Relaxion for the EW scale hierarchy

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Outline

- Introduction

  Cosmological relaxation of the EW scale

- Hierarchical relaxion scales with multiple axions

  Clockwork relaxion & UV completion

- Constraints on relaxion windows

- Further issues

- Conclusion

* EW scale 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**

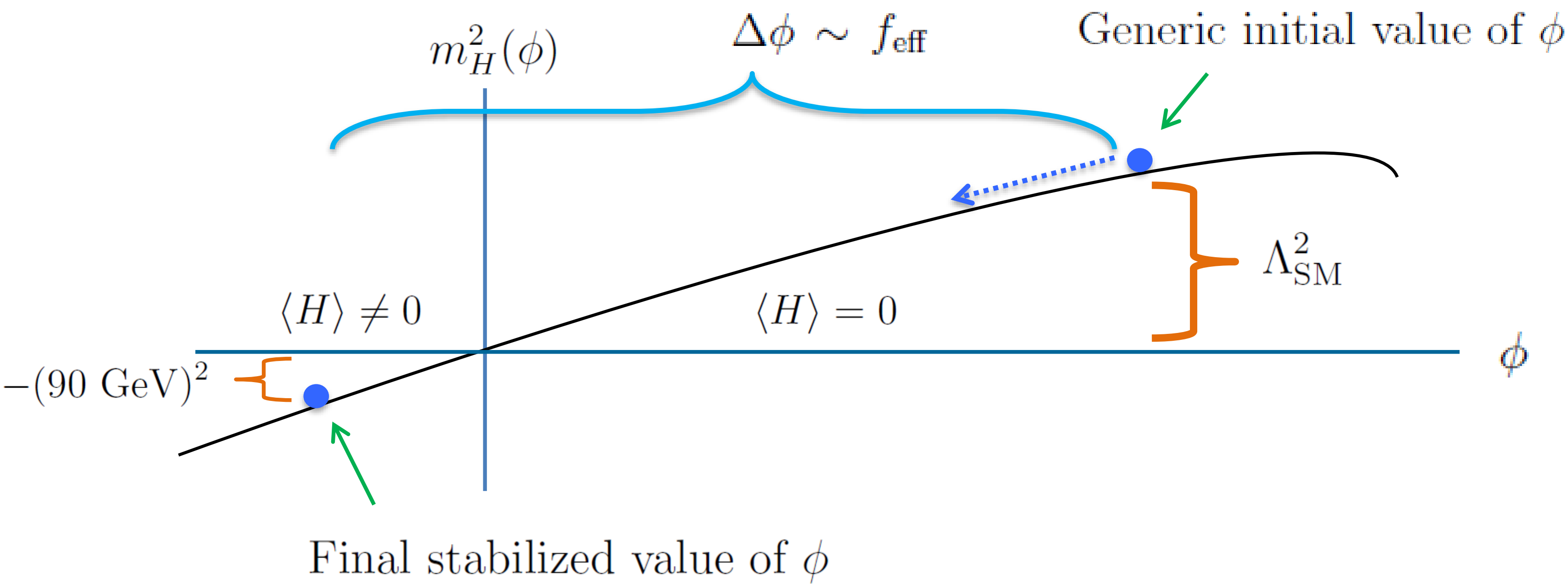
- N-Naturalness, …

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

A pseudo-Nambu-Goldstone boson (=**relaxion**) ϕ scans the Higgs mass²

from $\Lambda_{\rm SM}^2 \gg v^2 \;\; (v = 246 \text{ GeV})$ to $-(90 \text{ GeV})^2$:

