Relaxion for the EW scale hierarchy

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

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

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Outline

- Introduction

  Cosmological relaxation of the EW scale

- Hierarchical relaxion scales with multiple axions

  Clockwork relaxion

- Observational constraints (see S.H. Im's talk)

- Relaxion dynamics at high reheating temperature

- Conclusion

* 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, …

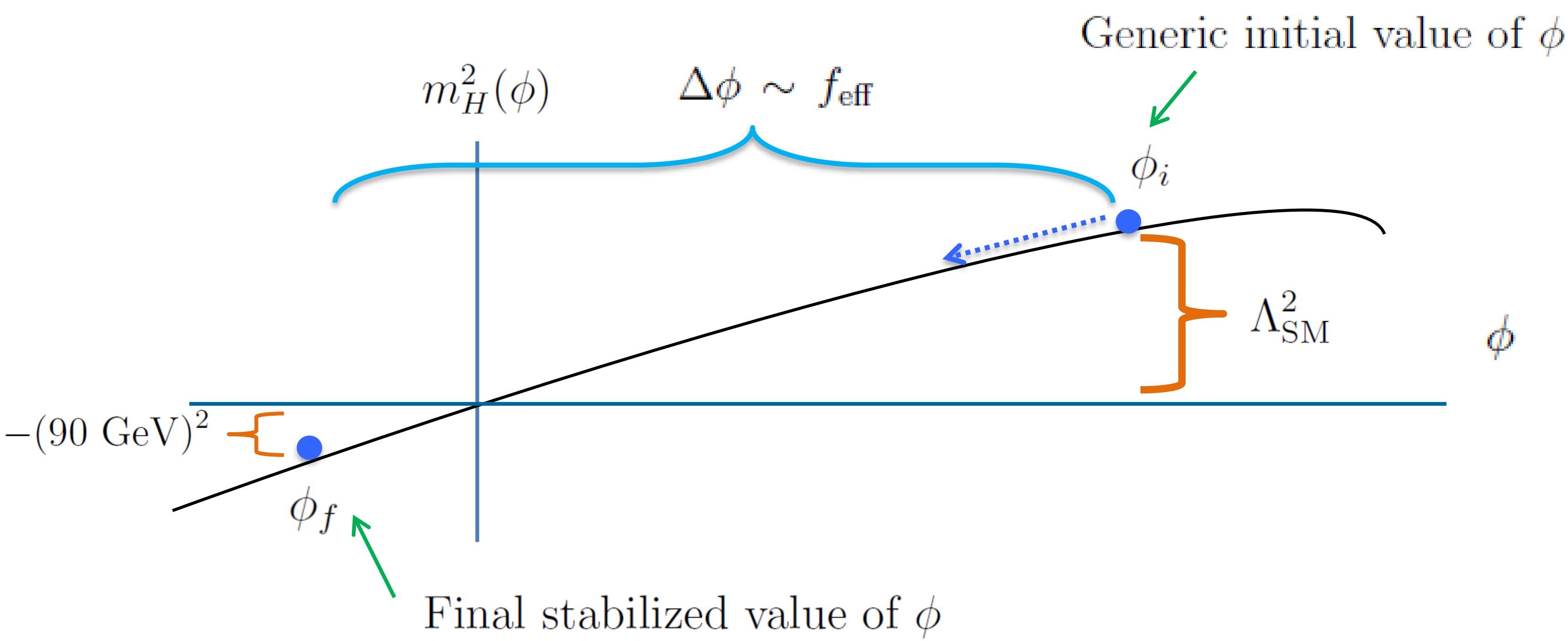
- Anthropic selection with multiverse

- **Cosmological relaxation**, …..

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 $m_H^2(\phi_i) \sim \Lambda_{\rm SM}^2 \gg v^2 \quad (v = 246~{\rm GeV})$ to $m_H^2(\phi_f) \sim -(90~{\rm GeV})^2$:

