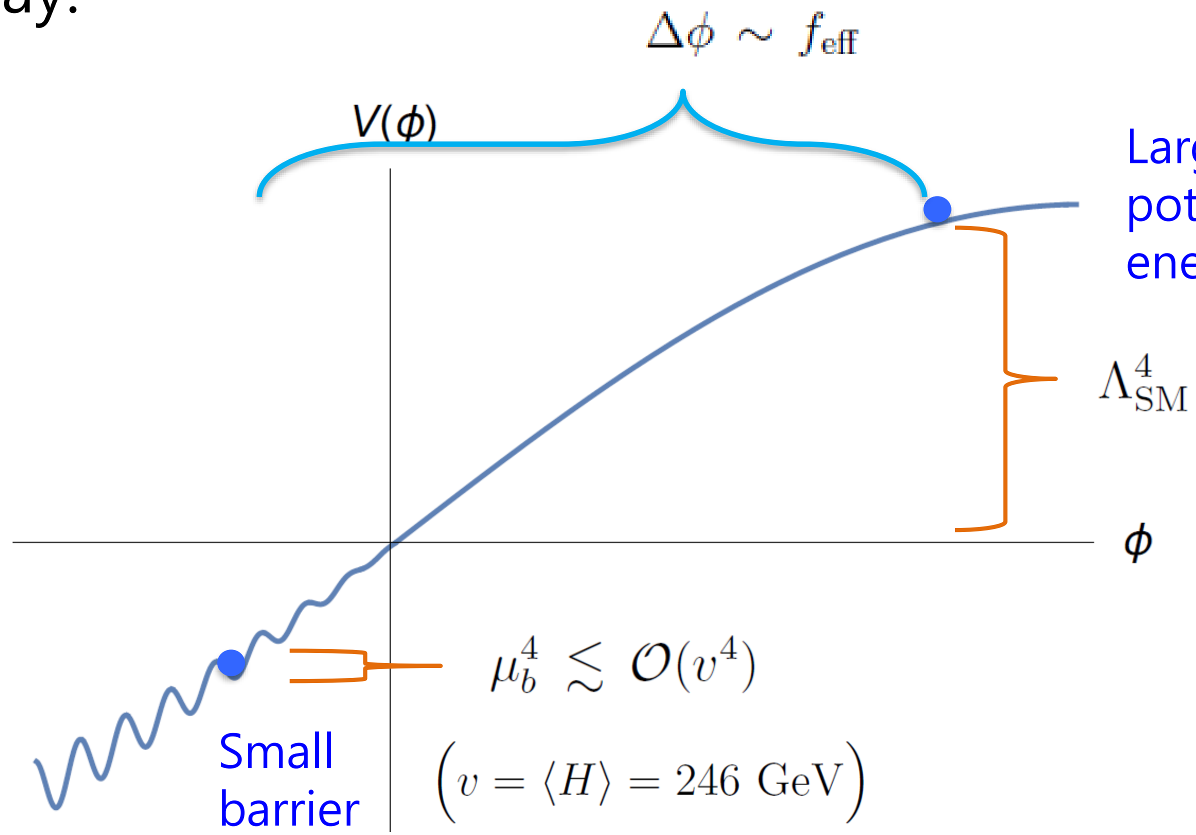
$$(n=1)$$

* $SU(2)\times U(1)$-preserving new physics (NP) around TeV:

$$\rightarrow \quad \mu_b^4(H=v) \sim \left(200 \text{ GeV}\right)^4$$

$$(n=2)$$

Price to pay:



➔ Requires a cosmological history with <u>long time of energy dissipation</u> and also <u>long excursion of the relaxion</u>

