Nayara Fonseca

DESY

Based on joint work with:

- Lima, Machado, Matheus (Phys. Rev. D 94, 015010 (2016);
- Harling, Lima, Machado, Servant (working in progress).

Blois, May 31st, 2017

Outline

1. The Relaxion Idea

2. How to generate large-scale hierarchies?

- **Using *N*-site models :** NF, Lima, Machado, Matheus; Phys.Rev. D94 (2016) 015010
- **From Warped Space:** NF, Harling, Lima, Machado, Servant; working in progress.

3. Concluding Remarks

The Relaxion Idea

Graham, Kaplan, Rajendran; Phys. Rev. Lett. 115, 221801 (2015)

Before Relaxion:
Two different "solutions" to the SM hierarchy problem

1. **New dynamics at the weak scale:**

- **Natural solutions;**

- **We need BSM at ~ TeV scale;**

Eg.: SUSY & Composite Higgs Models.

2. **Anthropics** !?

3. Another option: The Relaxation Mechanism

Graham, Kaplan, Rajendran; Phys. Rev. Lett. 115, 221801 (2015)

Warming up…

$$V(h,\phi) = \frac{1}{2} m_H^2(\phi) h^2 + \cdots = \frac{1}{2}(-\Lambda^2 + g\Lambda\phi) h^2 + \cdots$$

The Relaxion Idea

3. Another option: The Relaxation Mechanism

Graham, Kaplan, Rajendran; Phys. Rev. Lett. 115, 221801 (2015)

Warming up…

high scale

the new field

$$V(h,\phi) = \frac{1}{2} m_H^2(\phi) h^2 + \cdots = \frac{1}{2}\left(\boxed{-\Lambda^2} + \boxed{g}\Lambda\boxed{\phi}\right) h^2 + \cdots$$

small coupling (spurion)

- ϕ scans $m_H^2(\phi)$ during the cosmological evolution;

- Arrange a mechanism so that ϕ stops where we want, precisely at the EW scale:

$$m_H^2(\phi_c) = -\Lambda^2 + g\Lambda\phi_c \ll \Lambda^2$$

The Relaxion Idea

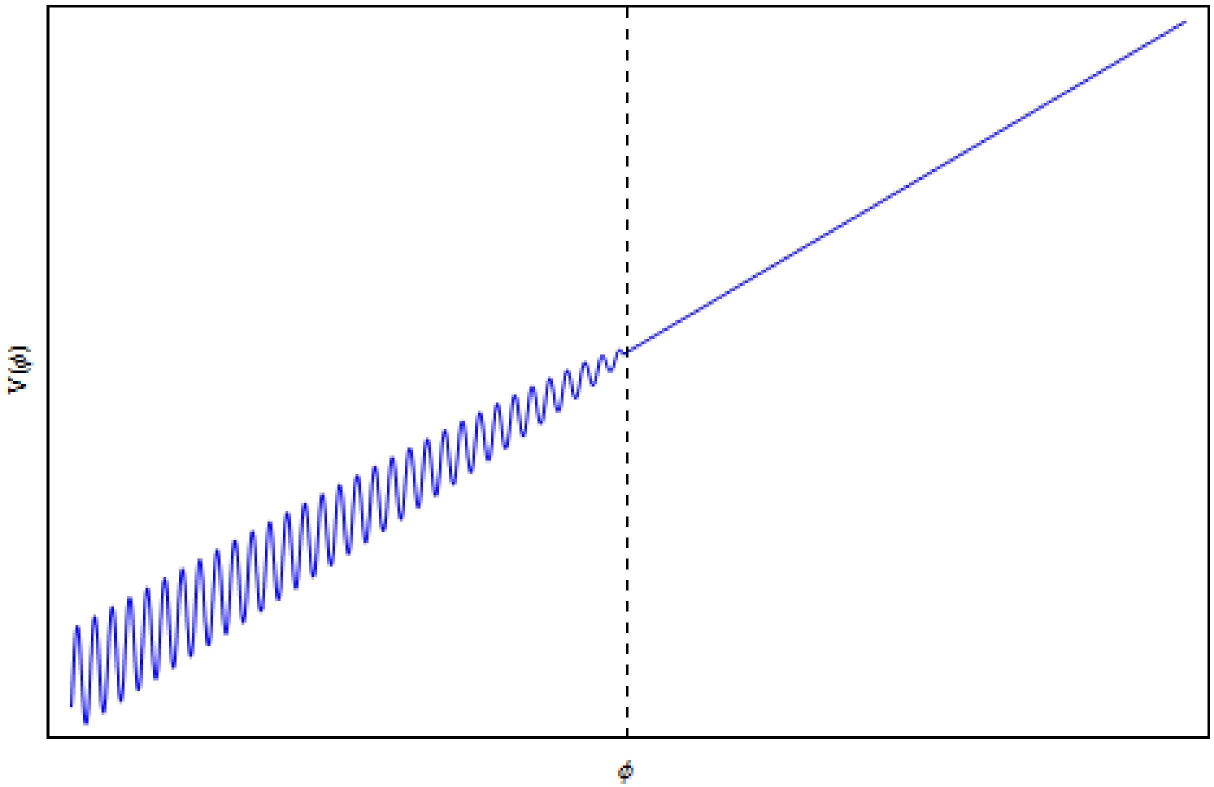
Closer Look

$m_H^2(\phi)$

"Slope term"

