Peccei-Quinn Relaxion

arXiv:1709.10025, KSJ and Chang Sub Shin (IBS-CTPU)

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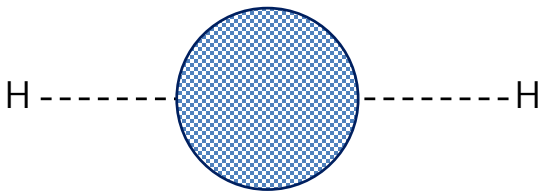
Outline

- Cosmological Relaxation of the Higgs Mass
- PQ Relaxion
- Relaxation with Stronger SM Couplings
- Summary and Discussion

❖ Cosmological Relaxation of the Higgs Mass

◆ EW hierarchy problem

- Higgs mass: Sensitive to unknown UV physics



$$\delta m_H^2 \sim \frac{M^2}{16\pi^2} \quad (M\text{: cutoff scale})$$

- Unnatural without new physics around TeV

  - SUSY, Extra dimensions, Strong EWSB, ⋯

▪ LHC experiments

- No signals for new physics around TeV

  - New approach to EW hierarchy problem?

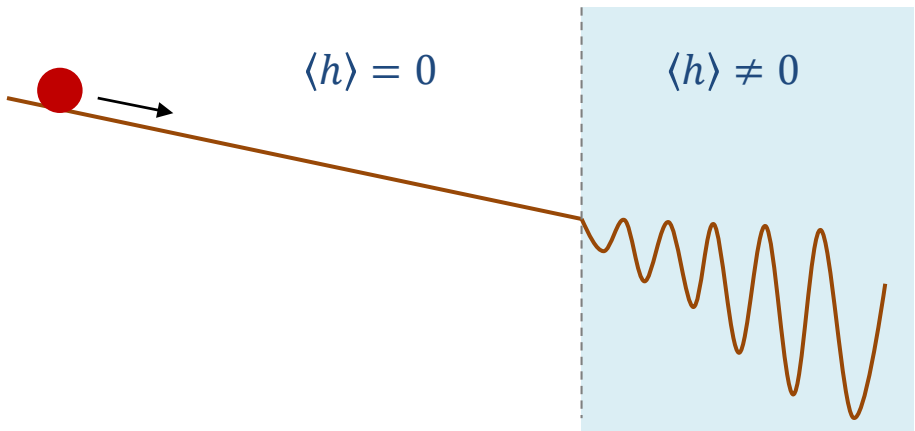
Graham, Kaplan, Rajendran 2015

◆ Cosmological relaxation of the Higgs mass

- Interplay between **Higgs** h and **Relaxion** ϕ

$$m_h^2 = m_h^2(\phi)$$

Cosmological evolution of ϕ to select the Higgs mass



- ϕ slow-rolls while scanning m_h^2 from $+M^2$ to negative, and stops by barriers formed by EWSB

- Potential terms for relaxation

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

- Sliding: $V_0 = M^4\left(-c_1\frac{\phi}{F} + c_2\frac{\phi^2}{F^2} + \cdots\right)$
- Higgs mass-squared: $m_h^2(\phi) = M^2\left(-k_0 + k_1\frac{\phi}{F} + \cdots\right)$
- Barriers: $V_{br}(\phi, h) = -\mu_{br}^4(h)\cos\left(\frac{\phi}{f}\right)$

$c_1 \geq \frac{k_1}{16\pi^2}$

- M: cutoff scale of the SM

- $\frac{M}{F} \ll 1$: explicit breaking of shift symmetry $\phi \to \phi + 2\pi f$