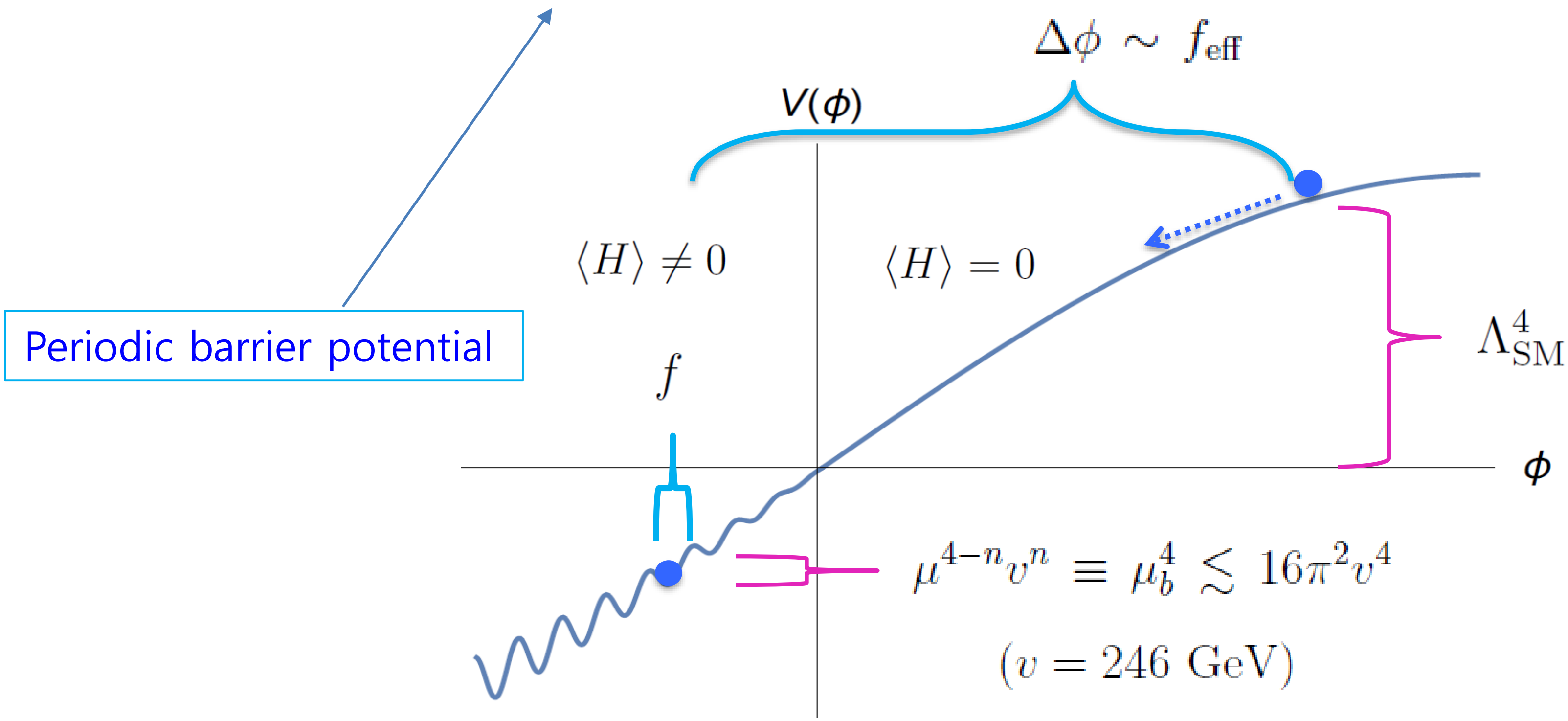
$$m_H^2(\phi)|H|^2 = \left(M_1^2 + M_2^2 \frac{\phi}{f_{\rm eff}} + \ldots\right)|H|^2 \quad (M_1 \sim M_2 \sim \Lambda_{\rm SM})$$



Another key component of the scheme is to stop the rolling relaxion at the right position by a barrier potential:

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

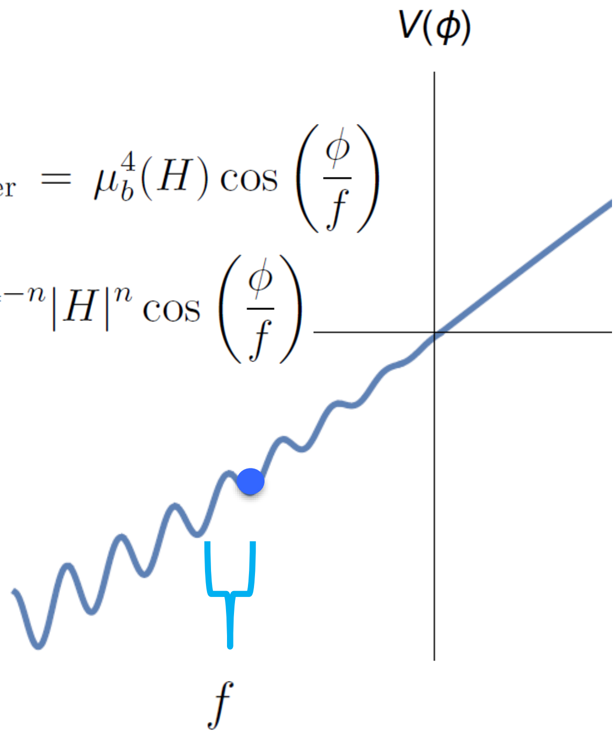
Sliding potential



Possible origin of the barrier potential:

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

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



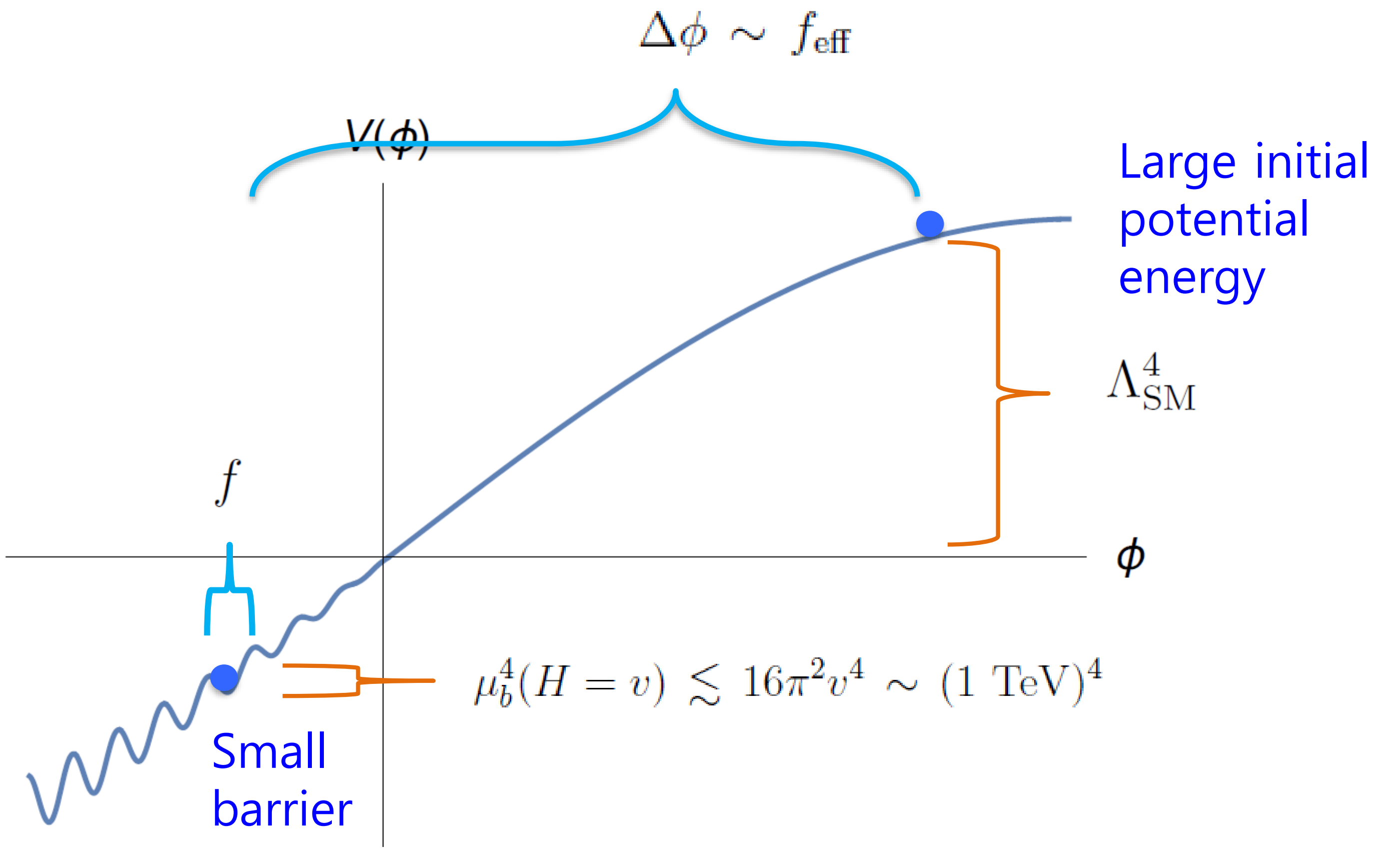
* QCD: $\frac{1}{32\pi^2}\frac{\phi}{f}\left(G\tilde{G}\right)_{\rm QCD}$

