Relaxions

Workshop seminar 26/11/12
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Agenda:

- Introduction
- Model features
    - Barriers
    - Hubble friction
    - Gauge particle production
    - Relaxion particle production
    - Large barriers
- Model summary
- Observational prospects

Introduction

Hierarchy problem

$m_h^2 \simeq m_{h0}^2 + \Lambda^2$

Old suggestions:

→ Cancel contribution (e.g. SUSY)

→ Cut off contribution (e.g. composite)

New proposal (2015): Accept contribution and run the mass down with an axion.

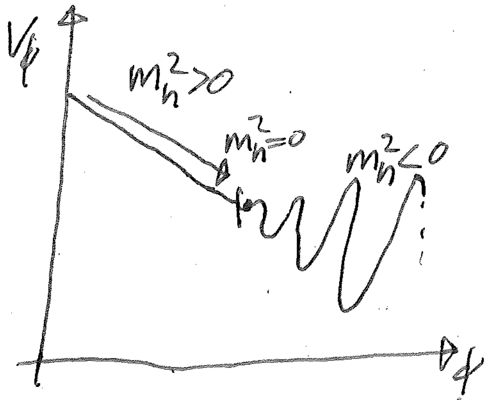
$\Rightarrow$ The relaxion

Graham
Kaplan
Rajendran
} GKR [1]

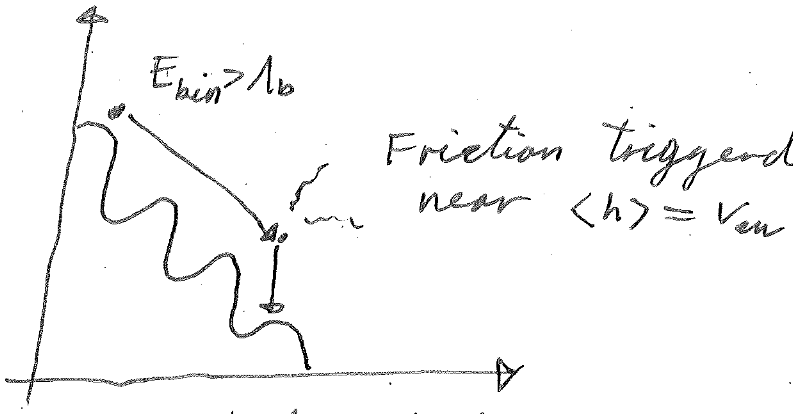
Couple the Higgs to an axion ϕ: ②

$$V \supset \underbrace{\frac{1}{2}(\Lambda^2 - g'\Lambda\phi)h^2}_{\text{Mass scan}} - \underbrace{g\Lambda^3\phi}_{\text{Slope}} + \underbrace{\Lambda_b^4 \frac{h^2}{v_{ew}^2}\cos\frac{\phi}{f}}_{\text{Barriers}}$$

Two classes:



Higgs dependent barriers



Higgs independent barriers

Cosine barriers from strong interaction

→ Could be QCD ?

↳ Strong CP-problem: No

$\theta_{QCD} < 10^{-10}$ set by VEV of ϕ

$\theta_{relaxion} \sim \frac{\Delta\phi}{f} \gg 1 \gg 10^{-10}$ ↯ No easy QCD-relaxion

Therefore:

⇒ QCD-relaxion requires additional dynamics [1]

⇒ Non-QCD-relaxion relys on new strong dynamics [2-6]

↳ We restrict ourselves to non-QCD

Barriers

The backreaction term is generated from new strong dynamics. Consider this sector to consist of new fermions L, L^c, N, N^c in the fundamental rep of a strong gauge group G, and let the relaxion couple to the field strength of G:

$$\mathcal{L} = -m_N N N^c - m_L L L^c + y H L N^c + \tilde{y} H^\dagger L^c N + \frac{\phi}{f} G \tilde{G} + h.c.$$

Let L, L^c be charged as left and righthanded leptons under the SM gauge groups and let N, N^c be SM singlets. The L, L^c then must be fairly heavy. If we integrate them out and rotate the fields to cancel the last term the potential becomes:

$$V \simeq \underbrace{N N^c}_{\substack{\sim 4\pi f^3 \\ \text{below } f}} \left(m_N + \frac{y \tilde{y}}{2 m_L} |H|^2 + \text{loop contri.} \right) \cos\left(\frac{\phi}{f}\right)$$

Higgs independent   Higgs dependent

Coincidence problem: For the h^2 term to be stable agenst

$$f \lesssim V_{ew}, \quad m_L \simeq \text{TeV} \quad \text{must be satisfied.}$$

While such a scale can be generated by dymensional transmutation, there is no reason why these conditions should hold.

