Relaxion for the EW scale hierarchy

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Physics in LHC and the Early Universe

Tokyo, Jan. 11, 2017

KC, S.H. Im, arXiv:1511.00132 & 1610.0068

KC, H. Kim, T. Sekiguchi, arXiv:1611.08569

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* Hierarchy problem of the Standard Model (SM)

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

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

If the SM cutoff (= Higgs mass cutoff) scale $\Lambda_{\rm SM}$ >> weak scale, this causes a fine-tuning problem.

* Possible solutions:

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

  SUSY, Composite Higgs, Extra Dim, ...

- Anthropic selection with multiverse

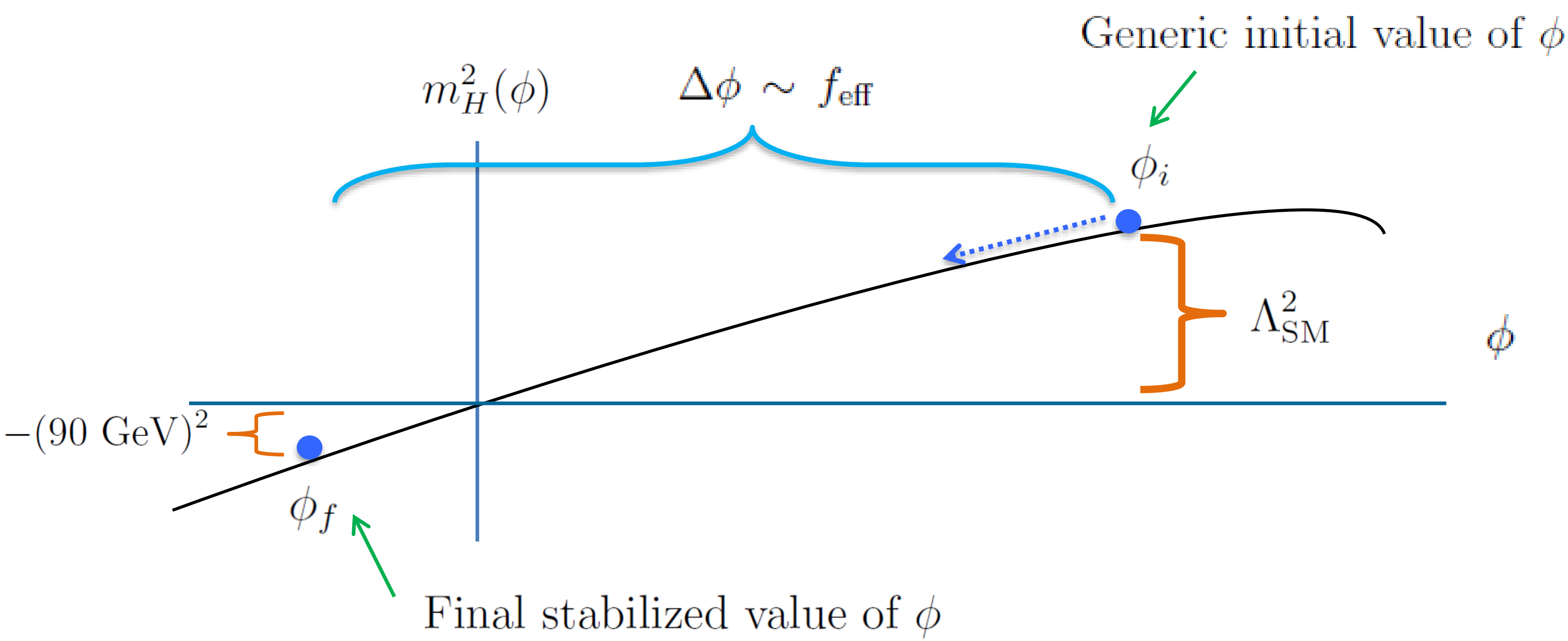
- **Cosmological relaxation**

- N-Naturalness, ...

Cosmological relaxation of the EW scale Graham, Kaplan, Rajendran '15

A pseudo-Nambu-Goldstone boson (=**relaxion**) ϕ whose cosmological evolution changes the Higgs mass from $m_H^2(\phi_i) \sim \Lambda_{\rm SM}^2 \gg v^2 \quad (v = 246 \text{ GeV})$ to $m_H^2(\phi_f) \sim -(90 \text{ GeV})^2$:

$$m_H^2(\phi)|H|^2 = \left(M_1^2 + M_2^2 \frac{\phi}{f_{\rm eff}} + ...\right)|H|^2 \quad (M_1 \sim M_2 \sim \Lambda_{\rm SM})$$