"Stopping term"

$$V(h,\phi) = \frac{1}{2}\Lambda^2\left(\frac{g\phi}{\Lambda}-1\right)h^2 + g\Lambda^3\phi + \epsilon\Lambda_c^4\left(\frac{\langle h\rangle}{\Lambda_c}\right)^n\cos\left(\frac{\phi}{f}\right) + \cdots$$



The Relaxion Idea

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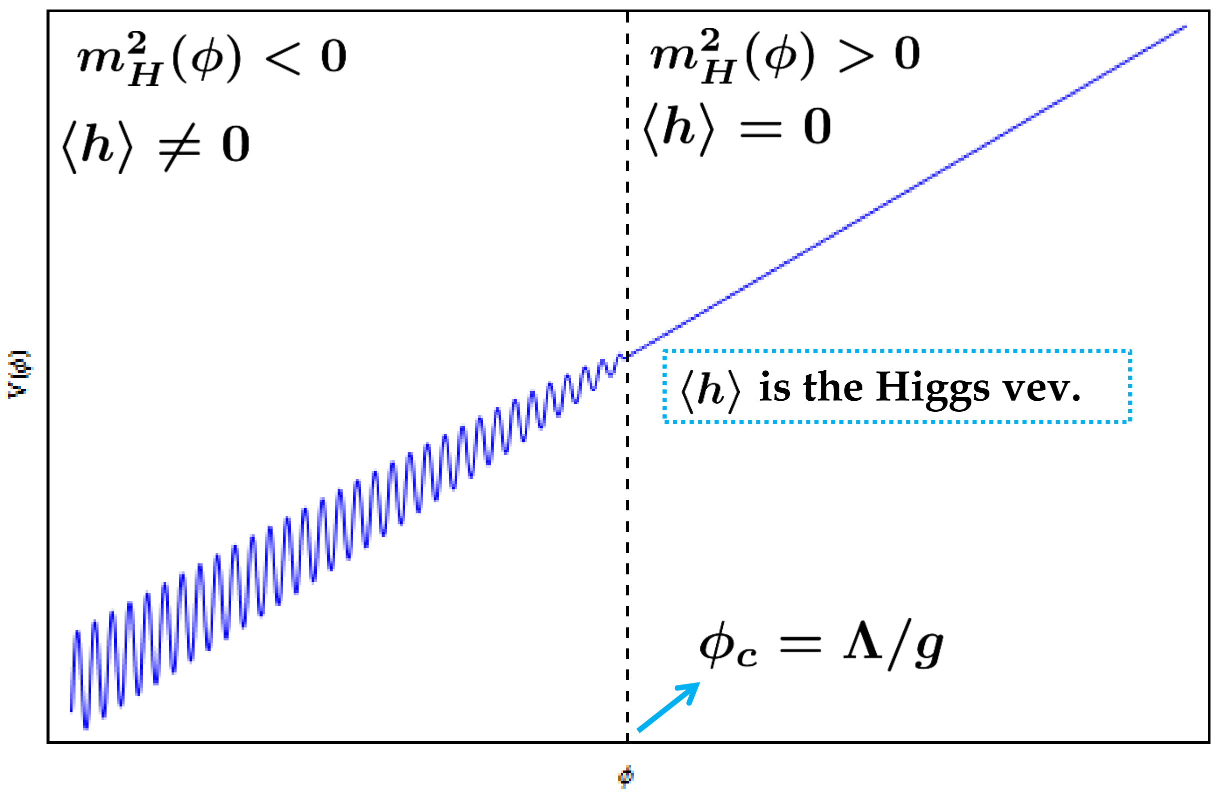