$\Rightarrow$ Higgs dependent barriers are associated with observable, weak scale fermions, but they also suffer from a coincidence of scales.*

*Ways to avoid this have been studied in [2]

Having a minima is not enough - we need dissipation to stop the relaxion. (4)

Hubble friction

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$ Klein-Gordon Scalar field in FRW

Cosmic expansion provides friction
- → No additional physics required
- → Strong during inflation

Original proposal by GKR: Hubble friction plus + Higgs dependent barriers with relaxation during inflation.

Inflation → Strong friction → Roll stops efficiently at $V' = 0$

Strong friction controls rolling speed:

$$\dot{\phi} = \dot{\phi}_{slow\,roll} = \frac{g\Lambda^3}{3H_I}$$ (ϕ still subdominant to inflaton)

Enforce subdominance to inflaton:

$$\left.\begin{array}{l} V_I \sim H_I^2 M_p^2 \\ V_\phi \sim \Lambda^4 \end{array}\right\} \quad V_I > V_\phi \Rightarrow \frac{\Lambda^2}{M_p} < H_I$$

Classical roll must dominate quantum fluctuations:

$$\left.\begin{array}{l} \Delta\phi_{classical} \sim H_I^{-1}\dot{\phi} \sim \frac{g\Lambda^3}{3H_I^2} \\ \Delta\phi_{quantum} \sim H_I \end{array}\right\} \quad \Delta\phi_{quantum} < \Delta\phi_{classical} \Rightarrow H_I < g^{1/3}\Lambda$$

Restriction on inflations scale:

$$\frac{\Lambda^2}{M_p} < H_I < g^{1/3}\Lambda \qquad (*)$$

Stopping condition:

$$V' = 0 \Rightarrow \Lambda_b^4 \sim g\Lambda^3 f \quad **$$

Inflation scale limits then limit the cut-off scale Λ:

$$\left.\begin{matrix} * \\ ** \end{matrix}\right\} \Rightarrow \Lambda < \left(\frac{\Lambda_b^4 M_p^3}{f}\right)^{\frac{1}{6}} \Leftrightarrow \boxed{\Lambda < 10^9\ \text{GeV}}$$

The original model requred transplankian fied excursions:

$$\Delta\phi \sim \frac{\Lambda}{g}, \quad g \ll 1 \Rightarrow \Delta\phi > M_p$$

Model also requires a very large # of e-folds

$$\Delta\phi \sim \dot{\phi}\Delta t \sim \dot{\phi}\frac{N_e}{H_I} \Rightarrow N_e \sim \left(\frac{H_I}{g\Lambda}\right)^2 \Rightarrow \quad 10^4 < N_e < 10^{60}$$

when stopped by H

$\Rightarrow$ The original GKR model can raise the cut-off scale Λ to 10^9 GeV but requres inflation with a very large # of e-folds and a limited range of inflationary scales.

Gauge boson particle production

Motivation:

→ Solution without strong inflation constraints

→ Avoid coincidence problem

Strategy:

- Higgs independent barriers → No coincidence prob.
- Relaxation after inflation

⇒ Need for a new <u>trigger</u> and source of <u>friction</u>

Answer: Particle production!

$$\ddot{\phi} + 3H\dot{\phi} + \underline{\underline{\Gamma\dot{\phi}}} + m^2\phi = 0$$

ϕ - decay ⇒ friction

Consider

$$\mathcal{L} \supset -\frac{\phi}{4F}\left(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

After EWSB

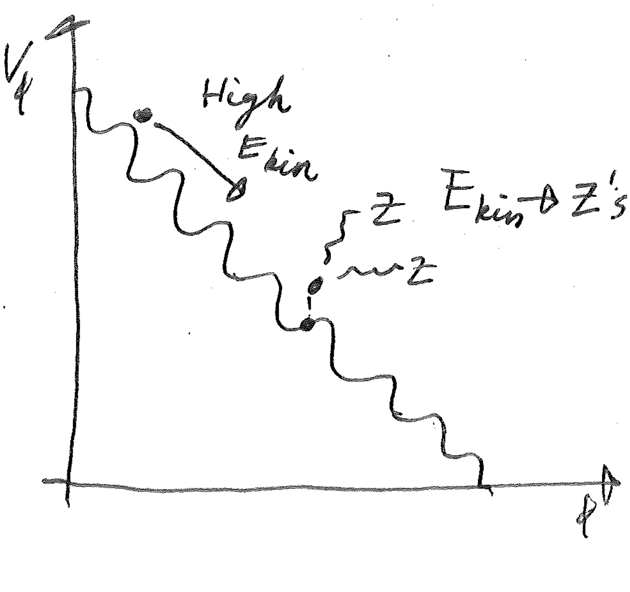
$$\mathcal{L} \supset -\frac{\phi}{F}\epsilon^{\mu\nu\rho\sigma}\left(2g_2^2\,\partial_\mu W^-_\nu\,\partial_\rho W^+_\sigma + (g_2^2-g_1^2)\,\partial_\mu Z_\nu\,\partial_\rho Z_\sigma - 2g_1g_2\,\partial_\mu Z_\nu\,\partial_\rho A_\sigma\right)$$