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

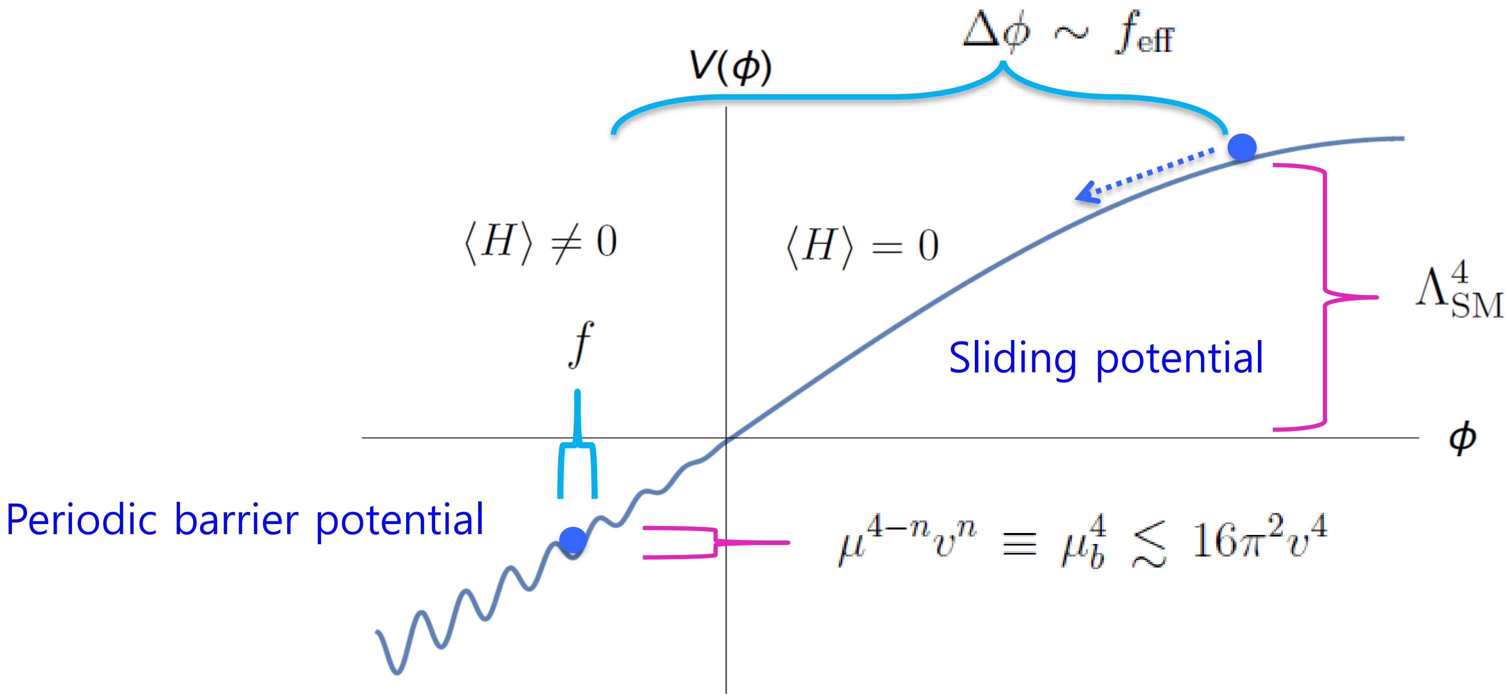


Relaxion potential to implement the necessary cosmological evolution:

i) **Sliding potential** enforcing the relaxion to move to decrease the Higgs mass^2

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

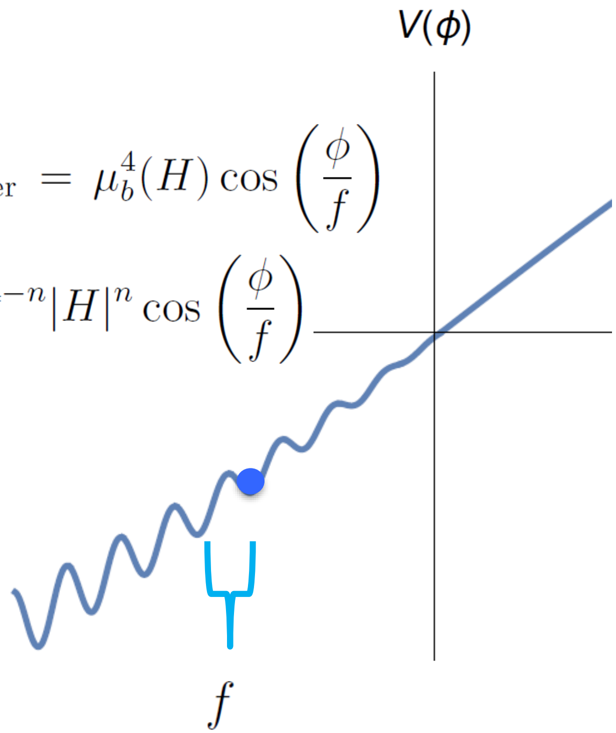
$$V = \mu^{4-n}|H|^n \cos\left(\frac{\phi}{f}\right) + \left(\Lambda_{\rm SM}^4 \frac{\phi}{f_{\rm eff}} + \dots\right) + \dots$$



