Relaxion for the EW scale hierarchy

Kiwoon Choi

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Outline

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* EW scale hierarchy problem of the Standard Model (SM)

\[ L_{\text{higgs}} = D_{\mu}H^\dagger D^{\mu}H - m_H^2 |H|^2 - \frac{1}{4} \lambda |H|^4 + y_t q_3 u_3^c + \ldots \]

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

If the SM cutoff (= Higgs mass cutoff) scale \( \Lambda_{\text{SM}} \gg \) 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) \( \phi \) scans the Higgs mass squared from \( \Lambda_{SM}^2 \gg v^2 \ (v = 246 \text{ GeV}) \) to \(- (90 \text{ GeV})^2\):

\[
m^2_H(\phi)|H|^2 = \left( M_1^2 + M_2^2 \frac{\phi}{f_{\text{eff}}} + \ldots \right) |H|^2 \quad (M_1 \sim M_2 \sim \Lambda_{SM})
\]

\[
m^2_H(\phi)
\]

\[
\Delta \phi \sim f_{\text{eff}}
\]

Generic initial value of \( \phi \)

\[
\langle H \rangle \neq 0 \\
-(90 \text{ GeV})^2
\]

\[
\langle H \rangle = 0 \\
\Lambda_{SM}^2
\]

Final stabilized value of \( \phi \)
Another key component of the scheme is to stop the rolling relaxion at the right position by a barrier potential:

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

\[ \Delta \phi \sim f_{\text{eff}} \]

For \( \langle H \rangle \neq 0 \):

\[ V(\phi) \]

For \( \langle H \rangle = 0 \):

\[ \Lambda_{SM}^4 \]

\[ \mu^{4-n}v^n \equiv \mu_b^4 \lesssim 16\pi^2v^4 \]

\( v = 246 \text{ GeV} \)
Possible origin of the barrier potential:

\[ V_{\text{barrier}} = \mu_b^4(H) \cos \left( \frac{\phi}{f} \right) \]

\[ = \mu^{4-n} |H|^n \cos \left( \frac{\phi}{f} \right) \]

* QCD:
\[ \frac{1}{32\pi^2} \frac{\phi}{f} \left( G \tilde{G} \right)_{QCD} \]
\[ \Rightarrow \mu_b^4(H = v) \sim m_u \Lambda_{QCD}^3 \sim (0.1 \text{ GeV})^4 \]

* New Physics (NP) around TeV:
\[ \Rightarrow \mu_b^4(H = v) \lesssim 16\pi^2 v^4 \sim (1 \text{ TeV})^4 \]
Price to pay:

- Needs i) cosmological energy dissipation
- Needs ii) long relaxion excursion $f_{\text{eff}} \gg f$

Large initial potential energy $\Lambda_{\text{SM}}^4$

Small barrier

$V(\phi)$

$\Delta \phi \sim f_{\text{eff}}$

$\mu_0^4(H = v) \lesssim 16\pi^2 v^4 \sim (1 \text{ TeV})^4$
How long excursion?

Higher $\Lambda_{\text{SM}}$ and lower barrier requires longer relaxion excursion.

$\frac{\Lambda_{\text{SM}}^4}{f_{\text{eff}}} \sim \frac{\mu_b^4}{f}$

$\Rightarrow \frac{f_{\text{eff}}}{f} \sim \frac{\Lambda_{\text{SM}}^4}{\mu_b^4}$

* QCD-induced barrier: $\mu_b \sim 0.1 \text{ GeV} \Rightarrow \frac{f_{\text{eff}}}{f} \sim \int_{t_i}^{t_f} \mathcal{H} dt \sim 10^{24} \left( \frac{10^{-10}}{\theta_{\text{QCD}}} \right) \left( \frac{\Lambda_{\text{SM}}}{\text{TeV}} \right)^4$

* NP-induced barrier: $\mu_b \lesssim 1 \text{ TeV} \Rightarrow \frac{f_{\text{eff}}}{f} \sim \int_{t_i}^{t_f} \mathcal{H} dt \gtrsim \left( \frac{\Lambda_{\text{SM}}}{\text{TeV}} \right)^4$

($\mathcal{H} = \text{Hubble expansion rate}$)

Relaxion excursion in angle unit & Dissipation time in Hubble unit (for energy dissipation by the Hubble friction)
Relaxion converts the weak scale hierarchy to a much bigger hierarchy in relaxion scales:

\[
\Lambda_{\text{SM}} \gg 1 \text{ TeV} \quad \Rightarrow \quad \frac{f_{\text{eff}}}{f} \sim \left(\frac{\Lambda_{\text{SM}}}{\text{TeV}}\right)^4 \gg 1
\]