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

* New Physics (NP) around TeV:

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

Price to pay:



➔ Needs i) cosmological energy dissipation

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

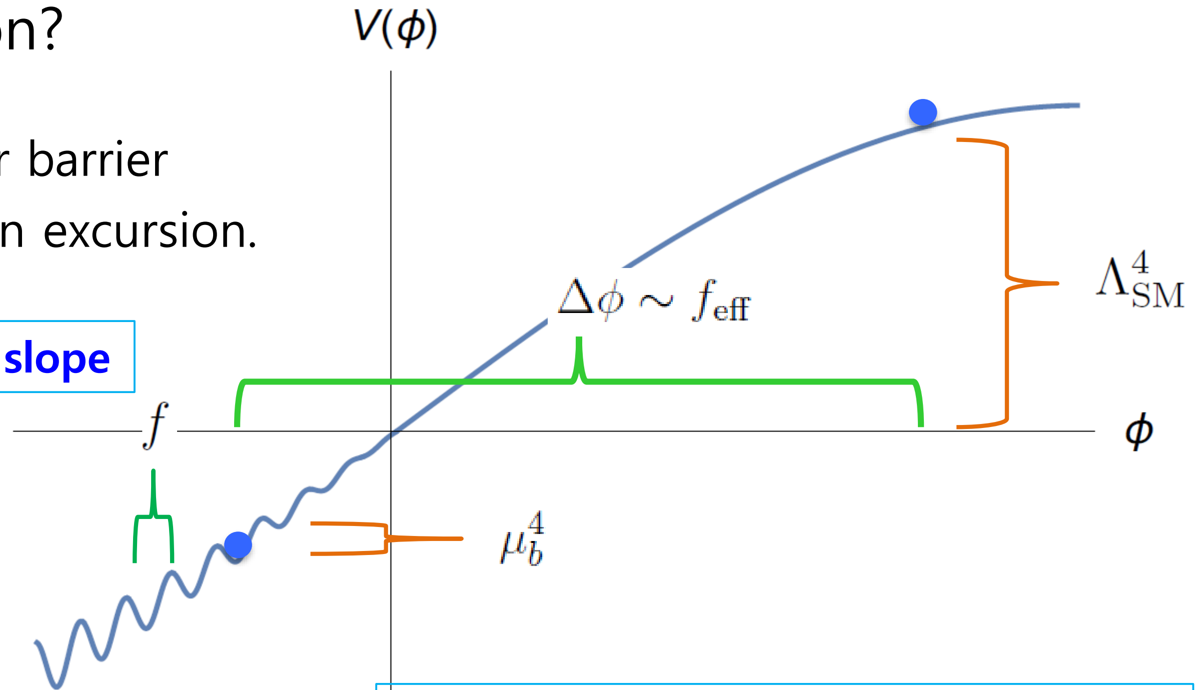
How long excursion?

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

Sliding slope ~ Barrier slope

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

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



Relaxion excursion in angle unit
& Dissipation time in Hubble unit
(for energy dissipation by the Hubble friction)

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

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

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

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

Weak scale hierarchy ➔ Relaxion scale hierarchy

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

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

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.

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

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

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

➔ 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 $\Lambda_{\rm dyn}$:

$$\mathcal{L} = -\frac{1}{4g^2}F^{a\mu\nu}F^a_{\mu\nu} - i\bar{\lambda}D\lambda - \frac{1}{2}\left(m_\lambda\lambda\lambda + {\rm h.c}\right)$$

Stringy (quantum gravity) instanton?