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

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

* New Physics around TeV:

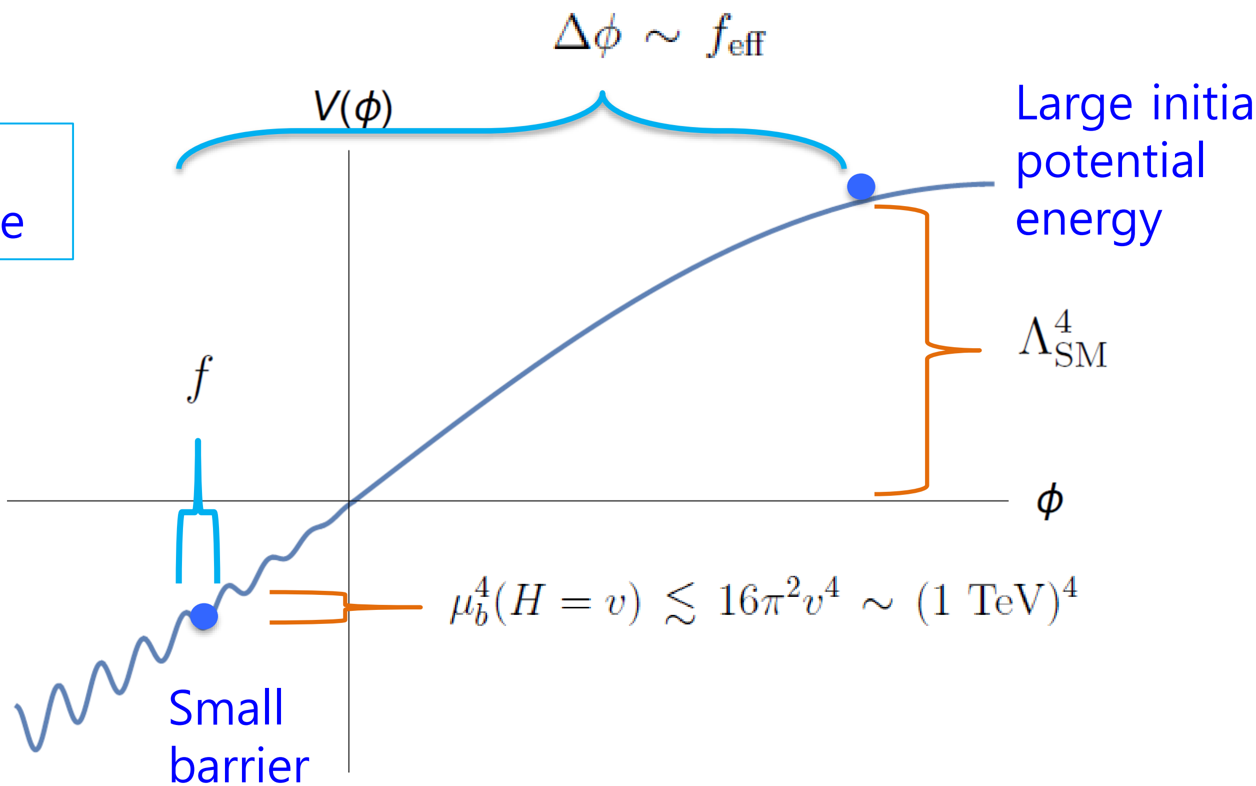
➔ $\mu_b^4(H=v) \lesssim 16\pi^2 v^4 \sim (1 \text{ TeV})^4$

Price to pay:

Sliding slope
$\sim$ Barrier slope

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

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



➔ Requires i) cosmological dissipation of the relaxion potential energy

(focus on the Hubble dissipation during the inflationary period)

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

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

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

Weak scale hierarchy ➔ Relaxion scale hierarchy

$$\boxed{\frac{\Lambda_{\rm SM}^2}{16\pi^2 m_H^2} \gg 1} \qquad \boxed{\frac{f_{\rm eff}}{f} \gtrsim \left(\frac{\Lambda_{\rm SM}^2}{16\pi^2 m_H^2}\right)^2}$$

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.

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

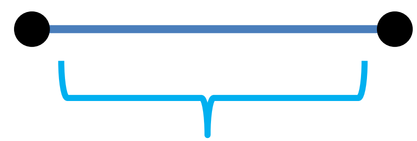
New-physics-induced barrier potential might be more plausible.