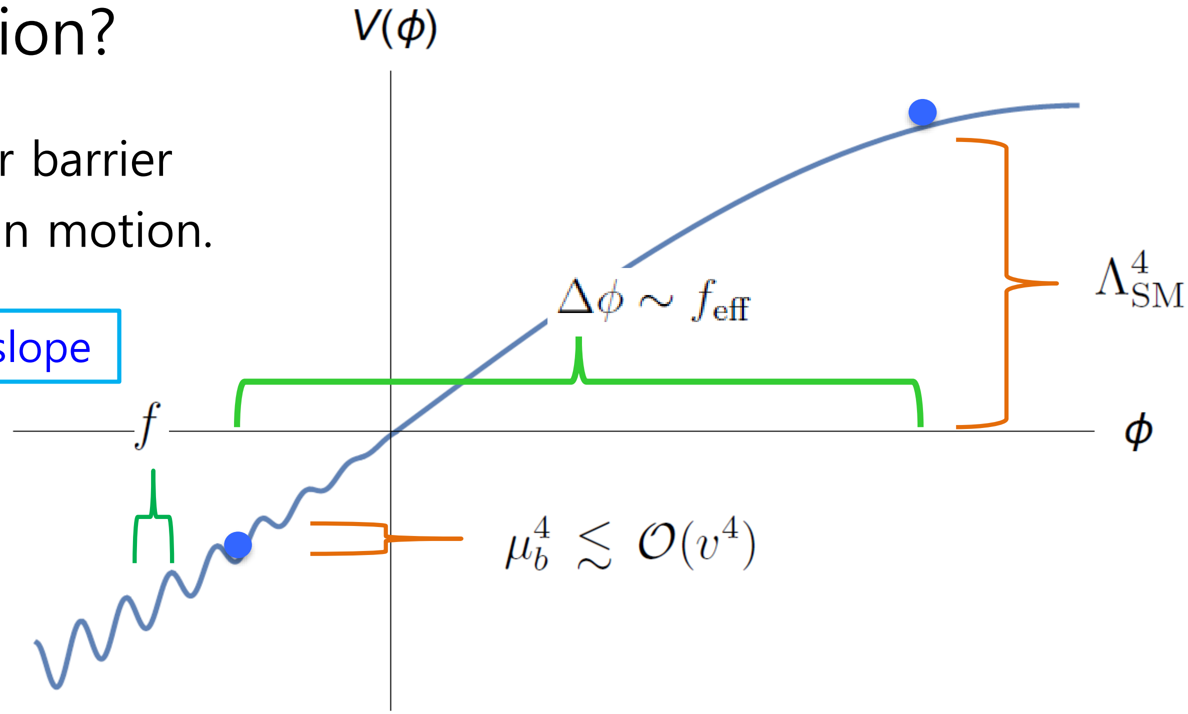
How long excursion?

Higher $\Lambda_{\rm SM}$ and lower barrier requires longer relaxion motion.

Sliding slope ~ Barrier slope

$$\frac{\Lambda_{\rm SM}^4}{f_{\rm eff}} \sim \frac{\mu_b^4}{f} \lesssim \frac{v^4}{f}$$

$$\Rightarrow \quad \frac{f_{\rm eff}}{f} \gtrsim \left(\frac{\Lambda_{\rm SM}}{v}\right)^4$$



* QCD-induced barrier:

Required inflationary e-foldings

$$\frac{f_{\rm eff}}{f} \sim 10^{15}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4 \qquad N_e \gtrsim {\rm Max}\left(10^{15}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4,\ 10^{12}\left(\frac{f}{10^9\ {\rm GeV}}\right)^2\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^8\right)$$

* NP-induced barrier with $\mu_b \sim 200\ {\rm GeV}$:

$$\frac{f_{\rm eff}}{f} \sim 10^{2}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4 \qquad N_e \gtrsim {\rm Max}\left(10^{2}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4,\ 10^{-25}\left(\frac{f}{\rm TeV}\right)^2\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^8\right)$$

Relaxion converts the weak scale hierarchy to a bigger hierarchy in relaxion scales:

Weak scale hierarchy ➔ Relaxion scale hierarchy

$$\boxed{\frac{\Lambda_{\rm SM}^2}{v^2} \gg 1}$$

$$(v = 174 \text{ GeV})$$

$$\boxed{\frac{f_{\rm eff}}{f} \gtrsim \left(\frac{\Lambda_{\rm SM}^2}{v^2}\right)^2}$$

The key point is that $f \ll f_{\rm eff}$ is stable against radiative corrections, thus technically natural, which can be assured by means of a discrete axionic shift symmetry.