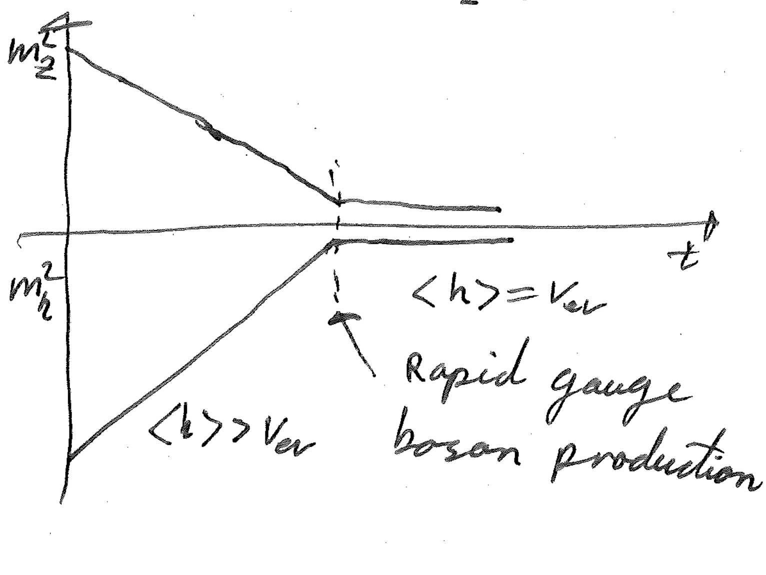
Suppressed by thermal effects

Tachyonic instability ⇒ rapid production

No instability

Trigger: Start with large VEV and $\langle h\rangle/m_Z \to 0$





The EOM of transverse Z modes can be written as

$$\ddot{Z}_\pm + \left(k^2 + m_Z^2 \mp k\frac{\dot{\phi}}{F}\right) Z_\pm = 0$$

$\Rightarrow$ Z_+ tachyonic for $m_Z \lesssim \frac{\dot{\phi}}{2F}$

$\Rightarrow$ Rapid Z production stops relaxion efficiently

The process can take place <u>during inflation</u> [3] if

$$\Lambda_b^2 \leq \dot{\phi}_{SR} \quad \text{and} \quad \Delta t_\phi < H^{-1}$$

Slow-roll with enough energy to pass barriers

Time to pass one barrier is small compared to Hubble (Hubble friction inefficient)

Since the parameter space allows much higher slow-roll velocities relaxation can take place with fewer e-folds

$\Lambda \lesssim 10^8\,\mathrm{GeV}$, $N_e \gtrsim 10^2$, coincidense problem resolved

<u>After inflation:</u> [4]

The gauge particle production model was initially thought to be able to decouple relaxation from inflation, but the recent paper by Nayara, Enrico, Ryosuke and Geraldine published last tuesday completely rules out this scenario.

$\Rightarrow$ Not viable after inflation at all [5-6]

Relaxion Particle Production (fragmentation) [5-6]

Previously unaccounted for: Resonant production of relaxions driven by the traversal of many minima by the classical background.

$\Rightarrow$ Present in all models

$\Rightarrow$ Relaxion can be self-stopping

Decompose the field:

$$\phi(x,t) = \phi_0(t) + \delta\phi(x,t)$$

$$\delta\phi(x,t) = \int \frac{d^3k}{(2\pi)^3} a_k \, v_k(t) \, e^{ikx} + h.c.$$

The EOM can be written as

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) + \frac{1}{2}V'''(\phi)\int\frac{d^3k}{(2\pi)^3}|v_k|^2 = 0$$

$$\ddot{v}_k + 3H\dot{v}_k + \left[e^{-2Ht}k^2 + V''(\phi)\right]v_k = 0$$

Friction, as consistent with energy conservation

Simplify with $H=0$, $a=1$ (fast process)

$$\ddot{v}_k + \left(k^2 - \frac{\Lambda_b^4}{f^2}\cos\frac{\phi}{f}\right)v_k = 0$$

Mathieu eq!

