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Realizing the relaxion from multiple axions and its UV completion with high scale supersymmetry

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Outline

- Review of the relaxion mechanism

  Huge relaxion excursion

- Relaxion from multiple axions

  Clockwork mechanism

- A UV completion with high scale SUSY

- Summary

Relaxion mechanism

Graham, Kaplan, Rajendran (2015)

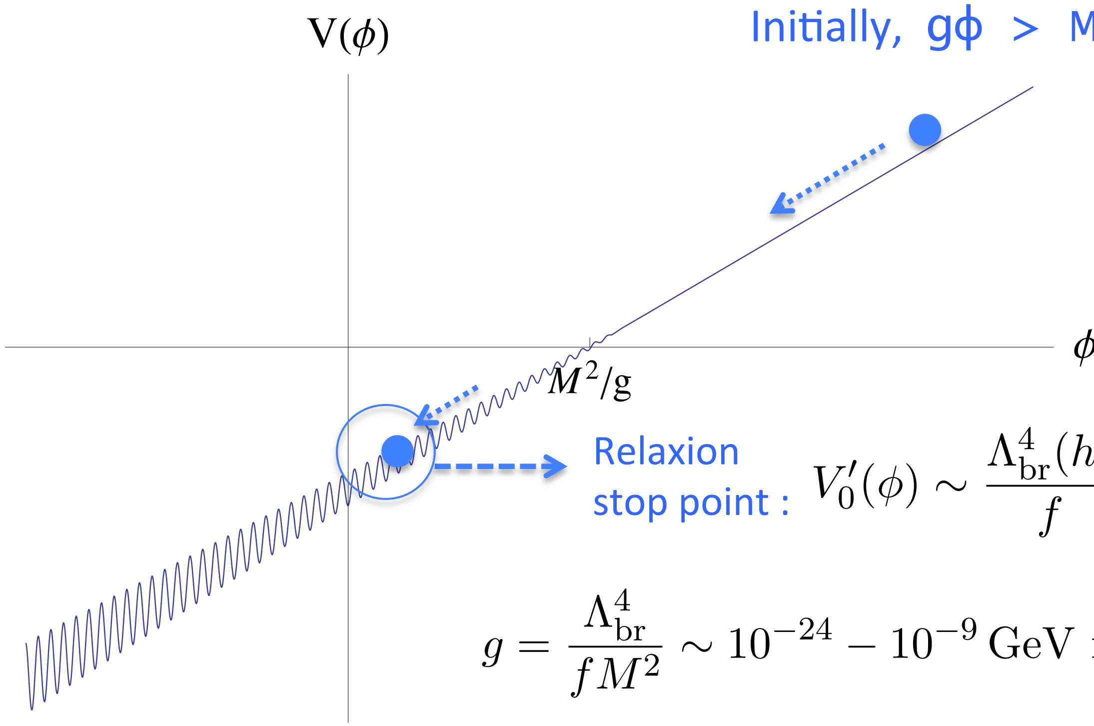
Relaxion-dependent Higgs mass — Relaxion rolling potential — Back reaction sector

$$V(\phi,h) = \left(-M^2 + g\phi\right)h^2 + V_0(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

g : *small* shift-symmetry (ϕ → ϕ + α) breaking parameter

$$\rightarrow \left(-M^2 + g\phi\right)h^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda_{\rm br}^4(h)\cos\left(\frac{\phi}{f}\right)$$

$$\Lambda_{\rm br}^4(h) \sim \begin{cases} y_u \Lambda_{\rm QCD}^3 h \\ \Lambda_{\rm HC}^2 h^2 \end{cases}$$



Relaxion stop point : $V_0'(\phi) \sim \frac{\Lambda_{\rm br}^4(h)}{f}$

$$\left(\frac{\langle h\rangle}{v}\right)^{1,2} = g\,\frac{M^2 f}{\Lambda_{\rm br}^4(h=v)}$$

$$g = \frac{\Lambda_{\rm br}^4}{fM^2} \sim 10^{-24} - 10^{-9}\,\text{GeV for } M = 100\ \text{TeV}$$