The QCD-induced barrier potential requires

* too long time of inflation for energy dissipation: $N_e \gtrsim 10^{15}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4$

* too big axion scale hierarchy: $\frac{f_{\rm eff}}{f} \sim 10^{15}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4$

* too large strong CP violation: $\theta_{\rm QCD} = \frac{\langle\phi\rangle}{f} \sim 1$

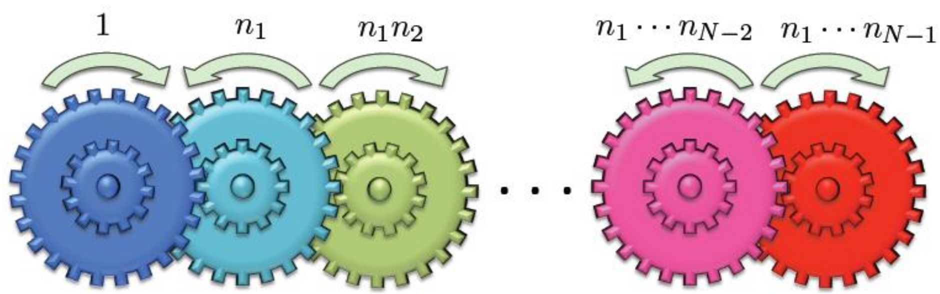
➔ NP-induced barrier potential (e.g. QCD-like force at TeV) is more favored.

Although technically natural, $f \ll f_{\rm eff}$ needs physical explanation.

Clockwork mechanism for exponentially big axion scale hierarchy

KC, Kim, Yun '14; KC, Im, 1511.00132; Kaplan, Rattazzi,1511.01827

Multiple axions with clockwork-couplings between nearby axions:



$$\rightarrow \quad \frac{\phi_1}{f_1} = -n_1 \frac{\phi_2}{f_2}, \quad \frac{\phi_2}{f_2} = -n_2 \frac{\phi_3}{f_3}, \quad \cdots \quad \frac{\phi_{N-1}}{f_{N-1}} = -n_{N-1} \frac{\phi_N}{f_N}$$

Relaxion field describing the overall rotation has an exponentially enhanced field range and hierarchical couplings:

$$\frac{\phi_1}{f_1} = \frac{\phi}{f}, \quad \frac{\phi_N}{f_N} = \frac{\phi}{f_{\rm eff}} \quad \left(f \sim f_1\right) \quad \rightarrow \quad \frac{f_{\rm eff}}{f} = n_1 n_2 \ldots n_{N-1} \sim e^N, \quad \Delta\phi = 2\pi f_{\rm eff}$$

Inflationary constraints on relaxion parameters

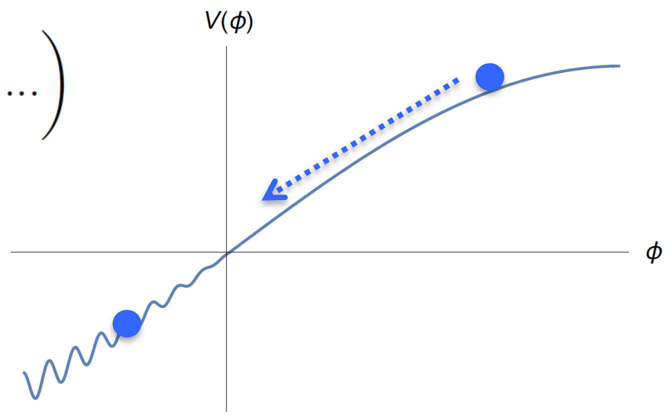
(Our approach and results are different from 1605.06908 in many respects.)

$$\boxed{\Lambda^2\left(c_1 + c_2\cos\left(\frac{\phi}{f_{\rm eff}} + \delta_1\right) + \ldots\right)|H|^2}$$

$$\boxed{\Lambda^4\left(c_3 + c_4\cos\left(\frac{\phi}{f_{\rm eff}} + \delta_2\right) + \ldots\right)}$$

$$\mathcal{L}_\phi = \Lambda^2\left(c_1 + c_2\frac{\phi}{f_{\rm eff}} + \ldots\right)|H|^2 + \Lambda^4\left(c_3 + c_4\frac{\phi}{f_{\rm eff}} + \ldots\right)$$

$$+\mu_b^4(H)\cos\left(\frac{\phi}{f}\right) + \frac{c_\gamma e^2}{16\pi^2}\frac{\phi}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$