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

Yet, the minimal QCD-induced barrier potential requires a too long time of energy dissipation and also a too big axion scale hierarchy:

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

\[
\text{NP-induced barrier:} \quad \frac{f_{\text{eff}}}{f} \sim \int_{t_i}^{t_f} \mathcal{H} dt \gtrsim \left(\frac{\Lambda_{\text{SM}}}{\text{TeV}}\right)^4
\]

NP-induced barrier potential appears to be more attractive.
Hierarchical axion couplings with multiple axions

A simple model to generate hierarchical axion scales:

**SU(n) gauge theory with softly broken SUSY**

* Add an elementary axion with sub-Planckian decay constant $f_1 \ll M_P$ at UV scales well above the SU(n) confinement scale $\Lambda_{\text{dyn}}$:

\[
\mathcal{L} = -\frac{1}{4g^2} F_{\mu\nu}^a F_{\mu\nu}^a - i\tilde{\lambda} D\lambda - \frac{1}{2} (m_\lambda \lambda \lambda + \text{h.c}) + \frac{1}{2} \partial^\mu \phi_1 \partial_\mu \phi_1 + \frac{1}{32\pi^2} \frac{\phi_1}{f_1} F_{\mu\nu}^a \tilde{F}_{\mu\nu}^a + e^{-S_{\text{inst}}} M_{\text{UV}}^4 \cos \left( \frac{\phi_1}{f_1} \right) \left( \frac{\phi_1}{f_1} \equiv \frac{\phi_1}{f_1} + 2\pi \right)
\]

* At scales $\sim \Lambda_{\text{dyn}}$, gaugino condensation is formed, producing a composite axion $\phi_2$ with a decay constant $f_2 \sim \Lambda_{\text{dyn}}$:

\[
\langle \lambda\lambda \rangle \sim \Lambda_{\text{dyn}}^3 e^{i\phi_2/f_2} \left( \frac{\phi_2}{f_2} \equiv \frac{\phi_2}{f_2} + 2\pi \right)
\]

⇒ Two axions $\phi_1$ and $\phi_2$ at scales around $\Lambda_{\text{dyn}}$
Axion potential at scales $\sim \Lambda_{\text{dyn}}$

\[ V = -\Lambda_{\text{dyn}}^4 \cos\left(\frac{\phi_1}{f_1} + n\frac{\phi_2}{f_2}\right) - m_\lambda \Lambda_{\text{dyn}}^3 \cos\left(\frac{\phi_2}{f_2}\right) - e^{-S_{\text{ins}}} M_{UV}^4 \cos\left(\frac{\phi_1}{f_1}\right) + \ldots \]

\[ m_{\phi_2} \sim \Lambda_{\text{dyn}} \gg m_{\phi_1} \quad (\Lambda_{\text{dyn}}^4 \gg m_\lambda \Lambda_{\text{dyn}}^3, \ e^{-S_{\text{ins}}} M_{UV}^4) \]

At scales $<< \Lambda_{\text{dyn}}$, the massive $\phi_2$ is integrated out, yielding a low energy effective potential of $\phi_1$:

\[ \frac{\phi_2}{f_2} \approx -\frac{1}{n} \frac{\phi_1}{f_1} \quad \Rightarrow \quad V_{\text{eff}} \approx -m_\lambda \Lambda_{\text{dyn}}^3 \cos\left(\frac{\phi_1}{nf_1}\right) - e^{-S_{\text{ins}}} M_{UV}^4 \cos\left(\frac{\phi_1}{f_1}\right) \]

$\Rightarrow$ Single axion $\phi_1$, but with two split axion scales in the low energy limit:

$\ f_1 \quad \text{and} \quad f_{\text{eff}} = nf_1$
Energy scales

\[ \mu \gg \Lambda_{\text{dyn}} : \quad V_{\text{UV}} = -e^{-S_{\text{ins}}} M_{\text{UV}}^4 \cos \left( \frac{\phi_1}{f_1} \right) \quad \left( f_1 < \frac{M_P}{2\pi} \right) \]

a light axion with sub-Planckian decay constant \( f_1 \ll M_P \)

\[ SU(n) \text{ confinement with gaugino condensation at } \Lambda_{\text{dyn}} \]

two axions (one is composite) with a particular form of mass mixing

\[ \mu \ll \Lambda_{\text{dyn}} : \quad V_{\text{eff}} = -m_\lambda \Lambda_{\text{dyn}}^3 \cos \left( \frac{\phi_1}{f_{\text{eff}}} \right) - e^{-S_{\text{ins}}} M_{\text{UV}}^4 \cos \left( \frac{\phi_1}{f_1} \right) \]

a light axion with split axion decay constants: \( f_1 \) and \( f_{\text{eff}} = n f_1 \)
Alignment Kim, Nilles, Peloso, 05