$\langle h\rangle = v$

Long field excursion of the relaxion

- Without fine-tuning of the initial position of the relaxion,

$$(-M^2 + g\phi)h^2 \quad \to \quad g\Delta\phi \gtrsim M^2$$

$$\Delta\phi \gtrsim \frac{M^2}{g} = f\left(\frac{M}{\Lambda_{\rm br}}\right)^4 = 10^{22}\ \text{GeV}\left(\frac{f}{10^{10}\ \text{GeV}}\right)\left(\frac{M}{100\ \text{TeV}}\right)^4\left(\frac{100\ \text{GeV}}{\Lambda_{\rm br}}\right)^4$$

- Hierarchy conversion :

$$M/v \gg 1 \quad \Rightarrow \quad \Delta\phi/f \gtrsim M^4/v^4$$

- A sensible EFT with a UV completion ?

Multiple axions : overall picture

$$V(\phi, h) = \mu_h^2(\phi)|h|^2 + V_0(\phi) + V_{\rm br}(\phi, h)$$

Relaxion-dependent Higgs mass

Relaxion rolling potential

Back reaction potential

$$\mu_h^2(\phi) = -M^2 + g\phi + \cdots$$

$$V_0(\phi) = gM^2\phi + g^2\phi^2 + \cdots$$

$$V_{\rm br}(\phi, h) = \Lambda_{\rm br}^4(h)\cos\left(\frac{\phi}{f}\right)$$

$$g \sim \frac{M^2}{f_{\rm eff}}$$

$$\mu_h^2(\phi) = -c_1 M^2 + c_2 M^2 \cos\left(\frac{\phi}{f_{\rm eff}} + \delta_h\right)$$

$$V_0(\phi) = c_3 M^4 \cos\left(\frac{\phi}{f_{\rm eff}} + \delta_0\right)$$

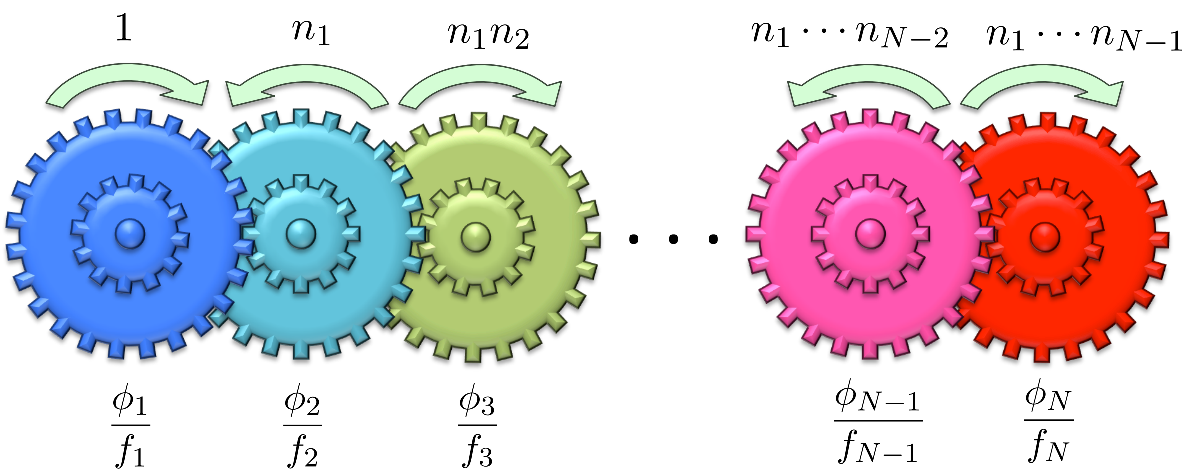
$$V_{\rm br}(\phi, h) = \Lambda_{\rm br}^4(h)\cos\left(\frac{\phi}{f} + \delta_{\rm br}\right)$$

with $f_{\rm eff} \sim e^{\xi N} f \quad (\xi \sim \mathcal{O}(1))$

N : number of axions

Clockwork mechanism for exponentially large f_{eff}

K. Choi, SH. Im (1511.00132); Kaplan, Rattazzi (1511.01827)



$$V_{\text{clock}} = \Lambda_1^4 \cos\left(n_1 \frac{\phi_1}{f_1} + \frac{\phi_2}{f_2}\right) + \Lambda_2^4 \cos\left(n_2 \frac{\phi_2}{f_2} + \frac{\phi_3}{f_3}\right) + \cdots + \Lambda_{N-1}^4 \cos\left(n_{N-1} \frac{\phi_{N-1}}{f_{N-1}} + \frac{\phi_N}{f_N}\right)$$