* Stabilization: $\dfrac{\Lambda^4}{f_{\rm eff}} \sim \dfrac{\mu_b^4}{f}$

* Classical evolution: $\dfrac{\dot\phi}{\mathcal{H}} > \mathcal{H} \quad \Rightarrow \quad \mathcal{H} < \mu_b\left(\dfrac{\mu_b}{f}\right)^{1/3}$ $\left(\mathcal{H} = \text{Hubble expansion rate}\right)$

* Stopping the moving relaxion with barrier: $\dot\phi^2 \lesssim \mu_b^4 \quad \Rightarrow \quad \mathcal{H}(t_{\rm stop}) \gtrsim m_\phi \sim \dfrac{\mu_b^2}{f}$

$\left(t_{\rm stop} = \text{the moment when the relaxion stops}\right)$

* Inflaton domination: $\mathcal{H} > \dfrac{\Lambda^2}{M_{\rm Pl}}$

$$\Rightarrow \qquad N_e \sim \frac{f_{\text{eff}}}{\dot{\phi}/\mathcal{H}} \gtrsim \frac{f^2\Lambda^4\mathcal{H}^2(t_s)}{\mu_b^8} \gtrsim \text{Max}\left(\frac{\Lambda^4}{\mu_b^4},\ \frac{f^2}{M_{\text{Pl}}^2}\frac{\Lambda^8}{\mu_b^8}\right)$$

$$\mu_b \ > \ 10^2\,\text{GeV} \times \left(\frac{\Lambda}{\text{TeV}}\right)\left(\frac{10^4}{N_e}\right)^{1/4}$$

$$\Lambda \ < \ f \ < \ 10^{16}\,\text{GeV} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \left(\frac{\mu_b}{10^2\,\text{GeV}}\right)^4 \left(\frac{N_e}{10^4}\right)^{1/2}$$

$$10^{-3}\,\text{eV} \times \left(\frac{\Lambda}{\text{TeV}}\right)^4 \left(\frac{10^2\,\text{GeV}}{\mu_b}\right)^2 \left(\frac{10^4}{N_e}\right)^{1/2} \ < \ m_\phi \sim \frac{\mu_b^2}{f} \ < \ 10\,\text{GeV} \times \left(\frac{\mu_b}{10^2\,\text{GeV}}\right)^2 \left(\frac{\text{TeV}}{\Lambda}\right)$$

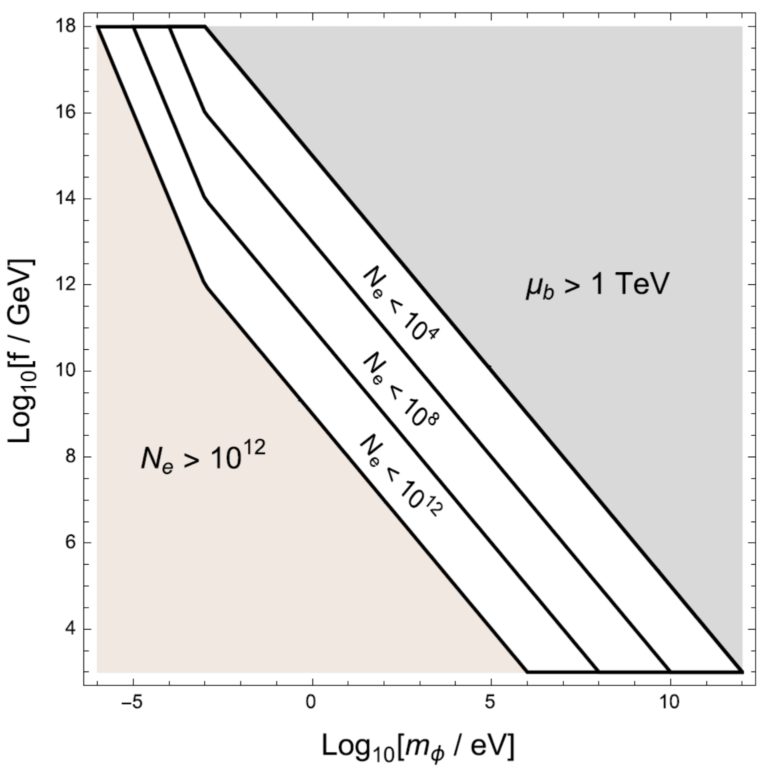
$$\text{Max}\left(m_\phi,\ \frac{\Lambda^2}{M_{\text{Pl}}}\right) \ < \ \mathcal{H}(t_{\text{stop}}) \ < \ \mu_b \left(\frac{\mu_b}{f}\right)^{1/3}$$