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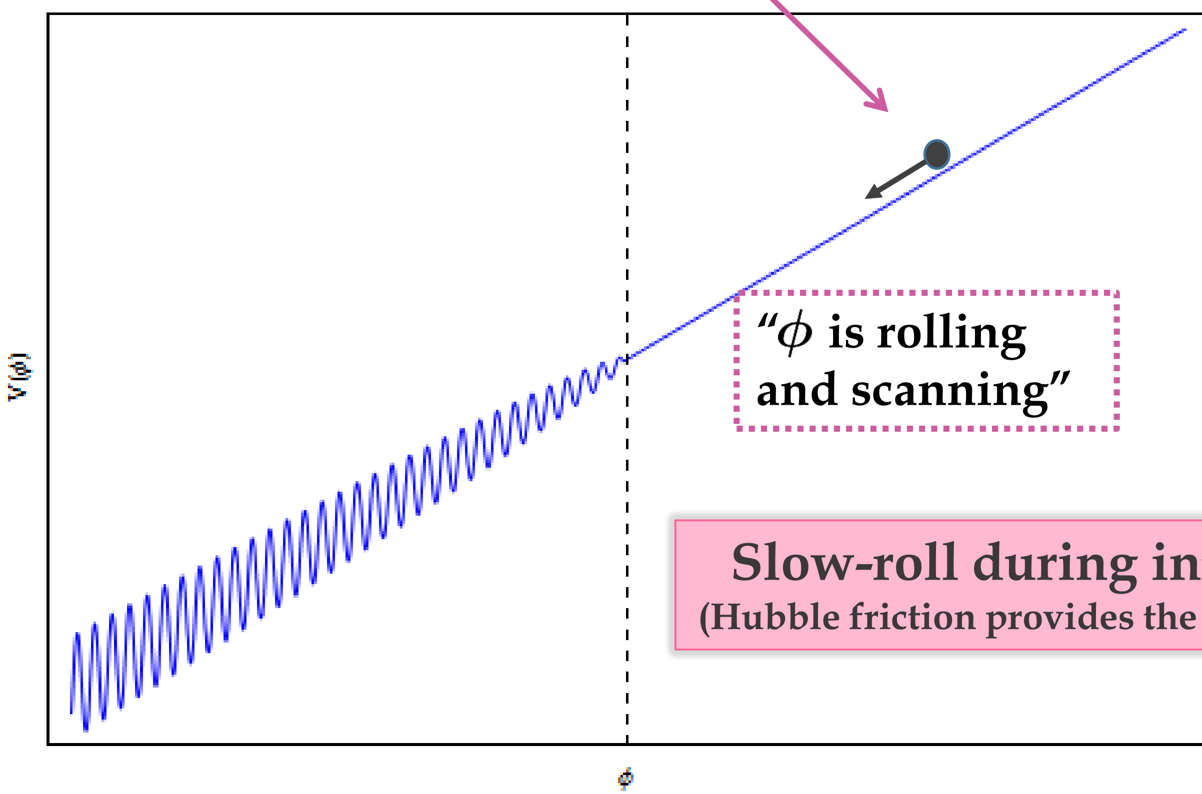


"ϕ is rolling and scanning"

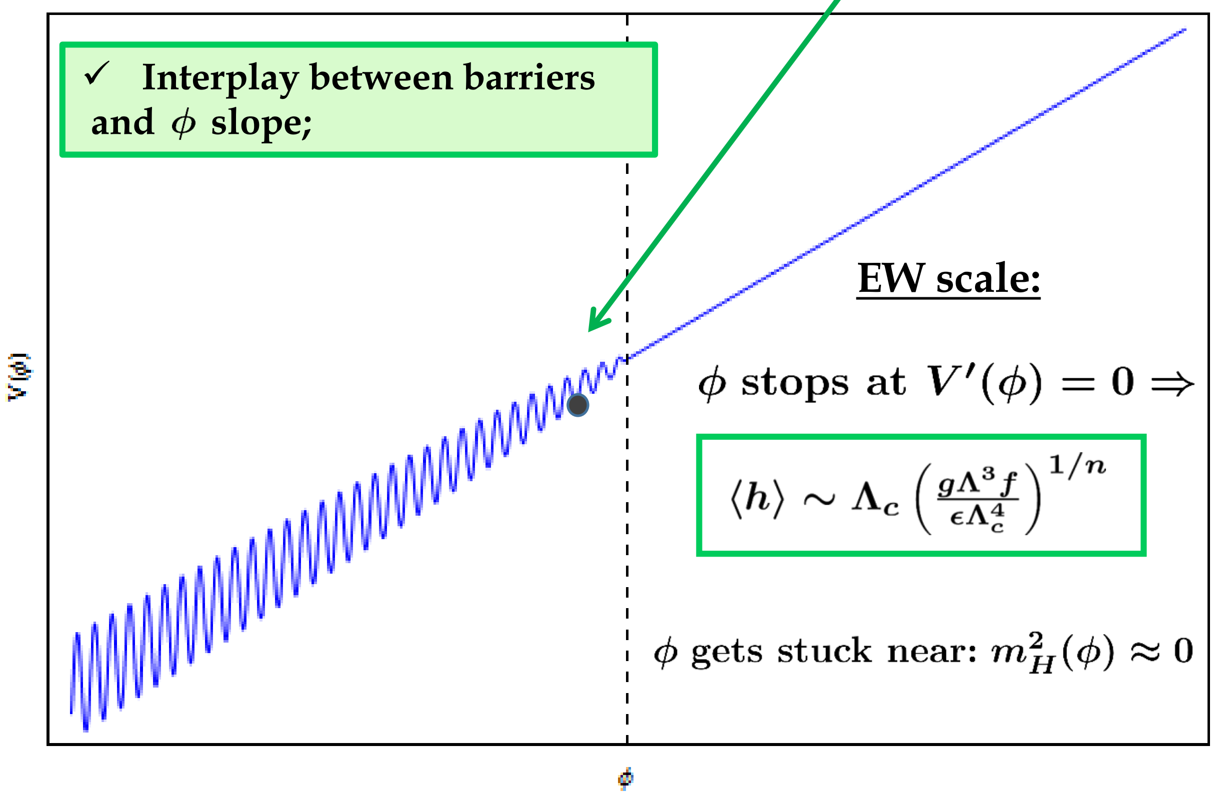
Slow-roll during inflation
(Hubble friction provides the dissipation)