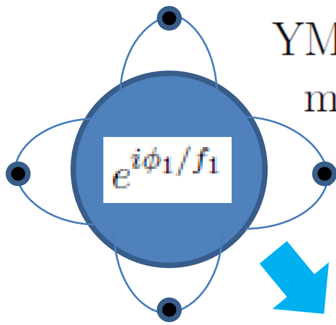
$$+\frac{1}{2}\partial^\mu\phi_1\partial_\mu\phi_1 + \frac{1}{32\pi^2}\frac{\phi_1}{f_1}F^{a\mu\nu}\tilde{F}^a_{\mu\nu} + e^{-S_{\rm ins}}M^4_{\rm UV}\cos\left(\frac{\phi_1}{f_1}\right) \qquad \left(\frac{\phi_1}{f_1} \equiv \frac{\phi_1}{f_1} + 2\pi\right)$$

* At scales $\sim \Lambda_{\rm dyn}$, gaugino condensation is formed, producing a composite axion ϕ_2 with a decay constant $f_2 \sim \Lambda_{\rm dyn}$:

$$\langle\lambda\lambda\rangle \sim \Lambda^3_{\rm dyn}e^{i\phi_2/f_2} \qquad \left(\frac{\phi_2}{f_2} \equiv \frac{\phi_2}{f_2} + 2\pi\right)$$

➔ Two axions ϕ_1 and ϕ_2 at scales around $\Lambda_{\rm dyn}$

Axion potential at scales $\sim \Lambda_{\rm dyn}$



YM-instanton-induced multi-gaugino vertex

$\langle \lambda\lambda \rangle \sim \Lambda_{\rm dyn}^3 e^{i\phi_2/f_2}$

bare gaugino mass

$m_\lambda \lambda\lambda + {\rm h.c}$

$(m_\lambda \ll \Lambda_{\rm dyn})$

stringy instanton

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

$$m_{\phi_2} \sim \Lambda_{\rm dyn} \gg m_{\phi_1} \qquad (\Lambda_{\rm dyn}^4 \gg m_\lambda \Lambda_{\rm dyn}^3,\ e^{-S_{\rm ins}} M_{\rm UV}^4)$$

At scales << $\Lambda_{\rm dyn}$, the massive ϕ_2 is integrated out, yielding a low energy effective potential of ϕ_1 :

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

➔ Single axion ϕ_1, but with two split axion scales in the low energy limit:

$$f_1 \quad \text{and} \quad f_{\rm eff} = n f_1$$

Energy scales

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

a light axion with sub-Planckian decay constant $f_1 \ll MP$

$SU(n)$ confinement with gaugino condensation at $\Lambda_{\rm dyn}$

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

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

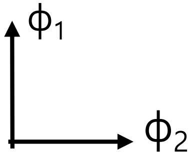
a light axion with split axion decay constants: f_1 and $f_{eff} = n f_1$

Alignment Kim, Nilles, Peloso, 05

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

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

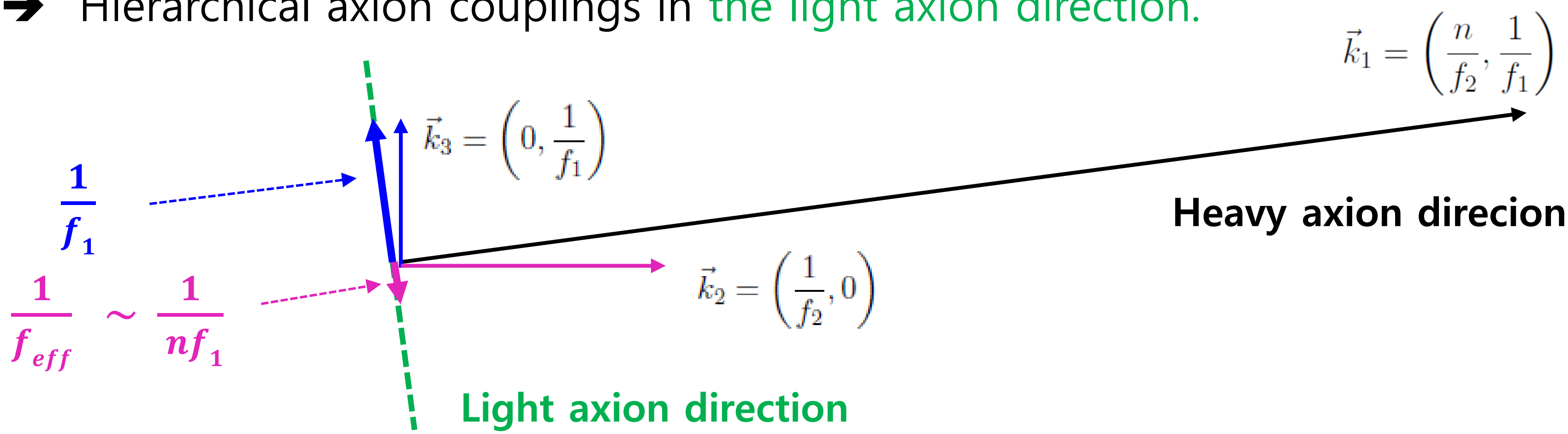
$$\vec{k}_1 = \left(\frac{n}{f_2}, \frac{1}{f_1}\right) \qquad \vec{k}_2 = \left(\frac{1}{f_2}, 0\right) \qquad \vec{k}_3 = \left(0, \frac{1}{f_1}\right)$$