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

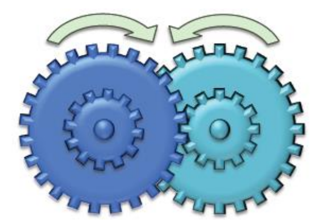
Clockwork axion: KC, Kim, Yun '1404.6209; KC, Im, 1511.00132; Kaplan, Rattazzi,1511.01827

A particular form of the Kim-Nilles-Peloso two axion model:

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



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

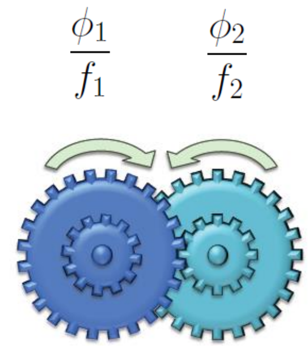


$$V_{\rm clockwork} = -\Lambda^4 \cos\left(\frac{\phi_2}{f_2} + n\frac{\phi_1}{f_1}\right)$$

$$U(1)_1 \times U(1)_2 \;\to\; U(1)_\phi$$

$$\left(U(1)_\phi : \frac{\phi_1}{f_1} \to \frac{\phi_1}{f_1} + \alpha, \quad \frac{\phi_2}{f_2} \to \frac{\phi_2}{f_2} - n\alpha\right)$$

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



One may introduce the clockwork potential by hand:

$$V_{\text{clockwork}} = \lambda\sigma_1^n\sigma_2 + \dots \quad \left(\langle\sigma_i\rangle = \frac{f_i}{\sqrt{2}}e^{i\phi_i/f_i}\right)$$

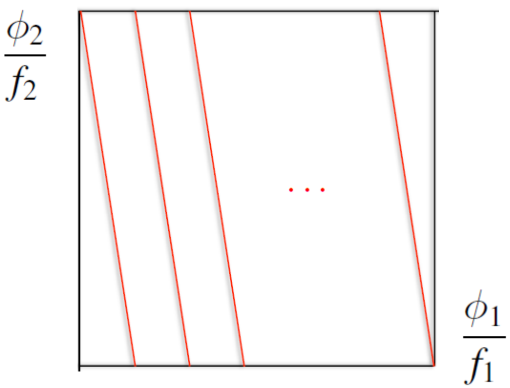
or generate it by non-perturbative dynamics:

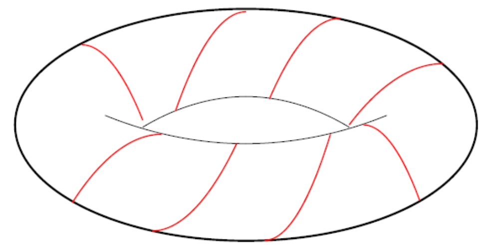
$$\mathcal{L}_{\text{clockwork}} = \{SU(n)\ \text{YM}\} + y_1\sigma_1\lambda\lambda + y_2\sigma_2\psi\psi^c + \dots$$

$$\Big(\lambda = SU(n)\text{-adjoint}, \quad \psi, \psi^c = n, \bar{n} \text{ of } SU(n)\Big)$$

Clockwork potential yields a flat direction with an axion monodromy structure, so an enhanced field range of the light axion:

$$V_{\text{clockwork}} = -\Lambda^4 \cos\left(\frac{\phi_2}{f_2} + n\frac{\phi_1}{f_1}\right) \quad \left(\text{or any periodic function of } \tfrac{\phi_2}{f_2} + n\tfrac{\phi_1}{f_1}\right)$$





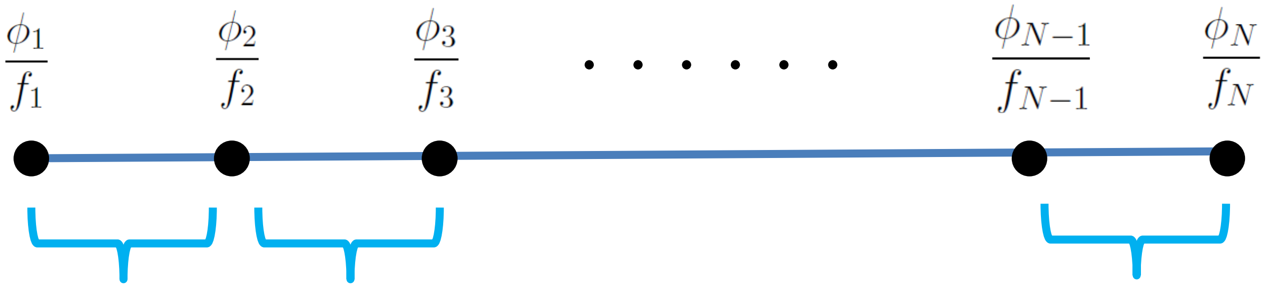
ϕ = canonically normalized light axion describing the flat direction with a field range $2\pi f_{\text{eff}}$

$$f_{\text{eff}} = \sqrt{n^2 f_2^2 + f_1^2}$$

$$\frac{\phi_1}{f_1} = \frac{\phi}{f_{\text{eff}}} + \text{heavy axion}, \quad \frac{\phi_2}{f_2} = -n\frac{\phi}{f_{\text{eff}}} + \text{heavy axion}$$