$$\left(\frac{\Delta\phi_1}{f_1},\ \frac{\Delta\phi_2}{f_2},\ \frac{\Delta\phi_3}{f_3},\ \cdots,\ \frac{\Delta\phi_N}{f_N}\right) = \left(1,\ -n_1,\ n_1 n_2,\ \cdots,\ (-1)^{N-1} n_1 \cdots n_{N-1}\right)$$

Flat direction

$$f_{\text{eff}} = \sqrt{\sum_{k=1}^{N} n_1^2 \cdots n_{k-1}^2 f_k^2} \sim n_1 \cdots n_{N-1} f \sim e^N f$$

Relaxion potentials from the "end axions"

$$\mathcal{L} = \frac{1}{2}\sum_{i=1}^{N}(\partial_\mu\phi_i)^2 + \Lambda_1^4\cos\left(n_1\frac{\phi_1}{f_1}+\frac{\phi_2}{f_2}\right) + \Lambda_2^4\cos\left(n_2\frac{\phi_2}{f_2}+\frac{\phi_3}{f_3}\right) + \cdots + \Lambda_{N-1}^4\cos\left(n_{N-1}\frac{\phi_{N-1}}{f_{N-1}}+\frac{\phi_N}{f_N}\right)$$

$V_{\rm clock}$

defines flat direction

$$+\,\epsilon_1\Lambda^4\cos\left(\frac{\phi_1}{f_1}\right) + \epsilon_N\Lambda^4\cos\left(\frac{\phi_N}{f_N}\right)$$

$\epsilon_1,\ \epsilon_N \ll 1$

Integrating out the heavy axions,

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu\phi_{\rm rel})^2 + \epsilon_1\Lambda^4\cos\left(\frac{\phi_{\rm rel}}{f_{\rm eff}}\right) + \epsilon_N\Lambda^4\cos\left(\frac{n_1\cdots n_{N-1}}{f_{\rm eff}}\phi_{\rm rel}\right)$$

$$\sim \frac{\phi_{\rm rel}}{f}$$

$$f_{\rm eff} \sim n_1\cdots n_{N-1}f \sim e^N f$$

Long periodic potential for relaxion rolling & Higgs mass scanning

Short periodic potential for back reaction

A UV model : Need for SUSY

$$V(\phi_k, h) = \sum_{k=1}^{N} \Lambda_k^4 \cos\left(n_k \frac{\phi_k}{f_k} + \frac{\phi_{k+1}}{f_{k+1}}\right)$$

defines flat direction (clockwork)

$$+ \left[-M_h^2 + c_1 M_h^2 \cos\left(\frac{\phi_1}{f_1} + \delta_1\right)\right] h^2 + c_1' M_h^4 \cos\left(\frac{\phi_1}{f_1} + \delta_1'\right) + \Lambda_{\rm br}^4(h) \cos\left(\frac{\phi_N}{f_N} + \delta_N\right)$$

M_h : Higgs mass cutoff

$c_1 > 1$

Relaxion-depedent Higgs mass

Relaxion rolling potential

Back reaction potential

Radiative correction from Higgs loop

$c_1' > 1$

- In order not to spoil the approximate flat direction determined by the clockwork potential,

$$\Lambda_{\text{cut-off}}^4 > \Lambda_k^4 \gg c_1' M_h^4 > M_h^4$$

- The Higgs mass cutoff must be well below the cut-off scale of the theory.
  → SUSY !