The Relaxion Idea

Closer Look

$m_H^2(\phi)$ "Slope term" "Stopping term"

$$V(h,\phi) = \frac{1}{2}\Lambda^2\left(\frac{g\phi}{\Lambda}-1\right)h^2 + g\Lambda^3\phi + \epsilon\Lambda_c^4\left(\frac{\langle h\rangle}{\Lambda_c}\right)^n\cos\left(\frac{\phi}{f}\right)+\cdots$$



The Relaxion Idea

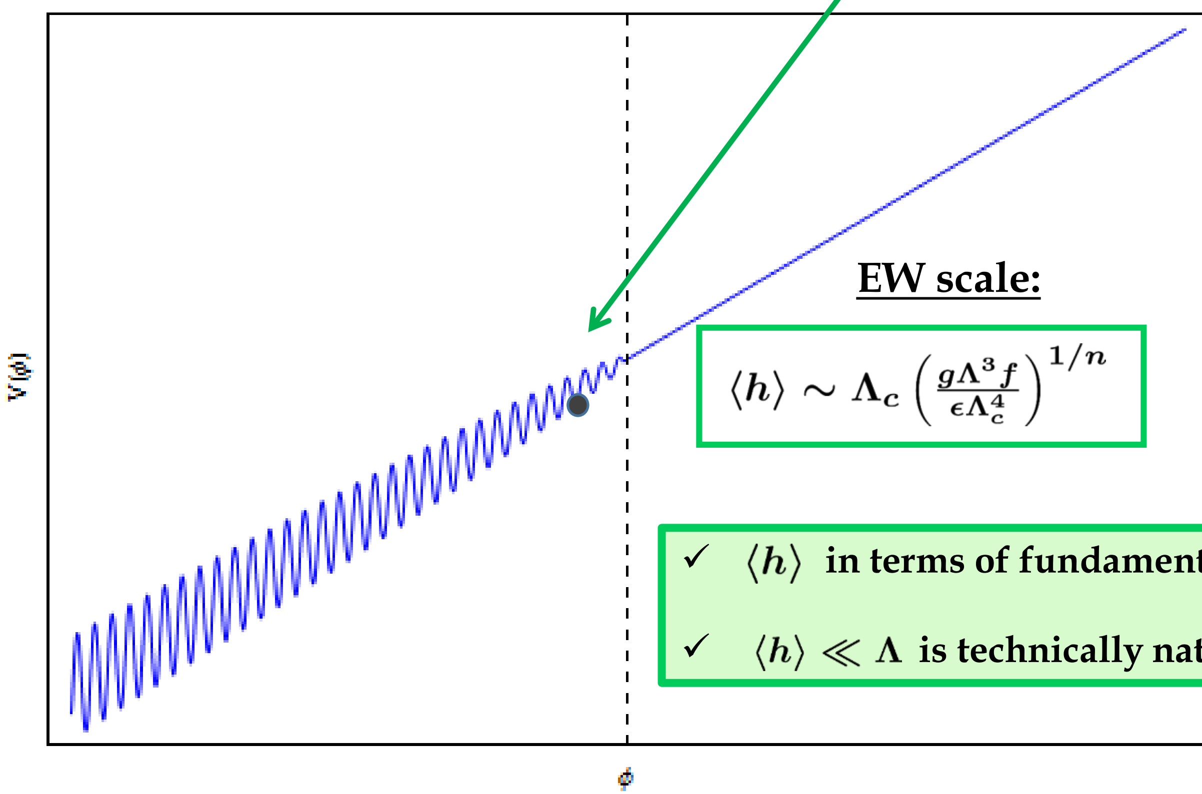
Closer Look

$m_H^2(\phi)$

"Slope term"

"Stopping term"

$$V(h,\phi) = \frac{1}{2}\Lambda^2\left(\frac{g\phi}{\Lambda}-1\right)h^2 + g\Lambda^3\phi + \epsilon\Lambda_c^4\left(\frac{\langle h\rangle}{\Lambda_c}\right)^n \cos\left(\frac{\phi}{f}\right) + \cdots$$



EW scale:

$$\langle h\rangle \sim \Lambda_c\left(\frac{g\Lambda^3 f}{\epsilon\Lambda_c^4}\right)^{1/n}$$

$\Lambda \sim 10^8$ GeV

$\Lambda_c \sim \mathcal{O}(1)$ TeV

- ✓ $\langle h\rangle$ in terms of fundamental parameters;
- ✓ $\langle h\rangle \ll \Lambda$ is technically natural.