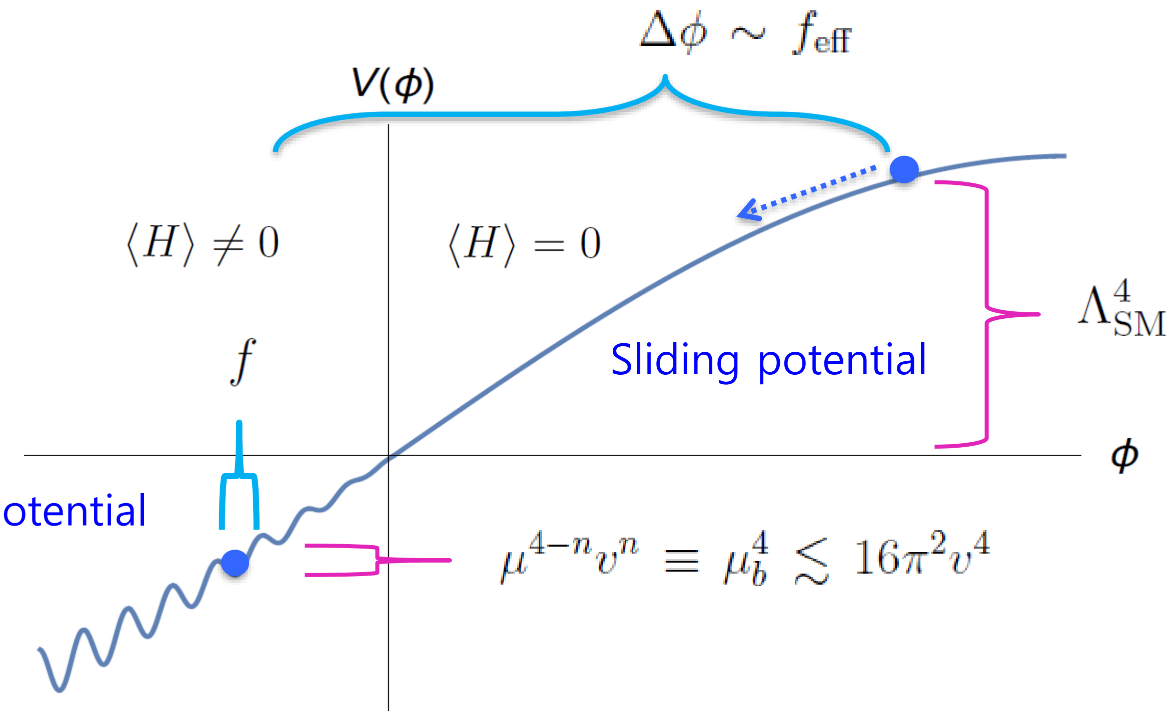


Key part of the scheme is the relaxion potential to implement the necessary cosmological evolution:

i) **Sliding potential** generated at $\Lambda_{\rm SM}$, which enforces the relaxion to move to change the Higgs mass

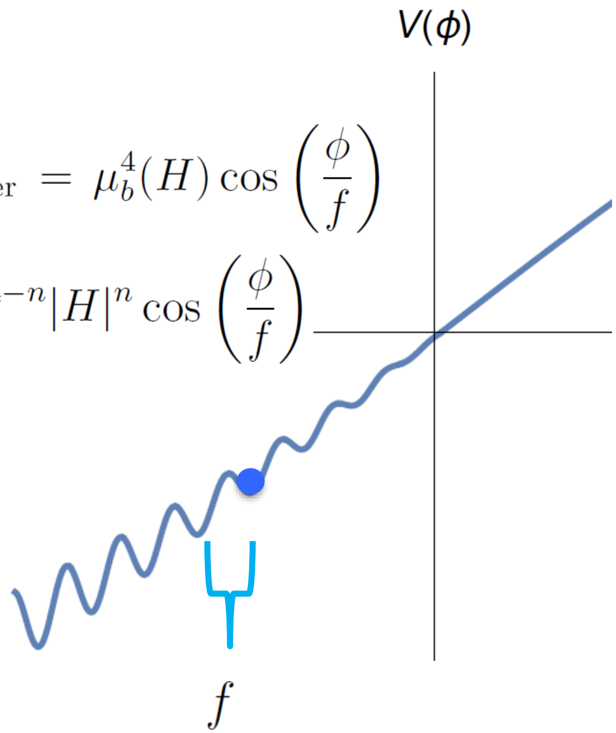
ii) **Periodic barrier potential** with Higgs-dependent height, generated at lower scales to stop the relaxion at the right position giving $m_H^2 = -(89\,{\rm GeV})^2$

$$V = \mu^{4-n}|H|^n \cos\left(\frac{\phi}{f}\right) + \left(\Lambda_{\rm SM}^4 \frac{\phi}{f_{\rm eff}} + \ldots\right) + \ldots$$



Possible origin of the barrier potential:

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



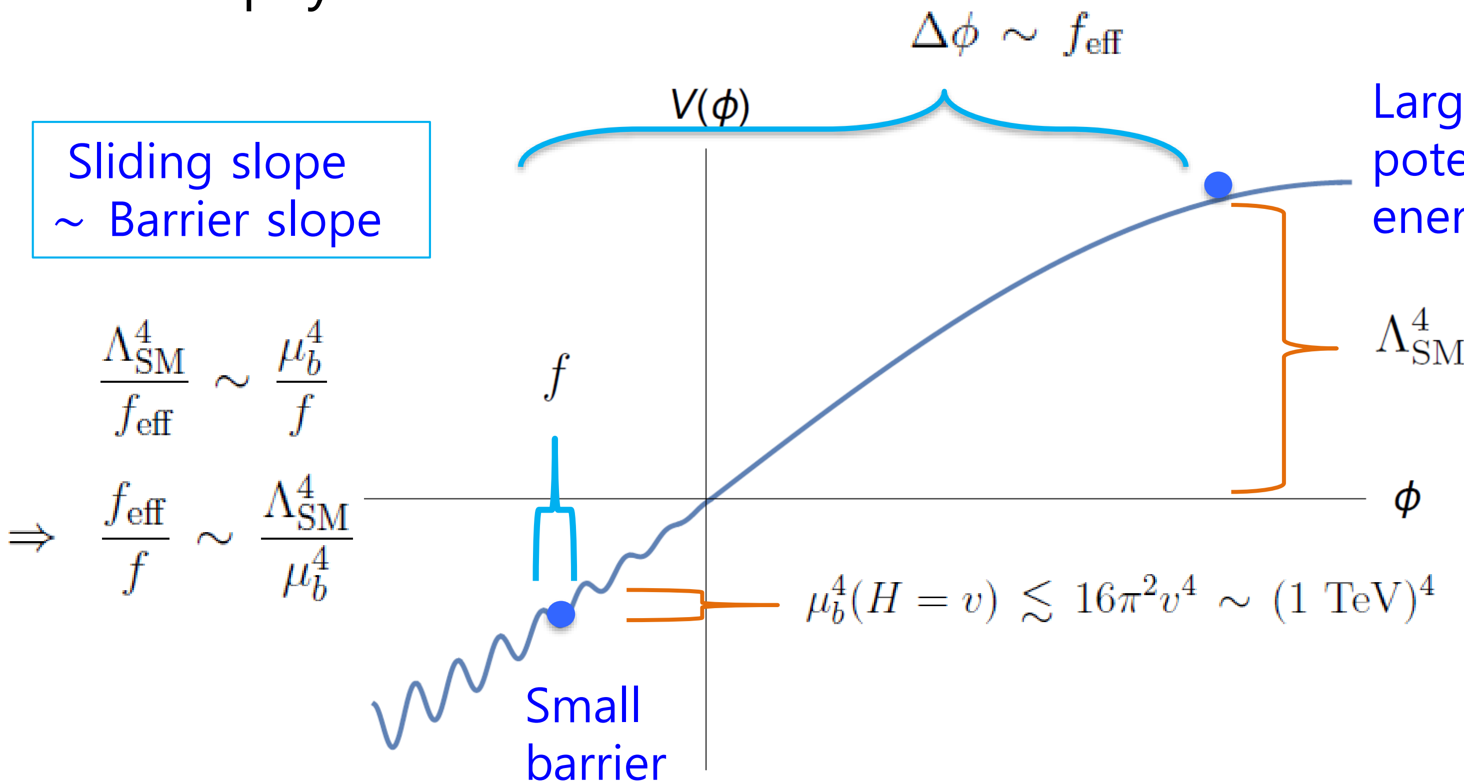
* QCD: $\frac{1}{32\pi^2}\frac{\phi}{f}\left(G\tilde{G}\right)_{\rm QCD}$

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

* New Physics around TeV:

➔ $\mu_b^4(H=v) \lesssim 16\pi^2 v^4 \sim (1~{\rm TeV})^4$

Price to pay:



➔ Requires i) cosmological dissipation of the relaxion energy

ii) long excursion $f_{\rm eff} \gg f$

(Higher $\Lambda_{\rm SM}$ and lower barrier require longer field excursion, and longer dissipation time.)

Relaxion converts the weak scale hierarchy to another hierarchy among the relaxion scales:

Weak scale hierarchy ➔ Relaxion scale (coupling) hierarchy

$$\Lambda_{\rm SM} \gg 1 \text{ TeV}$$

$$\frac{f_{\rm eff}}{f} \sim \left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4 \gg 1$$

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.

* **Relaxion excursion in angle unit & dissipation time in Hubble unit**

QCD-induced barrier: $\frac{f_{\rm eff}}{f} \sim \int_{t_i}^{t_f} \mathcal{H} dt \sim 10^{24} \left(\frac{10^{-10}}{\theta_{\rm QCD}}\right) \left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4$

New-physics-induced barrier: $\frac{f_{\rm eff}}{f} \sim \int_{t_i}^{t_f} \mathcal{H} dt \gtrsim \left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4$

➔ New-physics-induced barrier potential might be more promising.

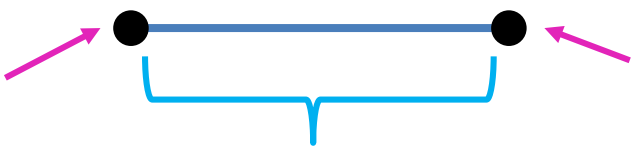
Yet we need an explanation for $f_{\rm eff} \gg f$.

Clockwork KC, Im, 1511.00132; Kaplan, Rattazzi,1511.01827

Two axions with a particular form of mass mixing

$$U(1)_i : \frac{\phi_i}{f_i} \to \frac{\phi_i}{f_i} + \alpha_i \qquad \frac{\phi_1}{f_1} \equiv \frac{\phi_1}{f_1} + 2\pi \qquad \frac{\phi_2}{f_2} \equiv \frac{\phi_2}{f_2} + 2\pi$$

$$V_1 = m_1^4 \cos\left(\frac{\phi_1}{f_1}\right) \qquad V_2 = m_2^4 \cos\left(\frac{\phi_2}{f_2}\right)$$



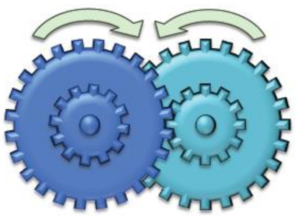
$$V_{\rm clockwork} = \Lambda^4 \cos\left(\frac{\phi_1}{f_1} + n\frac{\phi_2}{f_2}\right)$$