One of the difficulties is that the mechanism requires a long inflationary period:

$$N_e \gtrsim \mathrm{Max}\left(\frac{\Lambda^4}{\mu_b^4},\ \frac{f^2}{M_{\rm Pl}^2}\frac{\Lambda^8}{\mu_b^8}\right)$$

Generically large N_e requires a fine tuning in the inflaton sector, and therefore we might need to impose an upper bound on N_e:

Relaxion mass and decay constant with $N_e < 10^4,\ 10^8,\ 10^{12}$:



$$\mathcal{L}_\phi = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right) + \frac{c_\gamma e^2}{16\pi^2}\frac{\phi}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

$$\left(\mu_b^4(H) = \mu^2|H|^2,\ c_\gamma = \mathcal{O}(1)\right)$$

$$m_\phi \sim \frac{\mu_b^2}{f}$$

$$\mu_b < 1\ \mathrm{TeV}$$

$$f > \Lambda_{\rm SM} > 1\ \mathrm{TeV}$$

Relaxion dynamics during the reheating period:

$$T_{\rm max} \sim 3 \times 10^5\,{\rm GeV} \times \left(\frac{T_{\rm RH}}{\rm GeV}\right)^{1/2} \left(\frac{\mathcal{H}(t_{\rm end})}{\rm GeV}\right)^{1/4}$$

$$\Big(t_{\rm end} = \text{the moment when inflation is over}\Big)$$

What is the maximal values of $T_{\rm max}$ which can be compatible with the relaxion mechanism?

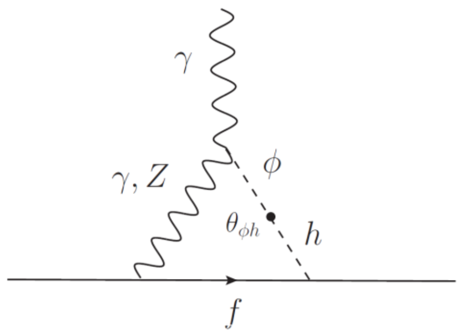
(Important issue, particularly for baryogenesis!)

KC, S.H. Im, H.J. Kim, work in progress

Further constraints mostly from the relaxion-Higgs mixing:

$$\mathcal{L}_\phi = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right) + \frac{c_\gamma e^2}{16\pi^2}\frac{\phi}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \dots \quad \left(\mu_b^4(H) = \mu^2|H|^2,\ c_\gamma = \mathcal{O}(1)\right)$$

* EDM:



* Rare meson decays:

$$\Phi \to \Phi' + \phi$$
$$\hookrightarrow \gamma\gamma, \ell\bar{\ell}, \pi\pi, \dots$$