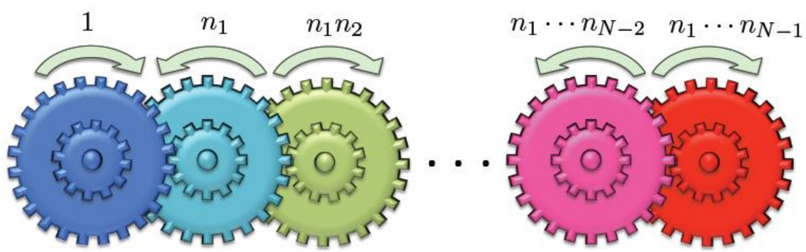
(In the limit $n \gg 1$, ϕ is aligned to ϕ_2: KNP alignment.)

One can repeat the clockwork with more axions to get an exponentially enhanced field range of the light axion:



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

clockwork gear



ϕ = canonically normalized light axion describing the collective rotation with an exponentially enlarged field range $2\pi f_{\text{eff}}$:

$$f_{\text{eff}} \sim n_1 n_2 \ldots n_{N-1} f \sim e^N f \quad \left(f_i \sim f\right)$$

Hierarchical effective couplings of ϕ induced by the boundary axion couplings:

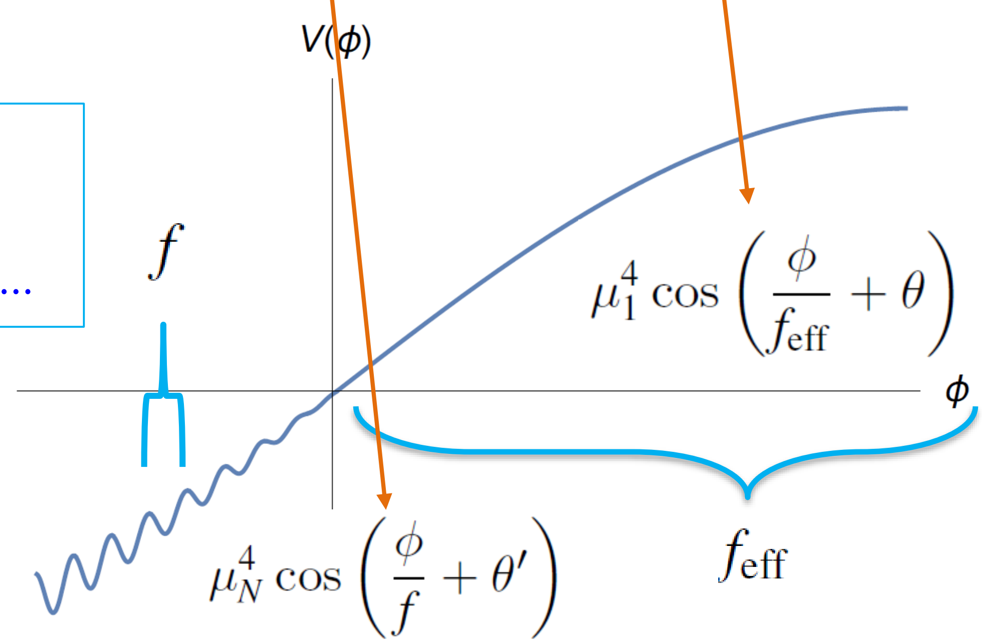
$$\frac{\phi_i}{f_i} = \left(\prod_{j=1}^{j=i-1} n_j\right)\frac{\phi}{f_{\rm eff}} + \text{heavy axions}$$

$$\rightarrow \quad \frac{\phi_1}{f_1} = \frac{\phi}{f_{\rm eff}} + \ldots, \qquad \frac{\phi_N}{f_N} = \frac{\phi}{f} + \ldots \qquad \left(f_{\rm eff} \sim e^N f\right)$$

$$\frac{1}{32\pi^2}\frac{\phi_N}{f_N}(F\tilde{F})_N + \frac{1}{32\pi^2}\frac{\phi_1}{f_1}(F\tilde{F})_1 \;\rightarrow\; \frac{1}{32\pi^2}\frac{\phi}{f}(F\tilde{F})_N + \frac{1}{32\pi^2}\frac{\phi}{f_{\rm eff}}(F\tilde{F})_1$$