N axions from N U(1)'s

$$U(1)_i : \quad X_i \to e^{i\beta_i} X_i, \quad Y_i \to e^{-3i\beta_i} Y_i \quad (i = 1, 2, ..., N)$$

X_i, Y_i : gauge-singlet chiral superfields

Murayama, Suzuki, Yanagida (1992)

Choi, Chun, Kim (1996)

$$W_1 = \sum_i \frac{X_i^3 Y_i}{M_*}$$

M_* : Cut-off scale such as the Planck or GUT scale

$$V(X_i, Y_i) = m_{X_i}^2 |X_i|^2 + m_{Y_i}^2 |Y_i|^2 + \left(A_i \frac{X_i^3 Y_i}{M_*} + \text{h.c} \right) + \frac{|X_i|^6}{M_*^2} + 9 \frac{|X_i|^4 |Y_i|^2}{M_*^2}$$

$$m_{X_i}^2 < 0, \; m_{Y_i}^2 > 0 \quad \to \quad X_i \sim Y_i \sim \sqrt{m_{\text{SUSY}} M_*}$$

$$X_i \propto e^{i\phi_i/f_i}, \quad Y_i \propto e^{-3i\phi_i/f_i}$$

N axions ϕ_i $(i = 1 \ldots N)$ with $f_i \sim \sqrt{m_{\text{SUSY}} M_*}$

Clockwork from a hidden sector dynamics

- Introduce (N - 1) hidden Yang-Mills sectors.

Gauge group $$G = \prod_{i=1}^{N-1} SU(p_i)$$

Vector-like charged matter fields $$\Psi_{ia} + \Psi^c_{ia}, \quad \Phi_i + \Phi^c_i \quad (i = 1, 2, ..., N-1; a = 1, 2, ..., n_i)$$

- The previous $U(1)_i$ charged field X_i couples to these matter fields through

$$W_2 = (X_1 \Psi_{1a} \Psi^c_{1a} + X_2 \Phi_1 \Phi^c_1) + (X_2 \Psi_{2a} \Psi^c_{2a} + X_3 \Phi_2 \Phi^c_2) + \cdots + \left(X_{N-1} \Psi_{N-1a} \Psi^c_{N-1a} + X_N \Phi_{N-1} \Phi^c_{N-1}\right)$$

$U(1)_{i,i+1} \times SU(p_i) \times SU(p_i)$ anomalies

Axion-dependent holomorphic gauge kinetic function of $SU(p_i)$

$$\tau_i = \frac{1}{g_i^2} + \frac{i}{8\pi^2} \left(n_i \frac{\phi_i}{f_i} + \frac{\phi_{i+1}}{f_{i+1}} \right) + \theta^2 M_{\lambda_i}$$

Clockwork from a hidden sector dynamics

confining scale of SU(p_i)

$$\Lambda_i \gg m_{\rm SUSY}$$

gaugino condensation

$$W_{\rm np} \sim \langle \lambda_i \lambda_i \rangle \propto \left(\exp\left(-8\pi^2 \tau_i\right)\right)^{1/p_i}$$

$$V_{\rm clock} = \sum_{i=1}^{N-1} \frac{8\pi^2}{p_i} M_{\lambda_i} \Lambda_i^3 \cos\left(\frac{1}{p_i}\left(n_i \frac{\phi_i}{f_i} + \frac{\phi_{i+1}}{f_{i+1}}\right)\right)$$

Note $V_{\rm clock} \sim m_{\rm SUSY} \Lambda_i^3 \gg M_h^4 \sim m_{\rm SUSY}^4$

The flat direction is stable against radiative correction.

Relaxion-dependent Higgs mass

Superpotential to generate the MSSM μ-term

$$W_3 = \left(\frac{X_1^2}{M_*} + \frac{X_2^2}{M_*}\right) H_u H_d$$

Kim, Nilles (1984)

$$\mu_{\rm eff} = \mu_1 \exp\left(i2\frac{\phi_{\rm rel}}{f_{\rm eff}}\right) + \mu_2 \exp\left(-i2n_1\frac{\phi_{\rm rel}}{f_{\rm eff}}\right),$$
$$B\mu_{\rm eff} = b_1 \exp\left(i2\frac{\phi_{\rm rel}}{f_{\rm eff}}\right) + b_2 \exp\left(-i2n_1\frac{\phi_{\rm rel}}{f_{\rm eff}}\right)$$

$$f_{\rm eff} \sim n_1 \cdots n_{N-1} f \sim e^N f$$

where $|\mu_1| \sim |\mu_2| \sim \frac{f^2}{M_*} \sim m_{\rm SUSY}, \quad |b_1| \sim |b_2| \sim m_{\rm SUSY}^2$