The Relaxion Idea

"Typical" Predictions

- Natural model with $\Lambda \approx 10^8$ GeV;

- Extremely light axion-like states.

- Interactions with the SM through the mixing with the Higgs, suppressed by $\frac{1}{f}$ and/or g, ϵ.

Some concerns about the original idea

Let's check the symmetries

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\Lambda^2 \left(\frac{g\phi}{\Lambda} - 1\right) h^2 - g\Lambda^3\phi - \epsilon\Lambda_c^4 \left(\frac{\langle h \rangle}{\Lambda_c}\right)^n \cos\left(\frac{\phi}{f}\right)$$

UV completion? **<u>Spontaneous breaking of a Global Symmetry!</u>**

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UV completion? <u>Spontaneous breaking of a Global Symmetry!</u>

- $g = 0, \epsilon = 0$ ⇨ continuous shift symmetry: $\phi \to \phi + c$
  Nambu-Goldstone boson
- $\epsilon \neq 0$ ⇨ breaks the continuous shift symmetry to: $\phi \to \phi + 2\pi n f$
  Pseudo Nambu-Goldstone boson
- $g \neq 0$ ⇨ breaks the discrete shift symmetry!

Some concerns about the original idea

Let's check the symmetries

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\Lambda^2 \left(\frac{g\phi}{\Lambda} - 1\right) h^2 - g\Lambda^3\phi - \epsilon\Lambda_c^4 \left(\frac{\langle h\rangle}{\Lambda_c}\right)^n \cos\left(\frac{\phi}{f}\right)$$

UV completion? <u>Spontaneous breaking of a Global Symmetry!</u>

- ϵ term: $V \supset \epsilon\Lambda_c^4 \cos\left(\frac{\phi}{f}\right)$ ⇨ Breaks the continuous shift symmetry to: $\phi \to \phi + 2\pi n f$
- g terms: $V \supset g\Lambda^3\phi + \frac{1}{2}g\Lambda\phi h^2$ ⇨ g is the spurion that breaks the discrete shift symmetry!

⇨ ϕ is a pNGB (compact field range/periodicity)

⇨ g cannot break a gauge symmetry (the discrete shift symmetry is a redundancy)

Gupta, Komargodski, Perez, Ubaldi; JHEP 1602 (2016) 166

Some concerns about the original idea

Let's check the symmetries

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\Lambda^2\left(\frac{g\phi}{\Lambda} - 1\right)h^2 - g\Lambda^3\phi - \epsilon\Lambda_c^4\left(\frac{\langle h\rangle}{\Lambda_c}\right)^n \cos\left(\frac{\phi}{f}\right)$$

UV completion? <u>**Spontaneous breaking of a Global Symmetry!**</u>

- ϵ **term:** $V \supset \epsilon\Lambda_c^4 \cos\left(\frac{\phi}{f}\right)$ $\Rightarrow$ **Breaks the continuous shift symmetry to:** $\phi \to \phi + 2\pi n f$
- g **terms:** $V \supset g\Lambda^3\phi + \frac{1}{2}g\Lambda\phi h^2$ $\Rightarrow$ g **is the spurion that breaks the discrete shift symmetry!**

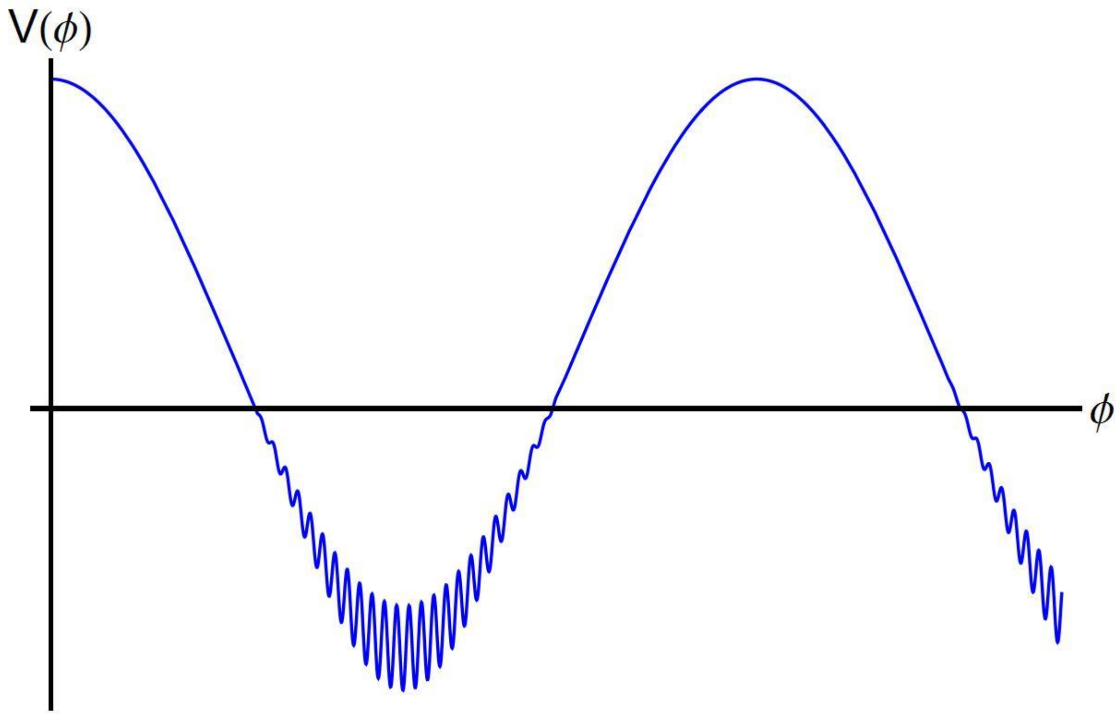
The ϕ operators must be periodic!