Generalizations, applications, continuum limit:

Talks by Mccullough, Kamenik, …



Observational constraints on relaxion parameters KC, Im, 1610.00680

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

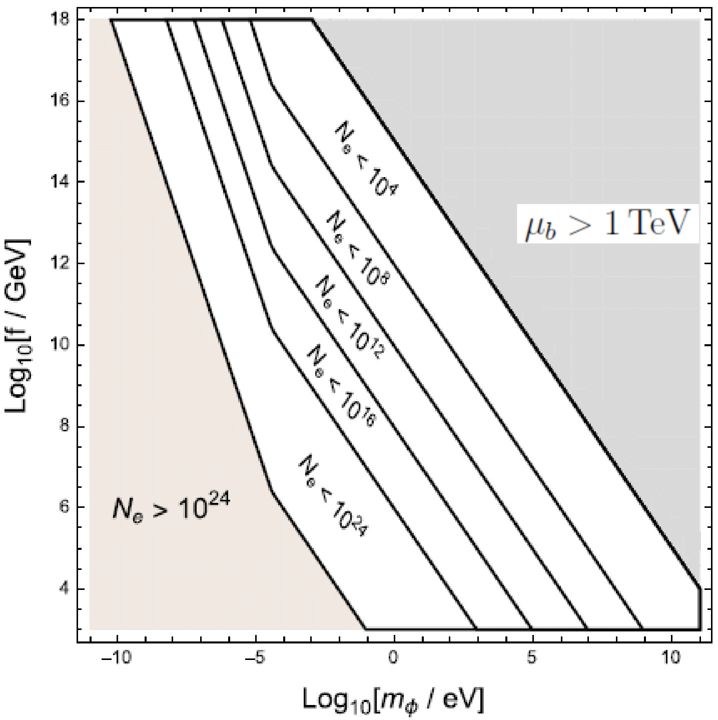
$$V_{\rm barrier} = \mu_b^4(H)\cos\left(\frac{\phi}{f}\right) = \mu^{4-n}|H|^n\cos\left(\frac{\phi}{f}\right) \quad \left(\mu_b \lesssim 1\,{\rm TeV}\right)$$

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

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:

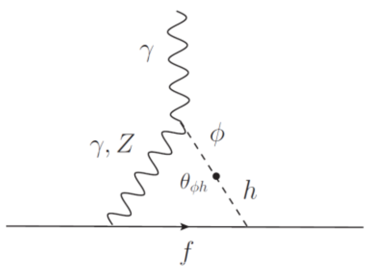
(see S.H. Im's talk for more details)

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

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

* 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

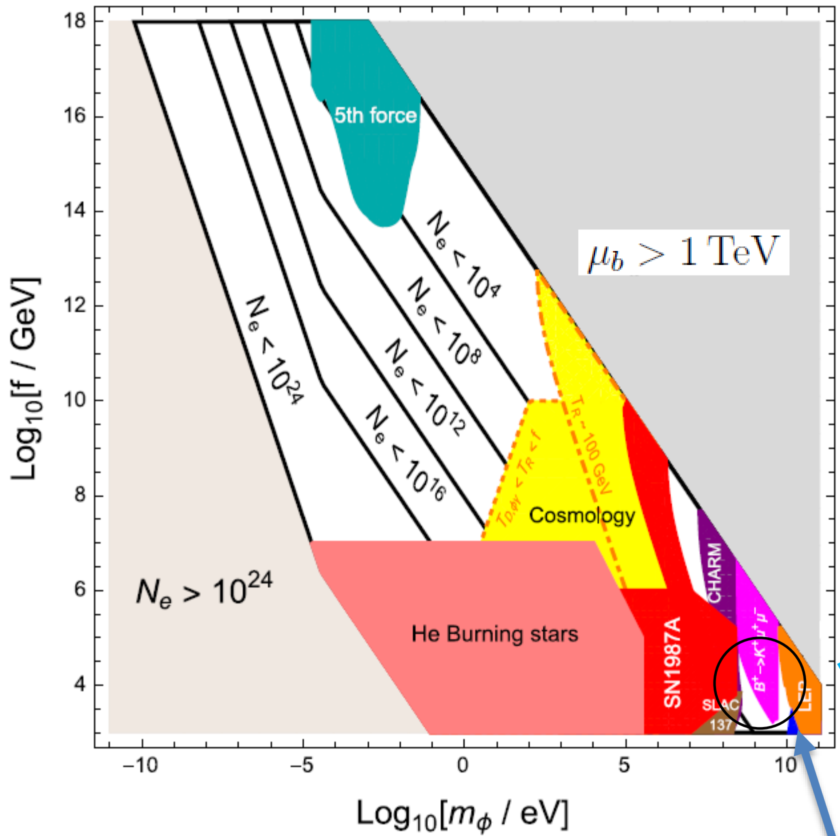
* Astrophysics: Star coolings (SN or He buring stars)