- Conditions for relaxation

1) High enough barriers to stop ϕ

$$\partial_\phi V_0 \sim \partial_\phi V_{br}$$

at time when $\langle h \rangle \sim v = 246$ GeV

$$\Rightarrow \frac{F}{f} \sim \left(\frac{M}{\mu_{br}(h=v)}\right)^4 \gg 1$$

- Conditions for relaxation

2) Small Hubble scale during inflation

$$\frac{\sqrt{V_0}}{M_{Pl}} < H_i < \left(\partial_\phi V_0\right)^{1/3}$$

for relaxion evolution to be dominated by classical rolling

3) Large number of e-folds

$$N_e > \frac{H_i^2}{\partial_\phi V_0} F$$

to scan m_h^2 from M^2 to negative

- Important issues
  - How much can M be raised?
  - Constraints on inflation, H_i and N_e
  - Large excursion of relaxion, $\Delta\phi \sim F \gg f$

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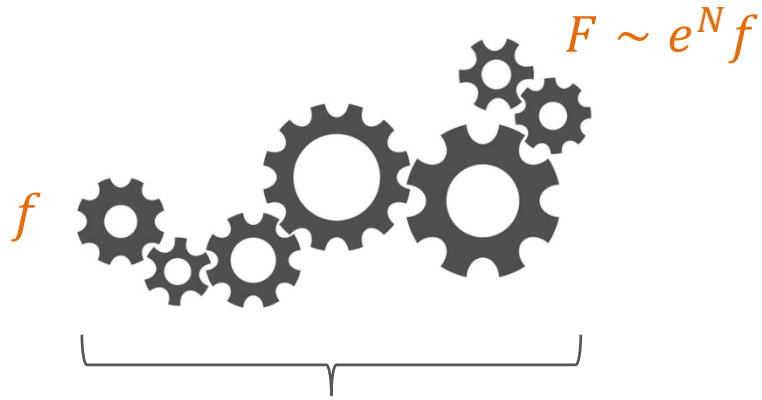
    → Clockwork mechanism



N cw axions for collective rotation

Choi, Im 2016
Kaplan, Rattazzi, 2016

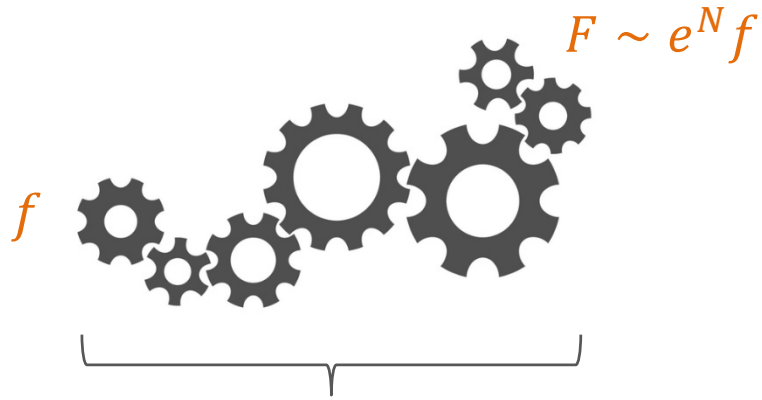
- Important issues

  - How much can M be raised?
  - Constraints on inflation, H_i and N_e

  → crucially depend on V_{br}

  - Large excursion of relaxion, $\Delta\phi \sim F \gg f$

    → Clockwork mechanism



N cw axions for collective rotation

Choi, Im 2016
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◆ Source of h-dependent barriers for ϕ

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

- QCD anomaly
  - Relaxion = QCD axion
  - $\mu_{br}^4 = y_u \Lambda_{QCD}^3 h$
  - Too large strong CP phase

Possible solutions:

Graham, Kaplan, Rajendran 2015

(1) slope of V_0 decreases after inflation: $M < 10^{4-6}$ GeV

(2) slope of V_{br} increases after inflation: $M < 10^7$ GeV

Nelson, Prescod-Weinstein 2017

- Hidden QCD anomaly
  - Relaxion ≠ QCD axion
  - $\mu_{br}^4 = \Lambda_{hid}^2 h^2$ due to gauge symmetry
  - Coincidence problem