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

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

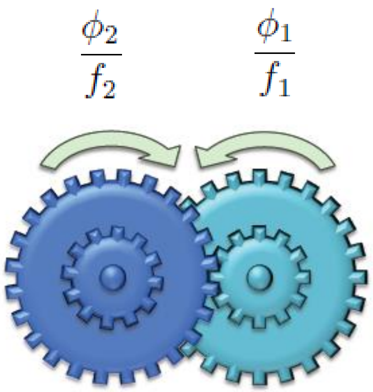
➔ Hierarchical axion couplings in the light axion direction.



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

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

$$\frac{\phi_2}{f_2} \approx -\frac{1}{n}\frac{\phi_1}{f_1} \quad :$$



Field range enhanced by clockwork: $\Delta\phi_2 = 2\pi f_2$ ➔ $\Delta\phi_1 = 2\pi n f_1$

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 >>1 for which the left wheel is much bigger than the right wheel.

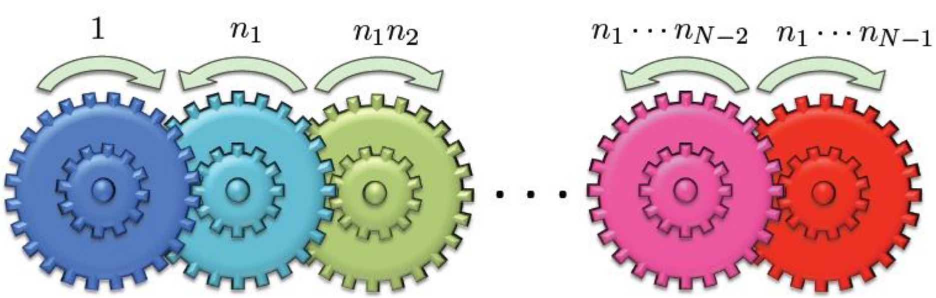
Exponentially big axion scale hierarchy with multiple axions

Clockwork between nearby axions:

$$\Omega_1\left(\frac{\phi_1}{f_1}+n_1\frac{\phi_2}{f_2}\right)+\Omega_2\left(\frac{\phi_2}{f_2}+n_2\frac{\phi_3}{f_3}\right)+...+\Omega_{N-1}\left(\frac{\phi_{N-1}}{f_{N_1}}+n_{N-1}\frac{\phi_N}{f_N}\right)+V_1\left(\frac{\phi_1}{f_1}\right)+V_N\left(\frac{\phi_N}{f_N}\right)$$

$$(\Omega_i \gg V_1, V_N)$$

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



➔ Light axion ϕ with an exponentially enhanced field range

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

and the hierarchical decay constants in the low energy limit:

$$V_{\rm eff} = V_1\left(\frac{\phi}{f_1}\right)+V_N\left(\frac{\phi}{f_{\rm eff}}\right) \quad (f_{\rm eff}=n_1 n_2 ... n_{N-1} f_1 \sim e^N f_1)$$

Known schemes to generate $f_{\rm eff}/f \gg 1$:

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

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

$$N_{\rm fields} = \mathcal{O}\left(f_{\rm eff}/f\right)$$

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 $Q \sim f_{\rm eff}/f$:

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

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

Typically the back-reaction completely changes the effective theory.