To get the axion scale hierarchy \( f_{\text{eff}}/f \gg 1 \), one may take the limit \( n \gg 1 \), which corresponds to the Kim-Nilles-Peloso alignment of the axion couplings:

\[
V = -\Lambda_{\text{dyn}}^4 \cos \left( \vec{k}_1 \cdot \vec{\phi} \right) - m_\lambda \Lambda_{\text{dyn}}^3 \cos \left( \vec{k}_2 \cdot \vec{\phi} \right) - e^{-S_{\text{ins}}} M_{\text{UV}}^4 \cos \left( \vec{k}_3 \cdot \vec{\phi} \right)
\]

\[
\vec{k}_1 = \left( \frac{n}{f_2}, \frac{1}{f_1} \right) \quad \vec{k}_2 = \left( \frac{1}{f_2}, 0 \right) \quad \vec{k}_3 = \left( 0, \frac{1}{f_1} \right)
\]

\[
\Rightarrow \quad V_{\text{eff}} = -m_\lambda \Lambda_{\text{dyn}}^3 \cos \left( \frac{\phi_1}{f_{\text{eff}}} \right) - e^{-S_{\text{ins}}} M_{\text{UV}}^4 \cos \left( \frac{\phi_1}{f_1} \right) \quad (f_{\text{eff}} = nf_1 \gg f_1)
\]

For \( n \gg 1 \), the two axion couplings \( \vec{k}_1 \) and \( \vec{k}_2 \) are aligned to be nearly parallel.

\[\Rightarrow\] Hierarchical axion couplings in the light axion direction.

\[
\vec{k}_1 = \left( \frac{n}{f_2}, \frac{1}{f_1} \right)
\]

\[
\vec{k}_2 = \left( \frac{1}{f_2}, 0 \right)
\]

\[
\vec{k}_3 = \left( 0, \frac{1}{f_1} \right)
\]

Light axion direction

Heavy axion direction
Field range enhanced by clockwork: \( \Delta \phi_2 = 2\pi f_2 \quad \Rightarrow \quad \Delta \phi_1 = 2\pi n f_1 \)

To generate a big axion scale hierarchy, one may repeat the clockwork with additional axions, while keeping \( n = O(1) \), rather than taking the limit: \( n \gg 1 \) for which the left wheel is much bigger than the right wheel.
**Exponentially big axion scale hierarchy with multiple axions**

Clockwork between nearby axions:

\[
\Omega_1 \left( \frac{\phi_1}{f_1} + n_1 \frac{\phi_2}{f_2} \right) + \Omega_2 \left( \frac{\phi_2}{f_2} + n_2 \frac{\phi_3}{f_3} \right) + \ldots + \Omega_{N-1} \left( \frac{\phi_{N-1}}{f_{N-1}} + n_{N-1} \frac{\phi_N}{f_N} \right) + V_1 \left( \frac{\phi_1}{f_1} \right) + V_N \left( \frac{\phi_N}{f_N} \right) \\
(\Omega_i \gg V_1, V_N)
\]

\[
\frac{\phi_1}{f_1} = -n_1 \frac{\phi_2}{f_2}, \quad \frac{\phi_2}{f_2} = -n_2 \frac{\phi_3}{f_3}, \quad \ldots \quad \frac{\phi_{N-1}}{f_{N-1}} = -n_{N-1} \frac{\phi_N}{f_N}
\]

→ Light axion $\phi$ with an exponentially enhanced field range

\[
\Delta \phi = 2\pi n_1 n_2 \ldots n_{N-1} f_1 \sim 2\pi e^N f_1 \quad (n_i = \mathcal{O}(1))
\]

and the hierarchical decay constants in the low energy limit:

\[
V_{\text{eff}} = V_1 \left( \frac{\phi}{f_1} \right) + V_N \left( \frac{\phi}{f_{\text{eff}}} \right) \quad (f_{\text{eff}} = n_1 n_2 \ldots n_{N-1} f_1 \sim e^N f_1)
\]
Known schemes to generate $f_{\text{eff}}/f \gg 1$:

1) **Alignment (two axions):** Kim, Nilles, Peloso ’05

Aligned axion couplings which might be achieved with $n \gg 1$, which requires a large number of gauge or charged matter fields:

$$N_{\text{fields}} = \mathcal{O}(f_{\text{eff}}/f)$$

2) **Monodromy (single axion):** Silverstein, Westphal ’08; Kaloper, Sorbo ’09

Flux or brane-induced axion potential which amounts to the energy density of a large flux or brane-charge $Q \sim f_{\text{eff}}/f$:

$$V \propto \left( \frac{\phi}{f} + 2\pi Q_0 \right)^p \quad (Q_0 = \text{integer-valued background flux or brane-charge})$$

The scheme assumes that the effective theory remains valid under a large change of the flux or brane-charge, $\Delta Q \sim f_{\text{eff}}/f$.

Typically the back-reaction completely changes the effective theory.

McAllister et. al. 1610.05320
3) **Clockwork (N axions):** KC, Kim, Yun ’14; KC, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827

Clockwork between nearby axions with \( N_{\text{axion}} \sim \ln \left( \frac{f_{\text{eff}}}{f} \right) \)

The scheme requires a specific form of the global charge assignment of N axions.

The clockwork scheme can be generalized to generate an exponentially small coupling of \( s=1/2 \) fermion, \( s=1 \) gauge boson, \( s=2 \) graviton, providing a new tool for model building. Giudice & McCullough, 1610.07962
UV completed SUSY clockwork relaxion model \textsuperscript{KC, Im, 1511.00132}

* Multiple axions

\( N \) global \( U(1) \) symmetries spontaneously broken at \( f \sim m_{\text{SUSY}} \) or \( \sqrt{m_{\text{SUSY}} M_P} \) by soft SUSY-breaking mass:

\[
U(1)_i : \quad X_i \rightarrow e^{-2i\alpha_i} X_i \quad (\text{or} \quad e^{-3i\alpha_i} X_i), \quad Y_i \rightarrow e^{i\alpha_i} Y_i \quad (i = 1, 2, ..., N)
\]

\[
\Rightarrow \quad W_1 = \lambda_i Y_i X_i^2 \quad \text{or} \quad \frac{Y_i X_i^3}{M_P}
\]

\[
V = -m^2_{\text{SUSY}} |X_i|^2 + \lambda^2_i |X_i|^4 \left( \text{or} \quad \frac{|X_i|^6}{M_P^2} \right) + ...
\]

\[
\langle X_i \rangle \sim \langle Y_i \rangle \sim m_{\text{SUSY}} \quad \text{or} \quad \sqrt{m_{\text{SUSY}} M_P}
\]
Hidden YM sector with gauge group: \( G = \prod_{i=1}^{N-1} SU(k_i) \)

Charged matter superfields: \( \Psi^c_i \), \( \Phi^c_{ia} \) (\( i = 1, 2, \ldots, N - 1; a = 1, 2, \ldots, n_i \))

with \( W_2 = \sum_{i=1}^{N-1} (X_i \Psi_i \Psi^c_i + X_{i+1} \Phi_{ia} \Phi^c_{ia}) \)

For \( f \gtrsim \Lambda_{\text{dyn}} \gtrsim m_{\text{SUSY}} \) (\( \Lambda_{\text{dyn}} = \) confinement scale of \( G \)),

threshold corrections to the holomorphic gauge kinetic functions:

\[
\Delta F_i = \frac{1}{8\pi^2} \ln (X_i X_{i+1}^{n_i}) = \frac{i}{8\pi^2} \left( \frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}} \right) + \ldots
\]

\( \Rightarrow \) \( V_{\text{clockwork}} \sim \frac{8\pi^2}{k_i} m_{\text{SUSY}} \Lambda_{\text{dyn}}^3 \cos \left( \frac{1}{k_i} \left( \frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}} \right) \right) \)