Graham, Kaplan, Rajendran 2015

- Higgs-independent barriers from closing Higgs loops

  ⇒ Relaxation works for Λ_{hid} around EW scale: $M < 10^7$ GeV

- Possible solution: multiple relaxions for double-scanning

Espinosa, Grojean, Panico, Pomarol, Pujols, Servant 2015

❖ Peccei-Quinn Relaxion

◆ PQ Relaxion

- Scheme to avoid the coincidence and strong CP problem
- **Relaxion** ϕ + **QCD axion** a
- ϕ and a play their respective roles via QCD-induced potential

  - ϕ selects the Higgs mass

  - a selects the strong CP phase

▪ Barrier potential

$$V_{br}(a,\phi,h) = -\mu_{br}^4(h)\cos\left(\frac{a}{f_a}+\frac{\phi}{f}\right) + \Delta V_{br}(a,\phi)$$

QCD: $\mu_{br}^4 = y_u \Lambda_{QCD}^3 h = (0.1GeV)^4 \frac{h}{v}$ with $v = 246$ GeV

- Hidden QCD-induced potential

$$\Delta V_{br} = \mu_a^4(\sigma)\cos\left(\frac{a}{f_a}\right) + \mu_\phi^4(\sigma)\cos\left(\frac{\phi}{f}\right)$$

  - Dependence on the inflaton σ s.t.

$$\mu_a^4(\sigma_0) \ll \mu_{br}^4(h=v) \ll \mu_a^4(\sigma_{inf})$$

$$\mu_\phi^4(\sigma_{inf}) \ll \mu_{br}^4(h=v) \ll \mu_\phi^4(\sigma_0)$$

  - Main source of stabilization

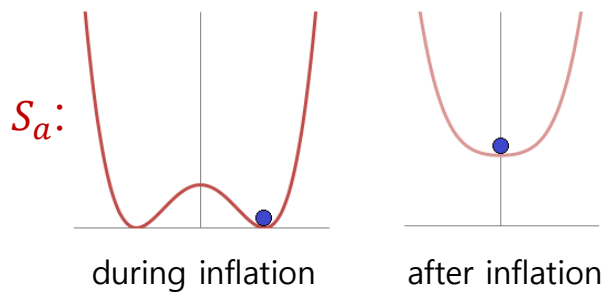
	During inflation $\sigma \simeq \sigma_{inf} \gg M$	After inflation $\sigma = \sigma_0 \ll M$
ϕ	QCD: μ_{br}^4	hidden QCD: μ_ϕ^4
a	hidden QCD: μ_a^4	QCD: μ_{br}^4

- How to obtain $\Delta V_{br}(a,\phi)$?
  - a and ϕ couple to hidden QCD anomalies via

$$\sum_{i=a,\phi} y_i S_i Q_i Q_i^c$$

  - Inflaton-dependent masses for S_a and S_ϕ

$$V = \left(M^2 - \kappa_a \sigma^2\right)|S_a|^2 + |S_a|^4 + \left(-M^2 + \kappa_\phi \sigma^2\right)\left|S_\phi\right|^2 + \left|S_\phi\right|^4$$



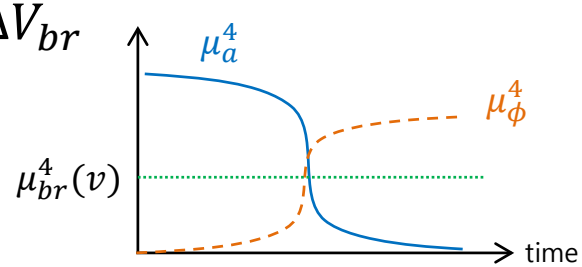
S_ϕ: in the opposite way

- How to obtain $\Delta V_{br}(a,\phi)$?
  - Hidden quarks obtain masses from $\langle S_i \rangle$
    - $m_{Q_a}(\sigma_{inf}) \geq y_a M,\ m_{Q_a}(\sigma_0) \approx 0 \quad \Rightarrow \quad \Lambda_a(\sigma_{inf}) > \Lambda_a(\sigma_0)$
    - $m_{Q_\phi}(\sigma_{inf}) \approx 0,\ m_{Q_\phi}(\sigma_0) \geq y_\phi M \quad \Rightarrow \quad \Lambda_\phi(\sigma_{inf}) < \Lambda_\phi(\sigma_0)$
  - Inflaton-dependent back-reaction potential