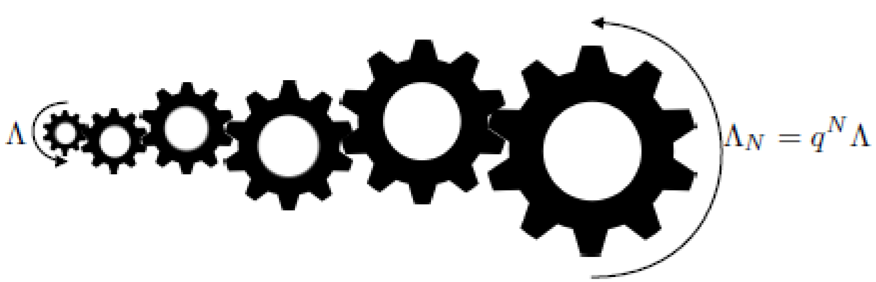
McAllister et. al. 1610.05320

3) Clockwork (N axions): KC, Kim, Yun '14; KC, Im, 1511.00132; Kaplan, Rattazzi,1511.01827

Clockwork between nearby axions with $N_{\rm axion} \sim \ln(f_{\rm eff}/f)$

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 KC, Im, 1511.00132

* Multiple axions

N global $U(1)$ symmetries spontaneously broken at $f \sim m_{\rm SUSY}$ or $\sqrt{m_{\rm SUSY} M_P}$

by soft SUSY-breaking mass:

$$U(1)_i: \;\; X_i \to e^{-2i\alpha_i} X_i \; \left(\text{or} \;\; e^{-3i\alpha_i} X_i\right), \;\; Y_i \to e^{i\alpha_i} Y_i \quad (i = 1, 2, ..., N)$$

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

$$V = -m_{\rm SUSY}^2 |X_i|^2 + \lambda_i^2 |X_i|^4 \left(\text{or} \;\; \frac{|X_i|^6}{M_P^2}\right) + ...$$

$$\langle X_i \rangle \sim \langle Y_i \rangle \sim m_{\rm SUSY} \;\; \text{or} \;\; \sqrt{m_{\rm SUSY} M_P}$$

* Dynamically generated clockwork

Hidden YM sector with gauge group: $G = \prod_{i=1}^{N-1} SU(k_i)$

Charged matter superfields: $\Psi_i + \Psi_i^c, \quad \Phi_{ia} + \Phi_{ia}^c \quad (i = 1, 2, ..., N-1;\ a = 1, 2, ..., n_i)$

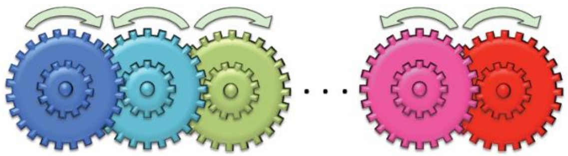
$$\text{with} \quad W_2 = \sum_{i=1}^{N-1} \left(X_i \Psi_i \Psi_i^c + X_{i+1} \Phi_{ia} \Phi_{ia}^c\right)$$

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

threshold corrections to the holomorphic gauge kinetic functions:

$$\Delta \mathcal{F}_i = \frac{1}{8\pi^2} \ln\left(X_i X_{i+1}^{n_i}\right) = \frac{i}{8\pi^2}\left(\frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}}\right) + \ldots$$

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



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

$$f_{\rm eff} = \sqrt{\sum_{i=1}^{N}\left(\prod_{j=i}^{N-1} n_j^2\right) f_i^2} \sim \left(\prod_{j=1}^{N-1} n_j\right) f_1 \sim e^{\xi N} f_1 \quad (\xi = \mathcal{O}(1))$$

* Higgs mass scanning by relaxion & the sliding potential

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

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

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

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

* Barrier potential

Another hidden color which confines at $\Lambda_{\rm HC} \sim$ weak scale

with hidden colored matter $L + L^c, N + N^c$ having

$$W_{\rm br} = H_u L N^c + H_d L^c N + X_1 L L^c \quad \left(\text{or } \frac{X_1^2}{M_P} L L^c\right)$$

$$\Rightarrow \quad V_{\rm br} \sim \frac{\Lambda_{\rm HC}^3}{m_{\rm SUSY}} |H|^2 \cos\left(\frac{\phi}{f} + \delta_1\right) \qquad (\, f_{\rm eff} \sim e^N f\,)$$