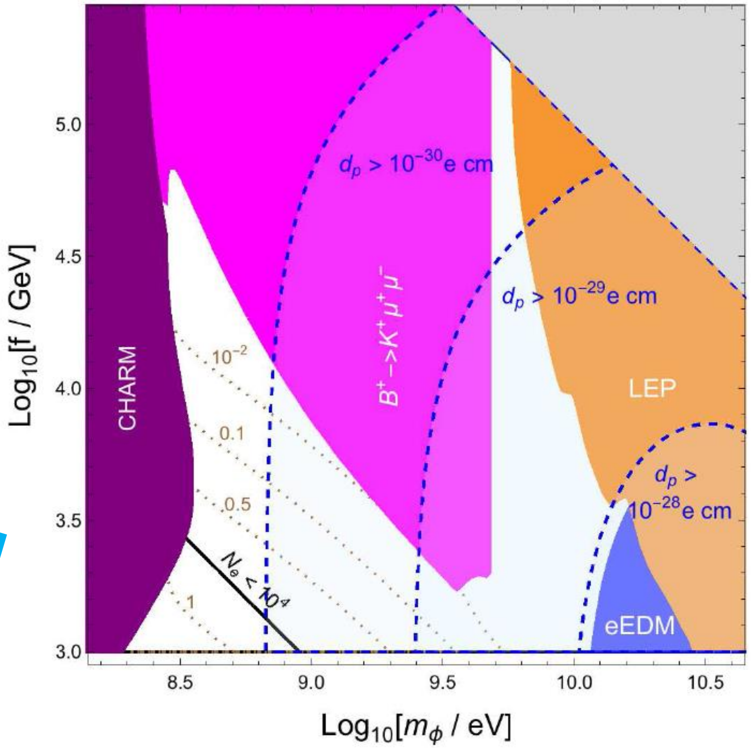
* Cosmology: Effects on BBN, CMB, dark radiation, X or γ ray backgrounds

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

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 $T_{RH} \gg v = 246\ \mathrm{GeV}$ 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.

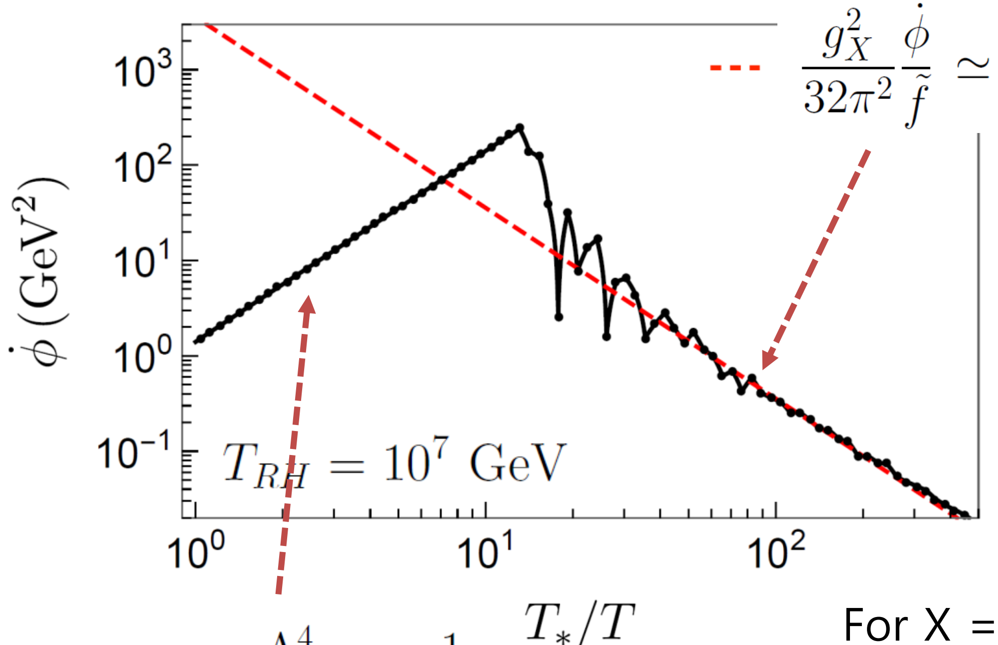
Indeed, in most of the favored parameter space, the Hubble friction after the reheating is not strong enough to slow down the relaxion motion to stop the relaxion at the right position after the EW phase transition.