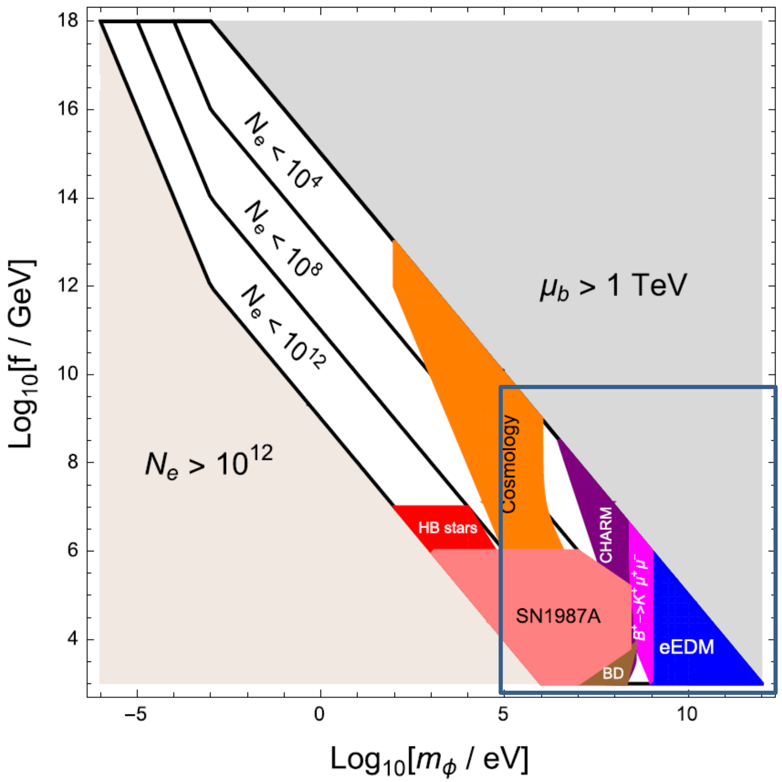
* Beam-dump experiments: $p + X \to \Phi + \dots$

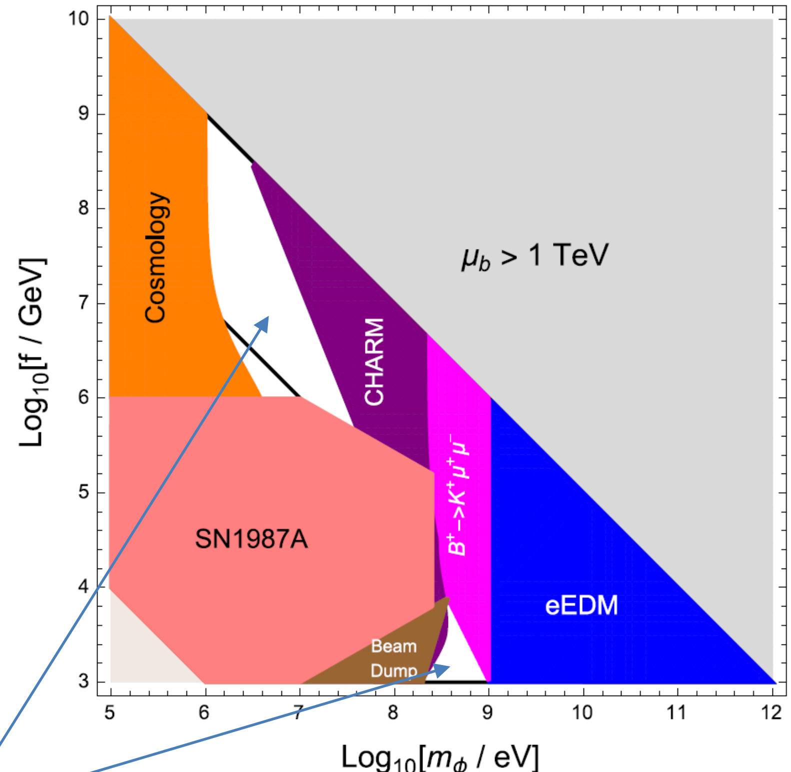
$$\hookrightarrow \Phi' + \phi$$
$$\hookrightarrow \gamma\gamma, \ell\bar{\ell}, \pi\pi, \dots$$

* Thermal production of relaxions in the early universe, and subsequent late relaxion decays:

Effects on BBN, dark radiation, diffuse X-rays, dark matter

Phenomenological constraints





These parameter region allowed by the present constraints can be probed by the future beam dump experiment. (e.g. SHiP)

Conclusion

Relaxion is a new approach to the hierarchy problem, achieving the light Higgs mass with a specially designed cosmological history.

The mechanism requires a big axion scale hierarchy, which might be achieved by the clockwork mechanism, and also a long inflationary period which may cause a fine tuning problem in the inflaton sector.

One of the key features of relaxion is the relaxion-Higgs mixing which can result in various phenomenological or cosmological consequences, and therefore observational constraints on the model parameters.

A key question is if the relaxion mechanism can accommodate successful generation of matter-antimatter asymmetry, dark matter, and the primordial density perturbation, which should be explored in future works.