Naturally $\mu_{\rm eff} \sim m_{\rm SUSY}$

$$|\mu_{\rm eff}|^2 = |\mu_1|^2 + |\mu_2|^2 + 2|\mu_1\mu_2| \cos\left(2(n_1+1)\frac{\phi_{\rm rel}}{f_{\rm eff}} + \delta_{\mu_1} - \delta_{\mu_2}\right),$$
$$|B\mu_{\rm eff}|^2 = |b_1|^2 + |b_2|^2 + 2|b_1 b_2| \cos\left(2(n_1+1)\frac{\phi_{\rm rel}}{f_{\rm eff}} + \delta_{b_1} - \delta_{b_2}\right)$$

$$\mathcal{D} = (m_{H_u}^2 + |\mu_{\rm eff}|^2)(m_{H_d}^2 + |\mu_{\rm eff}|^2) - |B\mu_{\rm eff}|^2$$

Higgs mass determinant

For an appropriate range of δ_μ and δ_b, the determinant can change its sign from positive to negative during $\Delta\phi_{\rm rel} = O(f_{\rm eff})$.

Relaxion rolling potential

$$W_3 = \left(\frac{X_1^2}{M_*} + \frac{X_2^2}{M_*}\right) H_u H_d$$

Radiative correction

$$\Delta K = \frac{X_1^2 X_2^{\dagger 2}}{M_*^2} + \text{h.c.}$$

$$V_0(\phi_{\rm rel}) = m_0^4 \cos\left(2(n_1+1)\frac{\phi_{\rm rel}}{f_{\rm eff}} + \delta\right)$$

$$m_0^4 \sim \frac{f_1^2 f_2^2}{M_*^2} m_{\rm SUSY}^2 \sim m_{\rm SUSY}^4$$

Back reaction potential

Graham, Kaplan, Rajendran (2015)

I. QCD

$$\boxed{W_{\rm br} = X_N Q Q^c} \;\rightarrow\; \frac{1}{32\pi^2}\frac{\phi_N}{f_N}G\tilde{G} \;\rightarrow\; \frac{1}{32\pi^2}\frac{\phi_{\rm rel}}{f}G\tilde{G} \qquad f = \frac{f_{\rm eff}}{\left(\prod_{i=1}^{N-1} n_i\right)} \sim f_N$$

$$\boxed{V_{\rm br}(h, \phi_{\rm rel}) \approx y_u \Lambda_{\rm QCD}^3 h \cos\left(\frac{\phi_{\rm rel}}{f} + \delta_{\rm br}\right)}$$

II. Hidden Color

$$\boxed{W_{\rm br} = \kappa_N \frac{X_N^2}{M_*} L L^c + \kappa_u H_u L N^c + \kappa_d H_d L^c N}$$

$L + L^c$: $SU(2)_L$ doublet

$N + N^c$: $SU(2)_L \times U(1)_Y$ singlet

Vector-like hidden colored matter fields

Integrating out L + L^c

$$\boxed{V_{\rm br}(h, \phi_{\rm rel}) \approx \frac{\kappa_u \kappa_d \sin(2\beta)}{m_L}\Lambda_{\rm HC}^3 h h^\dagger \cos\left(2\frac{\phi_{\rm rel}}{f} + \delta_{\rm br}\right)}$$

$$\Lambda_{\rm HC} < m_L \sim \kappa_N m_{\rm SUSY} < 4\pi v$$

to prevent the Higgs loop > v^2

Summary

- The relaxion mechanism requires a huge field excursion (typically trans-Planckian) due to the hierarchy between a Higgs mass cutoff scale and the weak scale.
- Our *clockwork* mechanism can yield an exponentially long relaxion direction $\sim e^N f$ within the compact field space of N periodic axions with their decay constants $\sim f$ well below the Planck scale.
- Our scheme finds a natural UV completion in high scale SUSY scenario in order to preserve the approximate flat relaxion direction against radiative correction.
- The required relaxion potential is generated by a superpotential term providing a natural solution to the MSSM μ-problem.
- The back reaction sector is restricted to make the (radiatively induced) Higgs independent part be subdominant.