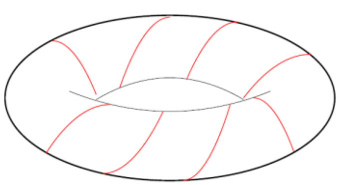
$$\Lambda \gg m_i$$

$$\Rightarrow \; U(1)_1 \times U(1)_2 \; \to \; U(1)_\phi \; \to \; \text{none}$$

$$\frac{\phi_2}{f_2} = -\frac{1}{n}\frac{\phi_1}{f_1}$$

$$\frac{\phi_2}{f_2} \qquad \frac{\phi_1}{f_1}$$



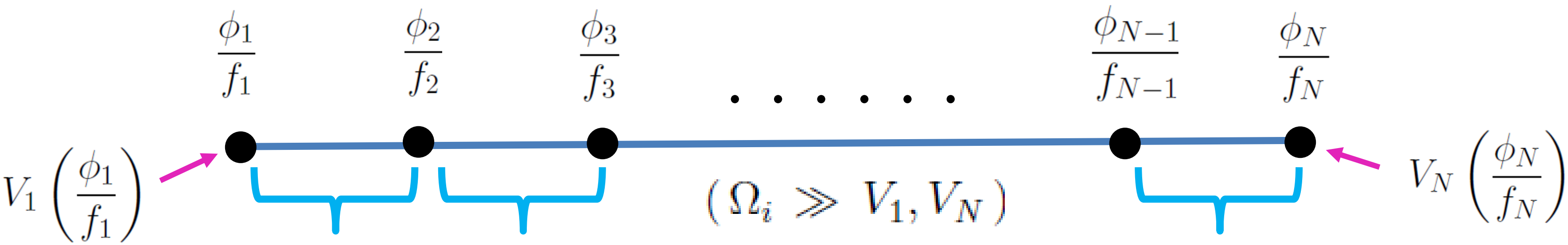


ϕ = light axion satisfying the clockwork constraint

$$\frac{\phi_1}{f_1} = \frac{\phi}{f}, \quad \frac{\phi_2}{f_2} = -\frac{1}{n}\frac{\phi}{f} \qquad (\, f \sim f_i \,)$$

$$\Rightarrow \quad V_{\rm eff}(\phi) = m_1^4 \cos\left(\frac{\phi}{f}\right) + m_2^4 \cos\left(\frac{\phi}{f_{\rm eff}}\right) \qquad (\, f_{\rm eff} = n f \,)$$

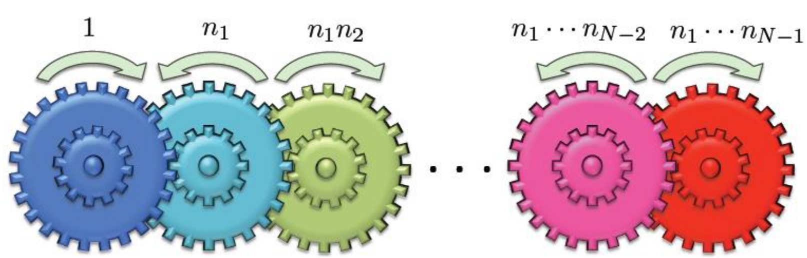
One can repeat the clockwork with more axions to get an exponentially big axion scale hierarchy.



$$\Omega_1\left(\frac{\phi_1}{f_1}+n_1\frac{\phi_2}{f_2}\right) \quad \Omega_2\left(\frac{\phi_2}{f_2}+n_2\frac{\phi_3}{f_3}\right) \quad \cdots\cdots \quad \Omega_{N-1}\left(\frac{\phi_{N-1}}{f_{N-1}}+n_{N-1}\frac{\phi_N}{f_N}\right)$$

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

clockwork gear



Lightest axion ϕ describing the collective rotation: $\frac{\phi_1}{f_1}=\frac{\phi}{f}, \quad \frac{\phi_N}{f_N}=\frac{1}{n_1 n_2 \ldots n_{N-1}}\frac{\phi}{f}=\frac{\phi}{f_{\rm eff}}$

i) exponentially enhanced field range: $\Delta\phi \sim n_1 n_2 \ldots n_{N-1} \sim e^N f \quad (f \sim f_i)$

ii) hierarchical effective couplings: $V_{\rm eff} = V_1\left(\frac{\phi}{f}\right)+V_N\left(\frac{\phi}{f_{\rm eff}}\right) \quad (f_{\rm eff} \sim e^N f)$

Clockwork scheme can be generalized to generate an exponentially small coupling (or mass) of s=1/2 fermion, s=1 gauge boson, and s=2 graviton.

Giudice & McCullough, 1610.07962

Clockwork mechanism can be realized also in appropriate extra-dim setup:

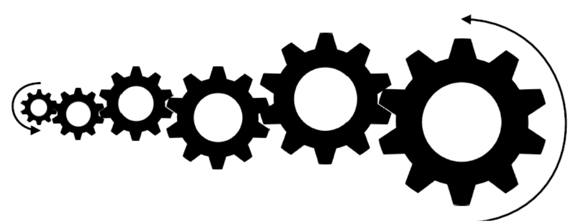
* 5D linear dilaton model which approximates the dual of Little String Theory

$$S_{\rm clockwork} = \int d^4x dy \sqrt{-g}\left[\frac{M_5^3}{2}\left(\mathcal{R} - \frac{1}{3}g^{MN}\partial_M S \partial_N S + 4e^{-2S/3}k^2\right) - e^{-S/3}\left(\frac{\delta(y)}{\sqrt{g_{55}}}\Lambda_0 + \frac{\delta(y-\pi R)}{\sqrt{g_{55}}}\Lambda_\pi\right)\right] \quad (\Lambda_0 = -\Lambda_\pi = 4kM_5^3)$$

➔ Clockwork geometry: $ds^2 = e^{-4k|y|/3}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$, $S = S_0 - 2k|y|$

* 5D scalar on clockwork geometry: $\Delta S = \int d^4x dy \sqrt{-g}\left(-\frac{1}{2}g^{MN}\partial_M \Phi \partial_N \Phi\right)$