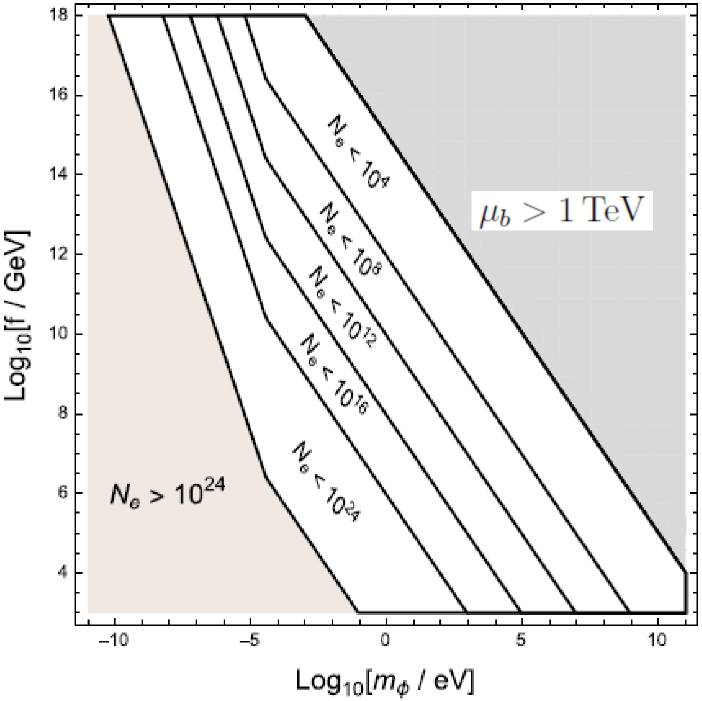
Cosmological relaxion windows KC, Im, 1610.00680

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

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

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

Relaxion mass & decay constant classified by the required inflationary e-folding number

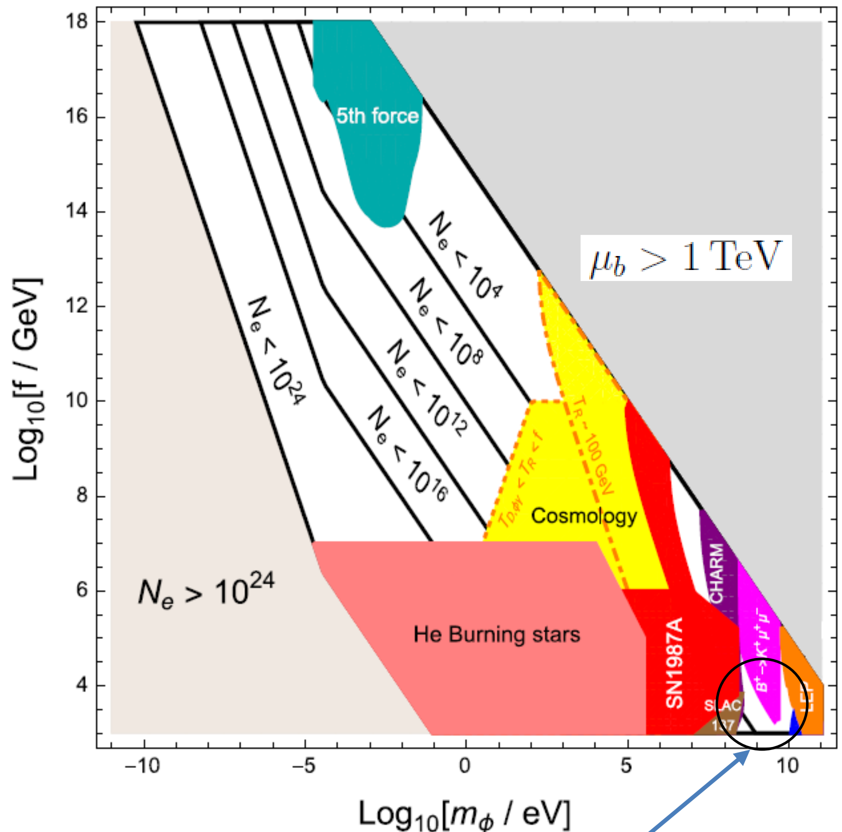


Colored regions are excluded by

- EDMs
- Rare meson decays
- Beam dump experiments
- Astrophysics & Cosmology
- LEP
- 5^{th} 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**

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

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 generated at $\Lambda_{\rm SM}$: Espinosa et al, 1506.09217; Evans et al, 1602.04812

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

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

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

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

- **Too long period of inflation:**

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

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

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

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

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:

(Talk by Hyungjin Kim)

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

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, which exclude most of the region with $m_\phi \gtrsim 100\,{\rm eV}$

- 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)