Relaxion fragmentation is surpressed by

1) Large Hubble friction
2) Large slope

Both of which can make fragmentation ineffective.
Fragmentation is effective for

$$H\dot{\phi}_{SR} < \frac{\pi \Lambda_b^8}{2f}\left(W_0\left(\frac{32\pi^2 f^4}{e\,\dot{\phi}_{SR}^2}\right)\right)^{-1} \quad \text{if} \quad \dot{\phi}_0 = \dot{\phi}_{SR}$$

or

$$g\Lambda^3 < \frac{\pi \Lambda_b^8}{2f\dot{\phi}_0^2}\left(W_0\left(\frac{32\pi^2 f^4}{e\,\dot{\phi}_0^2}\right)\right)^{-1} \quad \text{if} \quad \dot{\phi}_0 < \dot{\phi}_{SR}$$

A plot will follow later.

Here W_0 is the product log function

Last resort: <u>Large barriers</u>

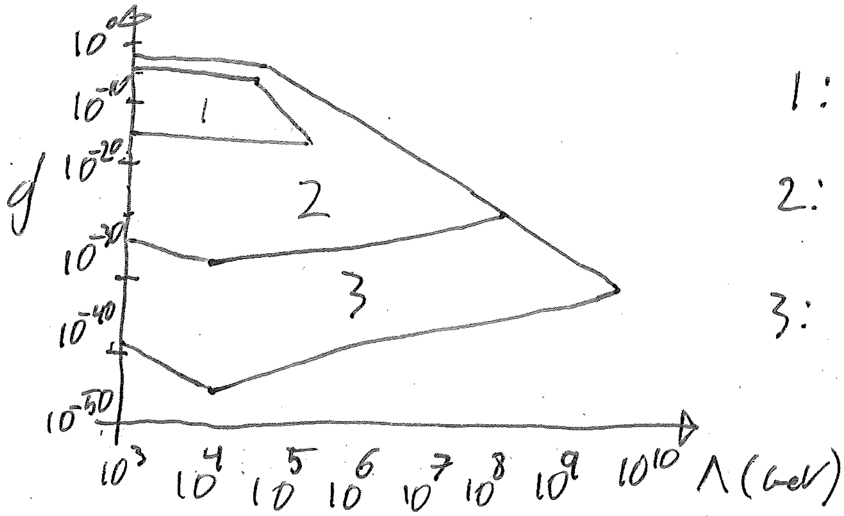
If nothing else works, i.e. if
1) Hubble friction inefficient $(\Delta t < H^{-1})$
2) Fragmentation inefficient (see above)
3) Gauge boson production not included

We can capture the relaxion by simply useing large enough barriers:

$$\Lambda_b^4 = \frac{1}{2}\dot{\phi}_{SR}^2$$

Model summary

Higgs dependent barriers during inflation



1: Fragmentation

2: Large barriers

3: Hubble friction

All senarios discussed:

	Higgs dependent barriers	Higgs independent barriers + gauge
During inflation	$\Lambda \leq 10^9$ GeV $H \geq 10^5$ GeV $N_e \geq 10$	$\Lambda \leq 10^8$ GeV $N_e \geq 10^2$
After inflation (or before)	$\Lambda \leq 10^6$ GeV	Not viable
Relaxion inflation preceding inflation	$\Lambda \leq 10^5$ GeV $N_e \leq 1$	

Another noteworthy model is the "double scanner" mechanism [2], which resolves the coincidence problem by way of a second light and weakly coupled scalar.

Observational prospects

The relaxion itself
→ Weakly coupled
→ Hard to detect

New fermions at EW scale
→ Should be visible at colliders
→ Predicted by all models with Higgs dependent barriers

Other possibilitudes
→ Domain walls?
→ GW signals?

Conclusion

- Relaxions can accomodate Higgs mass contributions of up to 10^9 GeV
- Relaxions feature a wealth of mechanisms and model building oppertunities
- Some models can be hard to observe

References

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[2] Cosmological Higgs-Axion Inteplay for a Naturally Small EW scale. J.R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolas, G. Servant
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[4] Higgs relaxation after inflation
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[5] Axion Fragmentation
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[6] Relaxion Fluctuations (Self-stopping Relaxion) and Overview of Relaxion Stopping Mechanisms
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