$$\mu_i^4(\sigma) = \min\left[m_{Q_i}(\sigma), \Lambda_i\right] \times \Lambda_i^3$$

hidden confining scale

$\Rightarrow$ Required properties to ΔV_{br}



- Alternative ways to get $\Delta V_{br}(a, \phi)$
  - Required dependence on a

    - Explicit PQ breaking by higher dim operators

$$\mu_a^4 = \epsilon f_a^3 \sigma \text{ with } \epsilon \ll 1$$

    for a scenario in which σ drops to zero after inflation.

  - Required dependence on ϕ

    - Inflaton-dependent confining scale

$$\Lambda_\phi(\sigma_{inf}) \ll H_i,\ \Lambda_{QCD} < \Lambda_\phi(\sigma_0)$$

◆ Relaxation of the EW scale

<u>During inflation</u>

$$V_{br} = -y_u \Lambda_{QCD}^3 h \cos\left(\frac{a}{f_a} + \frac{\phi}{f}\right) + \Delta V_{br}(a)$$

- h-dependent barriers for ϕ from QCD → Relaxation
- Potential for a from hidden QCD
- Requirement

  - a at the minimum after N_a e-folds:

$$N_a \sim \frac{H_i \Delta a}{\dot{a}} \ll N_e \Rightarrow \sqrt{\frac{f_a}{F}} M < \mu_a(\sigma_{inf})$$

  for correct relaxation process

◆ Relaxation of the EW scale

<u>After inflation</u>

$$V_{br} = -y_u \Lambda_{QCD}^3 h \cos\left(\frac{a}{f_a} + \frac{\phi}{f}\right) + \Delta V_{br}(\phi)$$

- h-independent barriers for ϕ from hidden QCD
- Potential for a from QCD → PQ mechanism
- Requirement

① small shift of ϕ after inflation

$$\frac{F}{f} > \left(\frac{M}{v}\right)^2$$

◆ Relaxation of the EW scale

- Requirement

② Reheating temperature:

$$T_{reh} < \Lambda_\phi(\sigma_0)$$

- Constraint from a tadpole for S_ϕ by hidden QCD

$$\Lambda_\phi(\sigma_{inf}) < 1TeV \left(\frac{y_\phi}{10^{-2}}\right)^{-\frac{2}{3}} \left(\frac{\mu_{br}(v)}{0.1GeV}\right)^{\frac{2}{3}} \left(\frac{m_{Q_\phi}(\sigma_{inf})}{10^9 GeV}\right)^{\frac{1}{3}}$$

note, $\Lambda_\phi(\sigma_{inf}) < \Lambda_\phi(\sigma_0)$

- T_{reh} above EW scale is compatible with relaxation

→ viable cosmology: baryogenesis, …

- Relaxation conditions
  - Cutoff scale of the Higgs mass:

$$M < 3 \times 10^7 \text{GeV} \left(\frac{f}{10^6 GeV}\right)^{-\frac{1}{6}} \left(\frac{\mu_{br}(v)}{0.1 GeV}\right)^{\frac{2}{3}}$$

  - Inflation:

$$H_i < 0.5 \text{MeV} \left(\frac{f}{10^6 GeV}\right)^{-\frac{1}{3}} \left(\frac{\mu_{br}(v)}{0.1 GeV}\right)^{\frac{4}{3}}$$

$$N_e > \left(\frac{F}{M_{Pl}}\right)^2$$

  - Field excursion:

$$\frac{F}{f} \sim 6 \times 10^{21} \left(\frac{\mu_{br}(v)}{0.1 GeV}\right)^{-4} \left(\frac{M}{10^5 GeV}\right)^4$$