\( \Rightarrow \) \( \frac{\phi_i}{f_i} = (-1)^{i-1} \left( \prod_{j=i}^{N-1} n_j \right) \frac{\phi}{f_{\text{eff}}} \) (\( \phi = \) lightest axion = relaxion)

\[
f_{\text{eff}} = \sqrt{\sum_{i=1}^{N} \left( \prod_{j=i}^{N-1} n_j^2 \right) f_i^2} \sim \left( \prod_{j=1}^{N-1} n_j \right) f_1 \sim e^{\xi N} f_1 \quad (\xi = \mathcal{O}(1))
\]
* Higgs mass scanning by relaxion & the sliding potential

\[ \Delta W = (X_N + X_{N-1}) H_u H_d \quad \text{or} \quad \frac{(X_N^2 + X_{N-1}^2) H_u H_d}{M_P} \]

\[ \Delta K = X_N X_{N-1}^* \quad \text{or} \quad \frac{X_N^2 X_{N-1}^2}{M_P^2} \]

\[ \Rightarrow \quad m_H^2 = c_1 m_{\text{SUSY}}^2 + c_2 m_{\text{SUSY}}^2 \cos \left( 2(n_{N-1} + 1) \frac{\phi}{f_{\text{eff}}} + \delta \right) \]

\[ V_0 = c_0 m_{\text{SUSY}}^4 \cos \left( 2(n_{N-1} + 1) \frac{\phi}{f_{\text{eff}}} + \tilde{\delta} \right) + \ldots \]

* Barrier potential

Another hidden color which confines at \( \Lambda_{\text{HC}} \sim \text{weak scale} \)

with hidden colored matter \( L + L^c, N + N^c \) having

\[ W_{\text{br}} = H_u L N^c + H_d L^c N + X_1 L L^c \left( \text{or} \frac{X_1^2}{M_P} LL^c \right) \]

\[ \Rightarrow \quad V_{\text{br}} \sim \frac{\Lambda_{\text{HC}}^3}{m_{\text{SUSY}}} |H|^2 \cos \left( \frac{\phi}{f} + \delta_1 \right) \quad \left( f_{\text{eff}} \sim e^{N f} \right) \]
Cosmological relaxion windows

\[ m_H^2(\phi) |H|^2 = \left( M_1^2 + M_2^2 \frac{\phi}{f_{\text{eff}}} + \ldots \right) |H|^2 \quad (M_1 \sim M_2 \sim \Lambda_{\text{SM}}) \]

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

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

Relaxion mass & decay constant classified by the required inflationary e-folding number
Colored regions are excluded by

- EDMs
- Rare meson decays
- Beam dump experiments
- Astrophysics & Cosmology
- LEP
- 5th force

KC & Im, 1610.00680
Flacke et al, 1610.02025

These regions can be probed by the SHiP or the improved EDM experiments.
Further issues

- **Coincidence problem**

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

Why new physics near \( v = 246 \text{ GeV} \) to generate the barrier potential?

One may avoid this problem through a double-scanning mechanism with a barrier generated at \( \Lambda_{\text{SM}} \): Espinosa et al, 1506.09217; Evans et al, 1602.04812

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

But this assumes the three phase parameters take the same value, which may cause a fine-tuning problem:

\[
\begin{align*}
V_{\text{barrier}} &= \epsilon \Lambda_{\text{SM}}^4 \left[ c_\phi \frac{\phi}{f_{\text{eff}}} \cos \left( \frac{\phi}{f} + \delta_1 \right) - c_\sigma \frac{\sigma}{f_{\text{eff}}} \cos \left( \frac{\phi}{f} + \delta_2 \right) + \frac{|H|^2}{\Lambda_{\text{SM}}^2} \cos \left( \frac{\phi}{f} \right) \right] \\
&\quad \left( \delta_1 = \delta_2 = 0 \right)
\end{align*}
\]
• Too long period of inflation:

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

One can avoid this problem by dissipating the relaxion energy through particle production: Hook & Marques-Tavares, 1607.01786

This scheme requires three hierarchical axion scales

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

\[ \left( f_{\text{eff}} \gg f \gg \tilde{f} \right) \]

which again can be achieved through the clockwork mechanism.

• Compatible with high reheating temperature?

Can be done with a relaxion coupling to the dark photon:

\[ \Delta \mathcal{L} = \frac{1}{16\pi^2} \frac{\phi}{f} X_{\mu \nu} \tilde{X}_{\mu \nu} \]

(Talk by Hyungjin Kim)
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:
  \[
  \frac{f_{\text{eff}}}{f} \sim \left( \frac{\Lambda_{\text{SM}}}{\text{TeV}} \right)^4 \gg 1
  \]

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

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

- Relaxion mass & decay constant are constrained by a variety of observational data, which exclude most of the region with \[ m_\phi \gtrsim 100 \text{ eV} \]
• There are yet many issues to be clarified:
  * Coincidence problem
  * Other ways of relaxion energy dissipation
  * UV completion
  * Compatibility with inflation, baryogenesis, dark matter, ...
    (high reheating temperature)