Some concerns about the original idea

The ϕ operators must be periodic!

Effectively, it is enough to have a hierarchy of decay constants: $F = nf \gg f$

$$V \sim A\cos\left(\frac{\phi}{F}\right) + B(h)\cos\left(\frac{\phi}{f}\right)$$



Eg.: D. E. Kaplan, R. Rattazzi; Phys.Rev. D93 (2016) no.8, 085007
K. Choi, S. H. Im; JHEP 1601 (2016) 149

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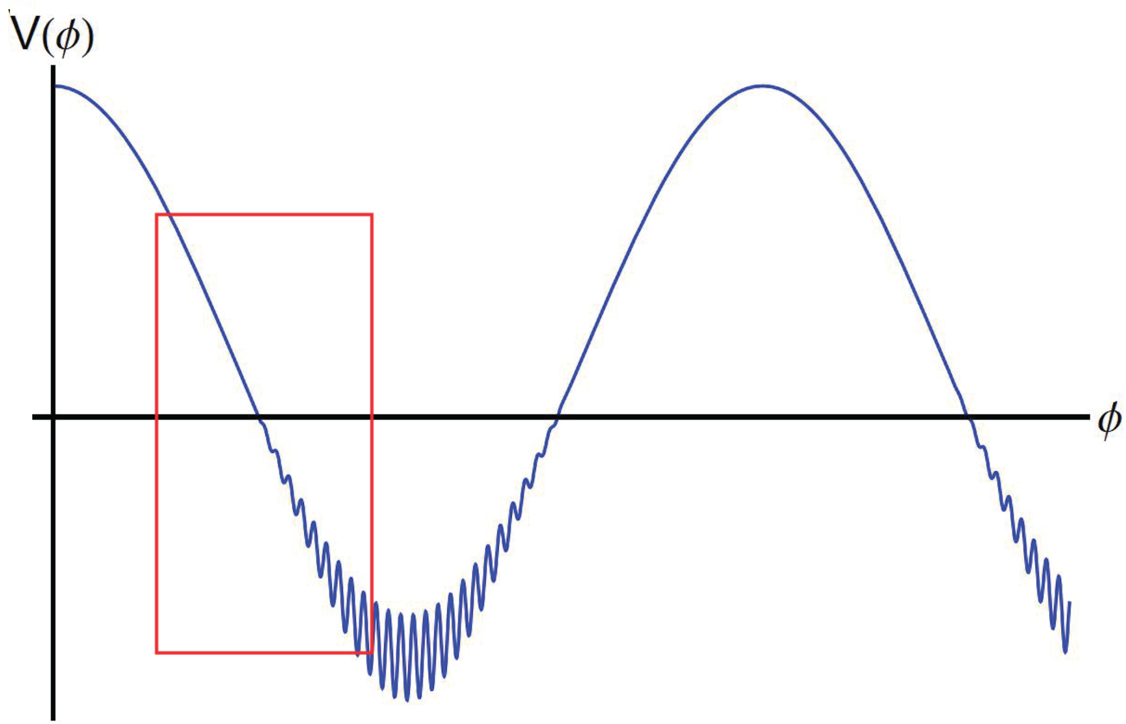

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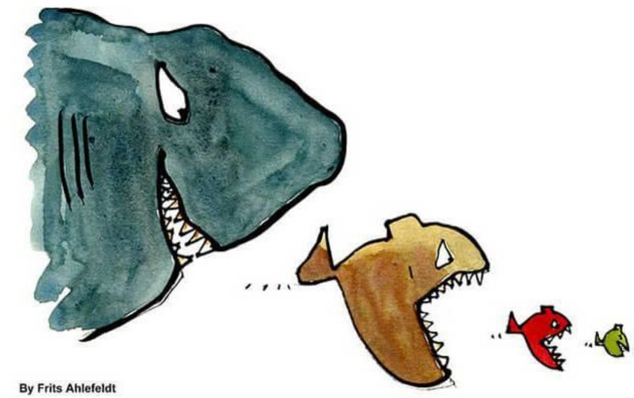
Outline



1. The Relaxion Idea

2. How to generate large-scale hierarchies?

- **Using *N*-site models :** NF, Lima, Machado, Matheus; Phys.Rev. D94 (2016) 015010.
- **From Warped Space:** NF, Harling, Lima, Machado, Servant; working in progress.