- Relaxion
  - Stabilized by hidden QCD after inflation

    ⇒ Different properties from other models

    c.f. Choi, Im 2016, Flacke et al 2017
  - Heavy mass

$$m_\phi = 10^2\text{GeV}\left(\frac{\mu_\phi(\sigma_0)}{10^4 GeV}\right)^2\left(\frac{f}{10^6 GeV}\right)^{-1}$$

    - decays into SM gauge bosons and hidden sector particles
  - Negligible mixing with the Higgs boson

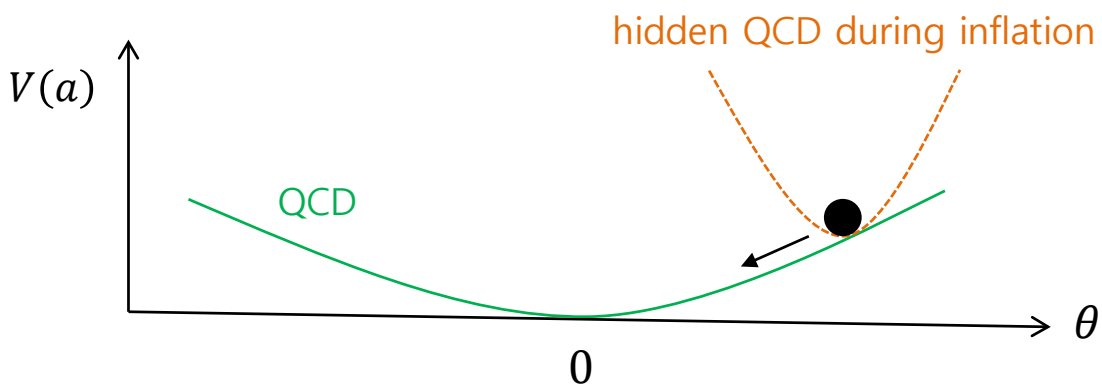
    - mixing due to QCD-induced potential $\propto h\cos\left(\frac{a}{f_a}+\frac{\phi}{f}\right)$

    - PQ mechanism: a fixed by QCD at $\frac{a}{f_a}+\frac{\phi}{f}\simeq 0$

- QCD axion
  - Contributes to dark matter
  - QCD axion from misalignment:

$$\Omega_a h^2 \sim 0.12 \left(\frac{f_a}{10^{12} GeV}\right)^{\frac{6}{5}} \theta_{ini}^2$$

- Initial angle fixed by ΔV_{br}



❖ Relaxation with Stronger SM Couplings

- Relaxation of the EW scale
  - Low scale inflation
  - Huge number of e-folds: fine-tuning of initial conditions
- Way to alleviate the constraints on inflation?
  - Stronger SM couplings during inflation:

$$\mu_{br}^4(\sigma_{inf}) \gg \mu_{br}^4(\sigma_0) = (0.1GeV)^4$$

  - Inflaton-dependent couplings:

$$\alpha_s(\sigma_{inf}, M) = \alpha_s(\sigma_0, M) + \Delta\alpha_s$$

$$y_i(\sigma_{inf}, M) = y_i(\sigma_0, M) + \Delta \mathrm{y}$$

- Constraints

1) Higgs-dependent barriers for ϕ during inflation

   - quarks lighter than the QCD scale

$$\Delta y \leq 2 \times 10^{-3} \frac{\Lambda_{QCD}(\sigma_{inf})}{\Lambda_{QCD}}$$