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.)

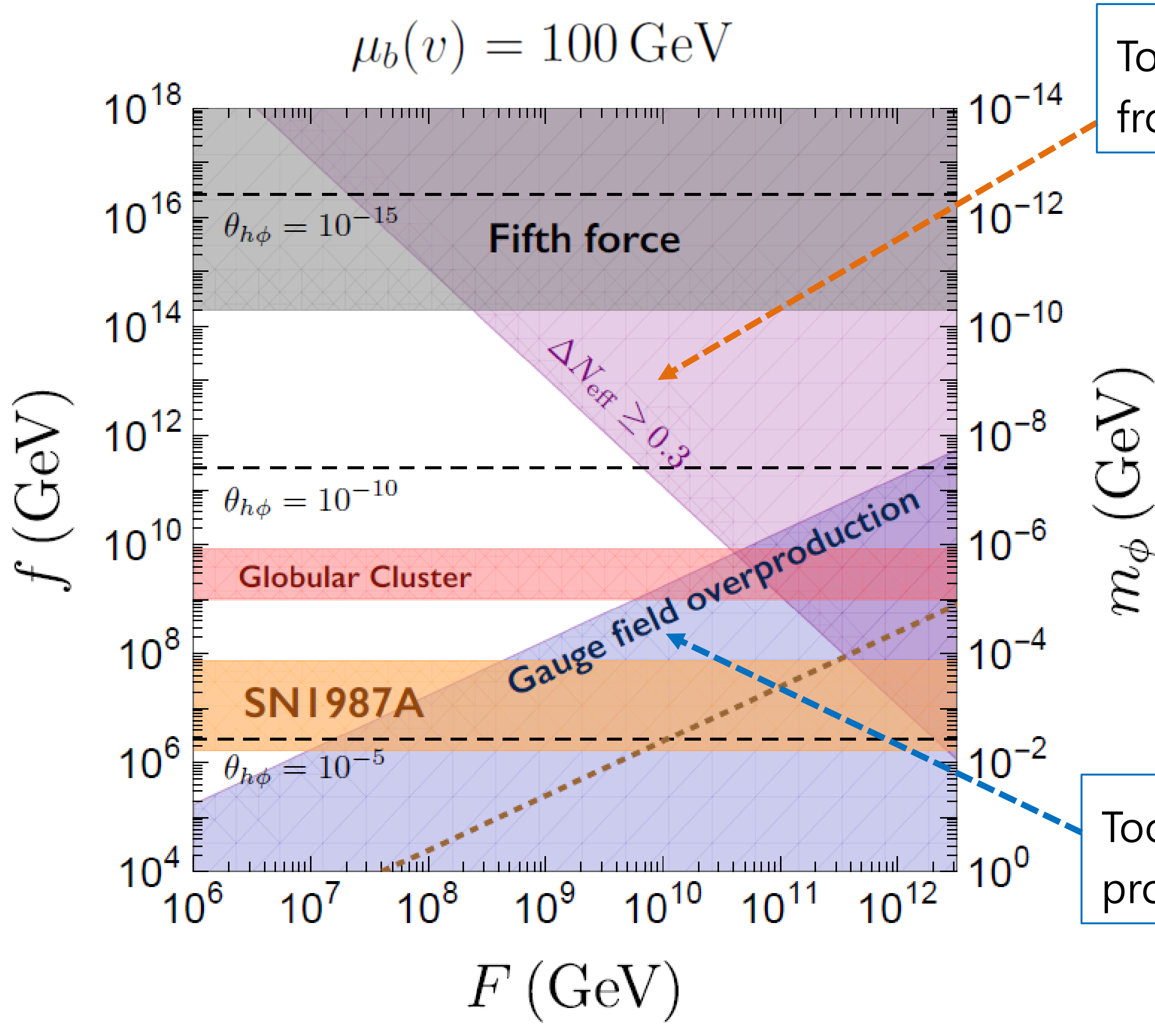
$$\left(V_0 = \frac{\Lambda^4}{f_{\rm eff}}\phi + \dots \right)$$

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 slow down the relaxion motion:

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

Yet there are further observational constraints:

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



Too much dark radiation from $\phi \to XX$

Too much dark radiation produced by rolling relaxion

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 the weak scale 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. '15

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

But this assumes that the three phase parameters take the same value, which would 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 '16

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 might 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 a 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.