3. Concluding Remarks

Realizing the Relaxion with *N*-site Models (‘*N*-Relaxion’)

NF, Lima, Machado, Matheus; Phys.Rev. D94 (2016) 015010

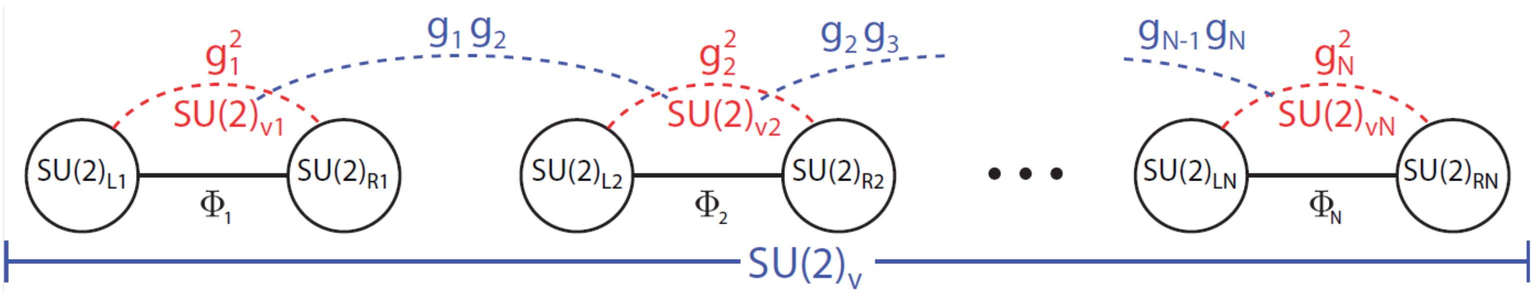
Main goals

- **Obtain a realization from an *N*-site model (find a model close to a deconstructed extra-dimension);**
- **pNGB as the relaxion;**
- **Generate an effective scale F much larger than f;**
- **Generalize to non-abelian symmetries.**

N-Relaxion

NF, Lima, Machado, Matheus; Phys.Rev. D94 (2016) 015010

- pNGB as the relaxion;
- Oscillations with hierarchical periods.



$$\Phi_j \to L_j \Phi_j R_j^\dagger$$

- **In the low energy limit, these fields are non-linearly realized:**

$\Phi_j = \frac{f}{2} e^{i\vec{\pi}_j \cdot \vec{\sigma}/f}$, $\vec{\pi}_j$ are the Nambu-Goldstone bosons.

$$\vec{\pi}^T \cdot M_\pi^2 \cdot \vec{\pi} \equiv \sum_{j=1}^{N-1} f^2 (g_j \vec{\pi}_j - g_{j+1} \vec{\pi}_{j+1})^2$$

$$\vec{\pi}^T \equiv \{\vec{\pi}_1, \cdots, \vec{\pi}_N\}$$

N-Relaxion: Message

NF, Lima, Machado, Matheus; Phys.Rev. D94 (2016) 015010

The zero mode η_0 (the would-be relaxion), and its profile is

$$\vec{\eta}_0 = \sum_{j=1}^{N} \frac{q^{N-j}}{\sqrt{\sum_{k=1}^{N} q^{2(k-1)}}} \vec{\pi}_j$$

Exponentially localized in the last site

$g_j \to q^j, \; 0 < q < 1$

$f_j \equiv f q^{j-N} \mathcal{C}_N$

Identical to the one obtained for a pNGB in the deconstruction of AdS_5.

$\eta_0 \equiv \sqrt{\vec{\eta}_0 \cdot \vec{\eta}_0}$

$$\mathcal{L}_\eta = \sum_{j=1}^{N} \left[\frac{1}{2} \partial_\mu \vec{\eta}_0 \cdot \partial^\mu \vec{\eta}_0 + f^4 (2 - \delta_{j,1} - \delta_{j,N}) q^{2j} \cos \frac{\eta_0}{f_j} \right] + \sum_{j=1}^{N-1} f^4 q^{2j+1} \sin \frac{\eta_0}{f_j} \sin \frac{\eta_0}{f_{j+1}}$$

Oscillating with different scales

$$f_j \equiv f q^{j-N} \mathcal{C}_N \quad \begin{cases} f_{\max} = f_1 \approx f/q^{N-1} \\ f_{\min} = f_N \approx f \end{cases}$$

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

Main goals

- Obtain a relaxion realization from a warped extra-dimension (AdS) model;