2) Higgs mass selected by relaxation: affected by $\Delta\alpha_s$ and Δy

$$m_h^2 = \left(6\lambda_h - 6\sum y_i^2 + \frac{3}{4}g_Y^2 + \frac{9}{4}g_2^2 + \cdots\right)\frac{M^2}{16\pi^2}$$

$$\Rightarrow \left|\Delta m_h^2\right| \simeq \left|\frac{\Delta y}{y} - 0.1\Delta\alpha_s\right| \times \frac{3y_t^2 M^2}{4\pi^2} < v^2$$

- Constraints

From 1) and 2)

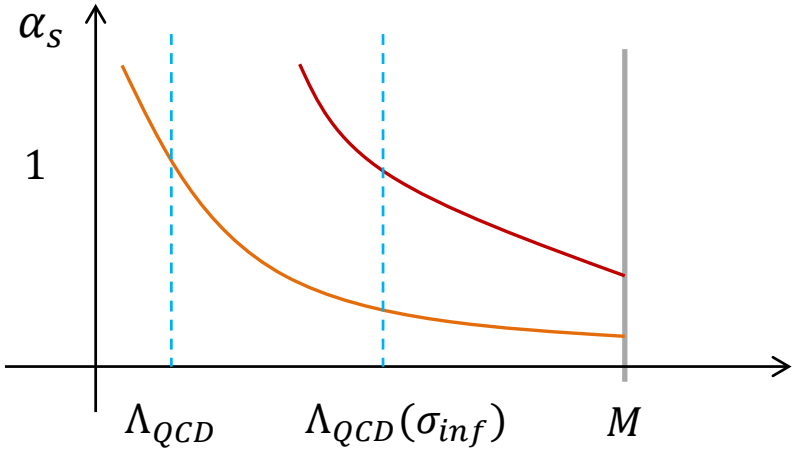
- Relaxation works for

$$M \leq \frac{10\ TeV}{\sqrt{\frac{|\Delta y|}{0.01} + \frac{|\Delta \alpha_s|}{0.1}}}$$

- Constraints

From 1) and 2)

- Stronger QCD: $\Lambda_{QCD}(\sigma_{inf}) < 100 \times \Lambda_{QCD}$ for $\Delta\alpha_s \sim 0.1$



$$\Rightarrow \mu_{br}(\sigma_{inf}, v) \simeq 10GeV \left(\frac{y_u+\Delta y}{0.01}\right)^{\frac{1}{4}} \left(\frac{\Lambda_{QCD}(\sigma_{inf})}{20GeV}\right)^{\frac{3}{4}}$$

note, $\mu_{br}(\sigma_0, v) \simeq 0.1$ GeV

- Relaxation with stronger SM during inflation
  - Relaxation conditions:

$$H_i < 0.2GeV \left(\frac{f}{10^6 GeV}\right)^{-\frac{1}{3}} \left(\frac{\mu_{br}(\sigma_{inf}, v)}{10GeV}\right)^{\frac{4}{3}}$$

$$\frac{F}{f} \sim 10^{10} \left(\frac{\mu_{br}(\sigma_{inf}, v)}{10GeV}\right)^{-4} \left(\frac{M}{10^4 GeV}\right)^4$$

$$N_e > 20 \left(\frac{F/f}{10^{13}}\right)^2 \left(\frac{f}{10^6 GeV}\right)^2$$

for $M \leq 10$ TeV

❖ Summary and Discussion

❖ Relaxation of the Higgs mass

- New approach to the EW hierarchy problem without new physics around TeV
- Viable parameter region determined mainly by the barrier potential
- EW scale $\ll$ cutoff scale of the Higgs mass $\ll M_{Pl}$

  $\rightarrow$ What new physics?

❖ Peccei-Quinn Relaxion

- Both relaxation and PQ mechanism via QCD

  - No strong CP and coincidence problem

  - Cutoff scale $\leq 10^7$ GeV

  - Reheating temperature above EW scale

  - Relaxion with heavy mass and negligible mixing with Higgs

  - QCD axion as dark matter

- Relaxing the constraints on inflation by stronger SM

  - Cutoff scale ≤ 10 TeV

Thank you!