Background geometry provides the clockwork gear among the massive KK modes of 5D scalar



$$\Phi(x, y=\pi R) \sim \frac{e^{-\pi k R}}{\sqrt{\pi R}}\phi_0(x) + \text{massive KK modes} \quad (\phi_0 = \text{zero mode})$$

Observational constraints on relaxion parameters KC, Im, 1610.00680

$$m_H^2(\phi)|H|^2 = \left(M_1^2 + M_2^2\frac{\phi}{f_{\rm eff}} + ...\right)|H|^2 \quad (M_1 \sim M_2 \sim \Lambda_{\rm SM})$$

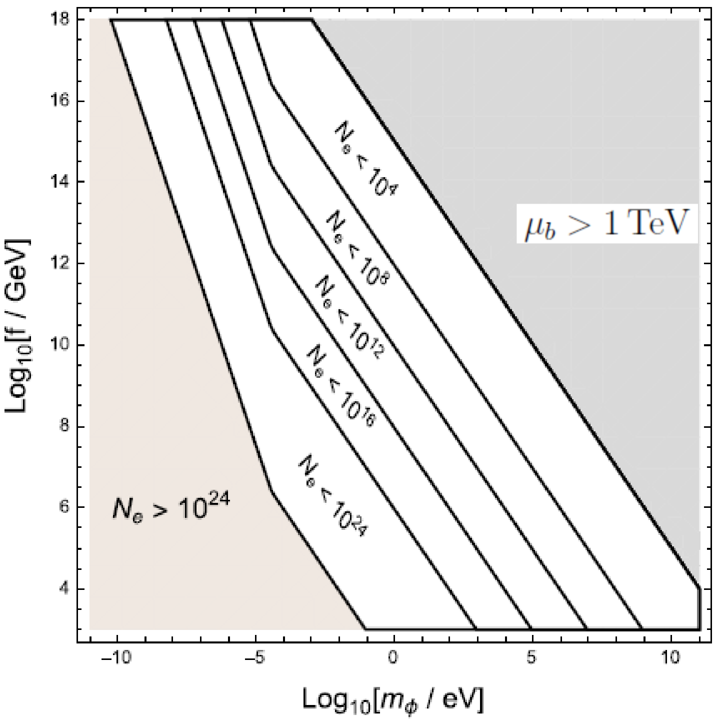
$$V_{\rm barrier} = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right) = \mu^{4-n}|H|^n\cos\left(\frac{\phi}{f}\right) \quad \left(\mu_b \lesssim 1\,{\rm TeV}\right)$$

$$\frac{f_{\rm eff}}{f} \sim \frac{\Lambda_{\rm SM}^4}{\mu_b^4}, \quad \dot{\phi} \lesssim \mu_b^2 \quad \Rightarrow \quad N_e = \int_{t_i}^{t_f}\mathcal{H}dt \gtrsim \max\left[\left(\frac{\Lambda_{\rm SM}}{\mu_b}\right)^4, \frac{f^2}{M_{\rm Pl}^2}\left(\frac{\Lambda_{\rm SM}}{\mu_b}\right)^8\right]$$

Cosmological relaxion window:

Relaxion mass & decay constant bounded by the acceptable inflationary e-folding number

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



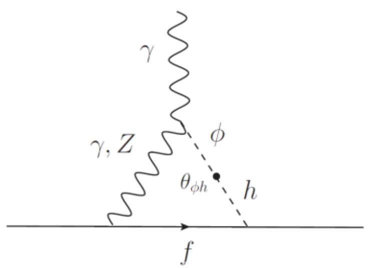
Low energy relaxion couplings induced by the relaxion-Higgs mixing:

$$V_b = \mu^2|H|^2\cos\left(\frac{\phi}{f}\right) = \mu_b^4(|H|)\cos\left(\frac{\phi}{f}\right) \Rightarrow \theta_{\phi h} \sim \frac{m_\phi^2}{m_h^2 - m_\phi^2}\frac{f}{v}\left(1+\frac{f m_\phi}{v^2}\right)^{-1}$$

$$\mathcal{L}_{\rm eff} = 2s_\theta\kappa\frac{\phi}{v}\left(\frac{1}{2}\partial_\mu\pi^0\partial^\mu\pi^0 + \partial_\mu\pi^+\partial^\mu\pi^-\right) - \frac{5s_\theta}{3}\frac{\phi}{v}m_\pi^2\left(\frac{1}{2}\pi^0\pi^0+\pi^+\pi^+\right)$$
$$- \frac{s_\theta}{6}\frac{g_2 m_N}{m_W}\phi\bar{N}N + s_\theta\frac{c_{h\gamma}\alpha}{4\pi v}\phi F^{\mu\nu}F_{\mu\nu} + \frac{c_{\phi\gamma}\alpha}{4\pi f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + s_\theta\sum_{l=e,\,\mu}\frac{m_l}{v}\phi\,\bar{\psi}_l\psi_l,$$

* LEP: $e^+e^- \to Z \to Z+\phi$ KC & Im, 1610.00680, Flacke et al, 1610.02025

* EDMs:



* Rare meson decays:

$$B \to K+\phi\ (\phi\to\mu^+\mu^-)$$

* Beam dump experiments: CHARM

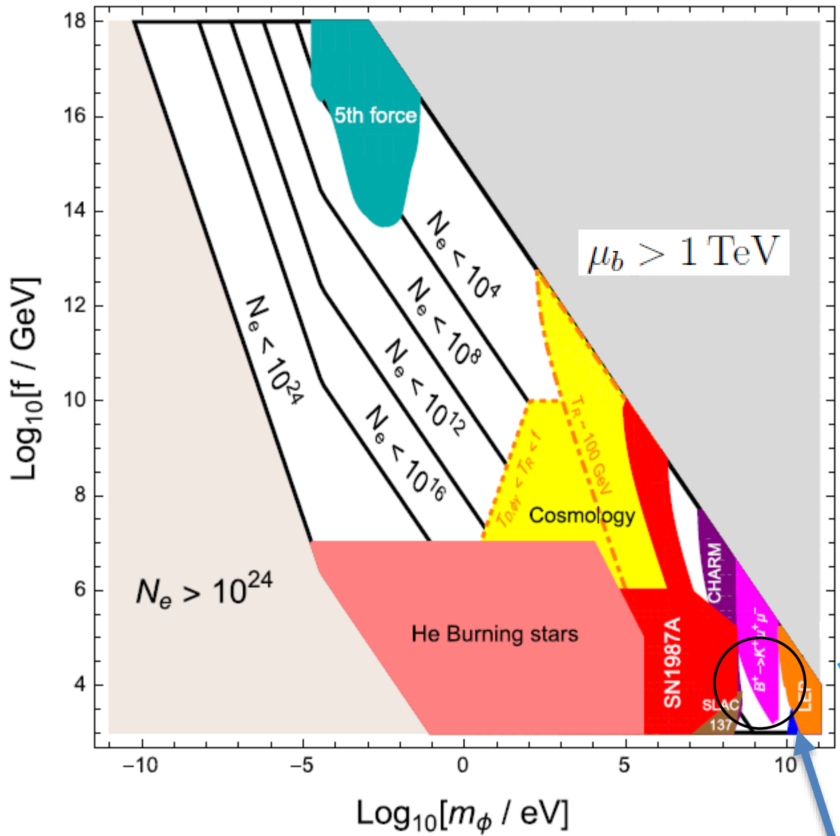
* Astrophysics: Star coolings (SN or He buring stars)

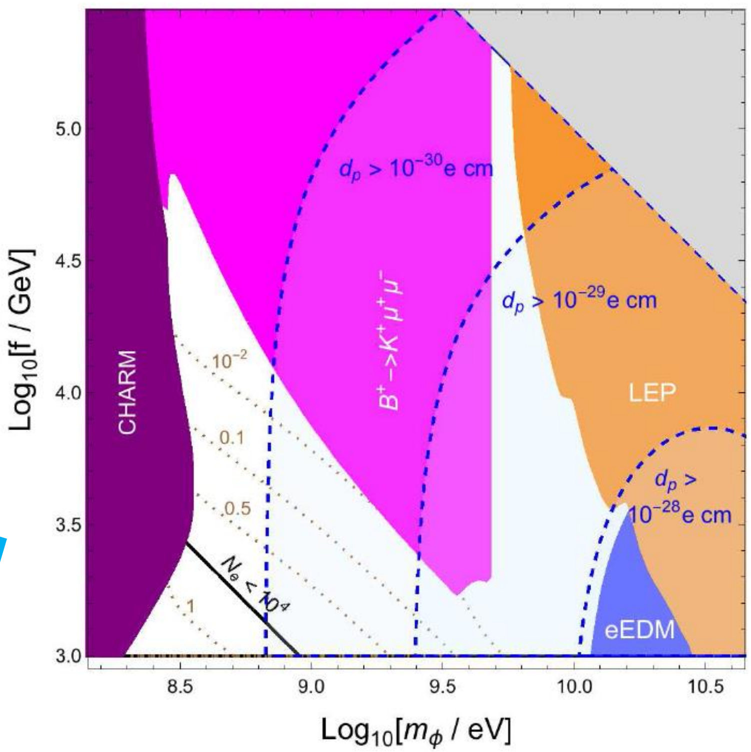
* Cosmology: Effects on BBN, CMB, dark radiation, X or γ ray backgrounds

* 5th force: $V(r) = -G_N\frac{m_A m_B}{r}(1+\epsilon_A\epsilon_B e^{-m_\phi r})$ $\left(\epsilon_{A,B} \propto \frac{1}{f}\left(\frac{\mu_b}{v}\right)^4 \propto m_\phi^2 f\right)$

Colored regions are excluded by LEP, EDMs , Rare meson decays , Beam dump experiments Astrophysics, Cosmology, 5th force

KC & Im, 1610.00680, Flacke et al, 1610.02025





This region can be probed by the SHiP or the improved EDM experiments.

Relaxion dynamics at high reheating temperature

KC, Kim, Sekiguchi, 1611.08569

Quite often we need $T_{RH} \gg v = 246 \text{ GeV}$ for viable cosmology, e.g. for successful baryogenesis.

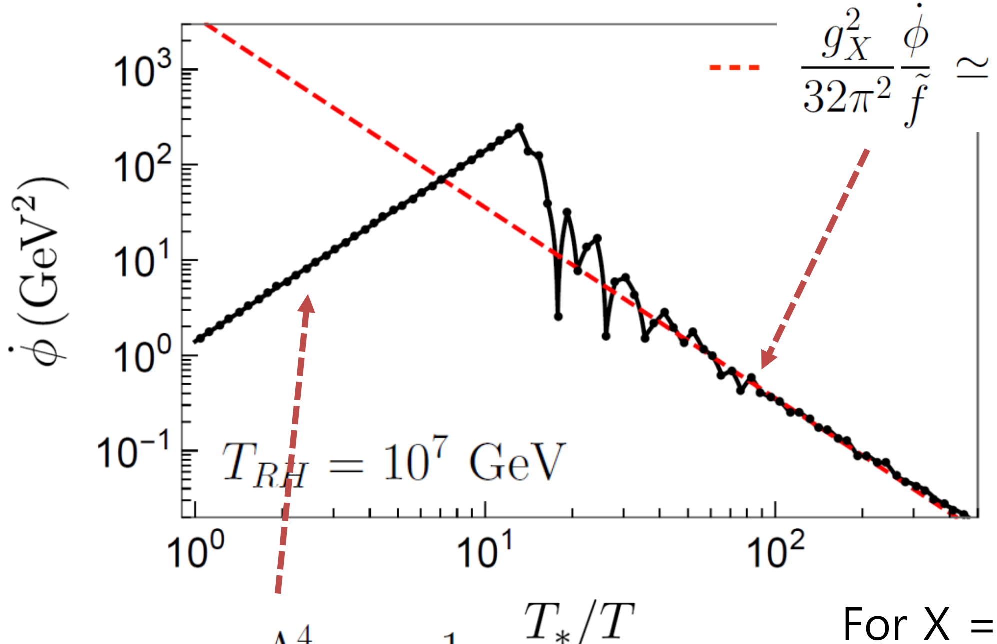
On the other hand, if $T_{RH} \gg v$, the barrier potential disappears after the reheating, and the relaxion is rolling down further, which may spoil the successful selection of the Higgs mass.

Indeed, in most of the favored parameter space, the Hubble friction after the reheating is not strong enough to slow down the relaxion motion to stop the relaxion at the right position after the EW phase transition.

We then need another mechanism to slow down the relaxion after reheating, and a simple solution is to introduce the axion-like coupling between the relaxion and a dark U(1) gauge boson X: $\frac{g_X^2}{32\pi^2}\frac{\phi}{\tilde{f}} X^{\mu\nu}\tilde{X}_{\mu\nu}$

Relaxion motion after reheating in the presence of $\frac{g_X^2}{32\pi^2}\frac{\phi}{\tilde{f}}X^{\mu\nu}\tilde{X}_{\mu\nu}$

No light $U(1)_X$ charged matter, so no thermal mass of X ($m_X(T) < H$)



$$\frac{g_X^2}{32\pi^2}\frac{\dot{\phi}}{\tilde{f}} \simeq 25 \times H \propto T^2$$

Deceleration by gauge field production:

Rolling relaxion induces a tachyonic instability of X

$$\dot{\phi} \sim \frac{\Lambda^4}{f_{\rm eff}}t \propto \frac{1}{T^2}$$

Acceleration by the sliding potential

(Hubble friction is negligible.)

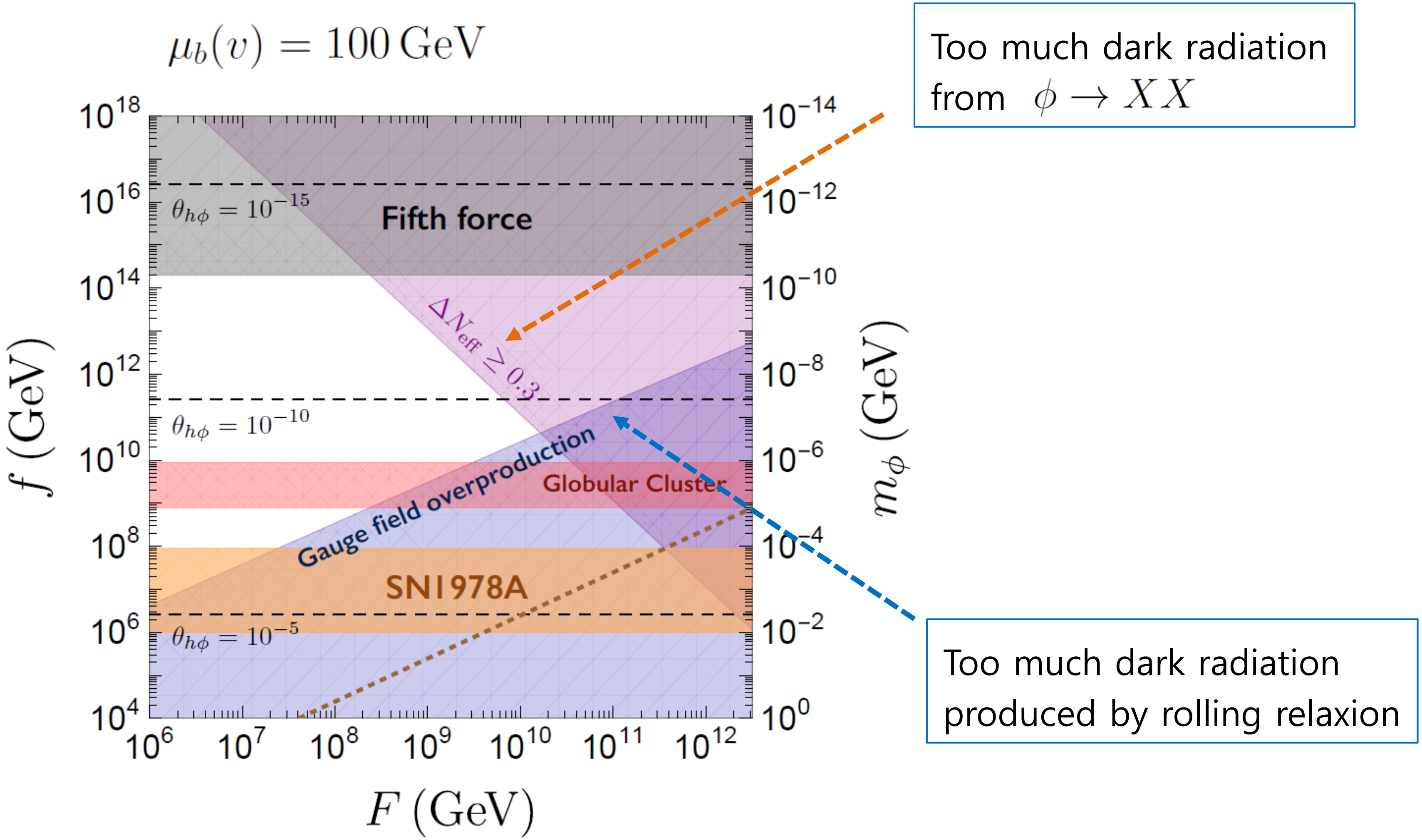
$$\left(V_0 = \frac{\Lambda^4}{f_{\rm eff}}\phi + \ldots \right)$$

For X = the $U(1)_Y$ gauge boson, due to the large thermal mass $m_X(T) >> H$, the gauge field production is not efficient enough to be useful for stopping the relaxion after the EW transition:

$$\frac{g_X^2}{32\pi^2}\frac{\dot{\phi}}{\tilde{f}} \simeq 5H\left(\frac{m_X(T)}{H}\right)^{2/3} \quad (m_X(T) \sim g'T \gg H)$$

Yet there are further observational constraints:

$$V_b = \mu_b^4(|H|) \cos\left(\frac{\phi}{f}\right) \qquad \frac{g_X^2}{32\pi^2}\frac{\phi}{\tilde{f}} X^{\mu\nu}\tilde{X}_{\mu\nu} \equiv \frac{1}{4}\frac{\phi}{F} X^{\mu\nu}\tilde{X}_{\mu\nu}$$



Further issues

- **Coincidence problem**

$$V_{\rm barrier} = \mu^2 |H|^2 \cos\left(\frac{\phi}{f}\right) \quad (\mathcal{O}(v) \lesssim \mu \lesssim \mathcal{O}(4\pi v))$$

Why new physics near $v = 246\,{\rm GeV}$ to generate the barrier potential?

One may avoid this problem through a double-scanning mechanism with a barrier potential generated at $\Lambda_{\rm SM}$: Espinosa et al, 1506.09217

$$V_{\rm barrier} = \epsilon \Lambda_{\rm SM}^4 \left[c_\phi \frac{\phi}{f_{\rm eff}} - c_\sigma \frac{\sigma}{\tilde{f}_{\rm eff}} + \frac{|H|^2}{\Lambda_{\rm SM}^2} \right] \cos\left(\frac{\phi}{f}\right)$$

But this assumes the three phase parameters take the same value, which may need an explanation from UV completion:

$$V_{\rm barrier} = \epsilon \Lambda_{\rm SM}^4 \left[c_\phi \frac{\phi}{f_{\rm eff}} \cos\left(\frac{\phi}{f} + \delta_1\right) - c_\sigma \frac{\sigma}{\tilde{f}_{\rm eff}} \cos\left(\frac{\phi}{f} + \delta_2\right) + \frac{|H|^2}{\Lambda_{\rm SM}^2} \cos\left(\frac{\phi}{f}\right) \right]$$

$$\left(\delta_1 = \delta_2 = 0 \right)$$

- **Too long period of inflation:**

$$N_e = \int_{t_i}^{t_f} \mathcal{H} dt \gtrsim \max\left[\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4, \frac{f^2}{M_{\rm Pl}^2}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^8\right]$$

This problem can be avoided in a **different relaxation scenario** with

i) Higgs mass-square scanned from $m_H^2 \sim -\Lambda^2$ to $m_H^2 = -(89\,{\rm GeV})^2$

ii) relaxion energy dissipation through gauge field production:

Hook & Marques-Tavares, 1607.01786

This new scenario requires

i) a specific form of relaxion couplings to the SM gauge fields

ii) Higgs-independent barrier potential

iii) three hierarchical axion scales:

$$V = \Lambda_{\rm SM}^4 \frac{\phi}{f_{\rm eff}} + \left(\Lambda_{\rm SM}^2 + \Lambda_{\rm SM}^2 \frac{\phi}{f_{\rm eff}}\right)|H|^2 + \Lambda_c^4 \cos\left(\frac{\phi}{f}\right) + \frac{1}{16\pi^2}\frac{\phi}{\tilde{f}}\left(W^{a\mu\nu}\tilde{W}^a_{\mu\nu} - B^{\mu\nu}\tilde{B}_{\mu\nu}\right)$$

$$\left(f_{\rm eff} \gg f \gg \tilde{f}\right)$$

Conclusion

- Cosmological relaxation of the Higgs mass is a new approach to the EW scale hierarchy problem.
- It requires a big hierarchy between the two axion scales, one for the Higgs mass scanning and another for the barrier potential:

$$\frac{f_{\rm eff}}{f} \sim \left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4 \gg 1$$

  Such a big axion scale hierarchy can be generated by the clockwork mechanism with multiple axions, yielding

$$f_{\rm eff}/f \sim e^N \quad (N = \text{number of axions})$$

- Relaxion mass & decay constant are constrained by a variety of observational data, excluding most of the region with $m_\phi \gtrsim 100\,{\rm eV}$.

- Introducing a coupling to dark U(1) gage boson, relaxion scheme can be compatible with high reheating temperature over a wide range of parameter space.

- Relaxion is a new baby in town, so deserves further attention, although she may not look cute enough to some of you.