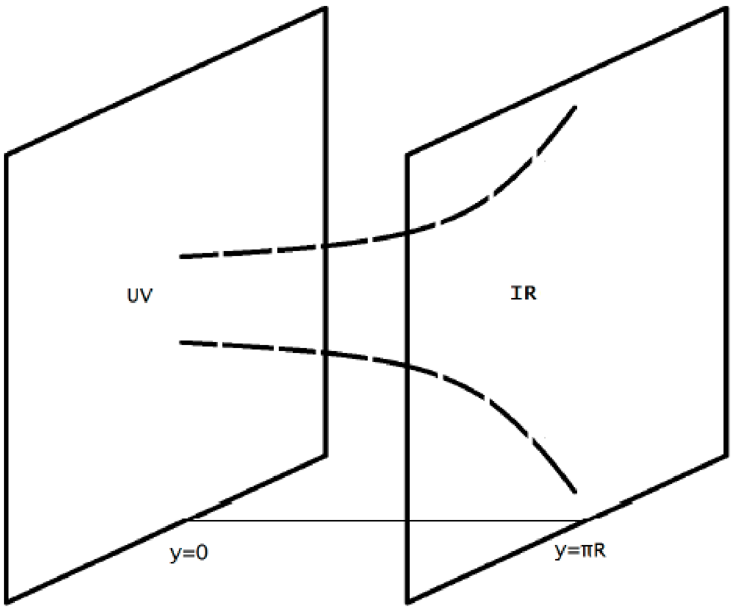
- Hierarchy from the geometry;

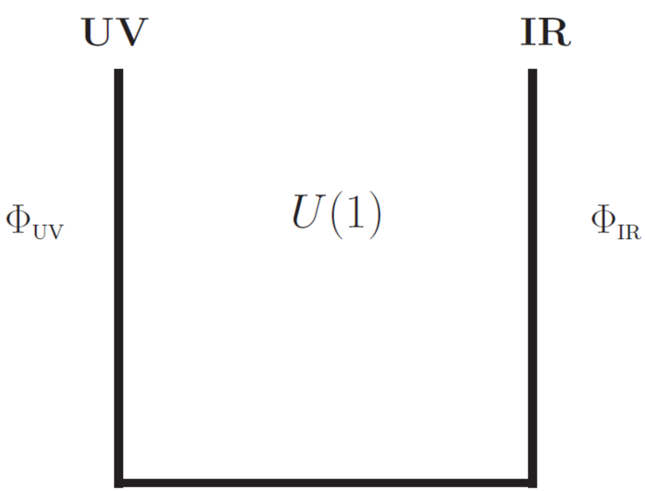
- pNGB as the relaxion;

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

U(1) **gauge symmetry in a slice of the** ***AdS_5*** **space that is spontaneously broken at the UV and IR branes by boundary scalar fields**





$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

$ds^2 = \frac{1}{(kz)^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$ conformal coordinates

$z = e^{ky}/k$

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

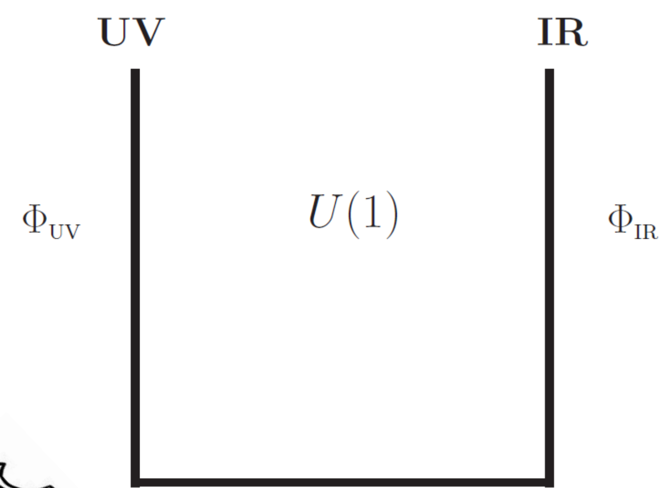
U(1) gauge symmetry in a slice of the AdS_5 space that is spontaneously broken at the UV and IR branes by boundary scalar fields

$$\Phi_i(x) = \frac{1}{\sqrt{2}}[v_i + h_i(x)]e^{i\pi_i(x)/v_i}$$

$$v_i \to \infty$$

$$A_\mu \,|_{UV,IR} = 0; \; \partial_5 \left(A_5/z\right) |_{UV,IR} = 0$$

Only a global subgroup of the original *U(1)* gauge symmetry survives.



See eg.:hep-ph/0510275

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

The boundary conditions are chosen such that there is a zero mode of A_5 in the spectrum

Scalar component of a 5D gauge boson

$$A_5(x,z) = \mathcal{N} z A_5^0(x)$$

$$\mathcal{N} \approx k\, e^{-kL}\sqrt{2kL}, \;\; kL \gg 1$$

- L is the size of the extra dimension;
- k is the curvature;
- g_5 is the 5D gauge coupling.

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

Anomalous couplings can be induced by brane-localized fermions appropriately charged under the residual global symmetry

$$\sim \int dz \, \frac{A_5}{k} \, \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}(x) G_{\rho\sigma}(x) \delta(z - z_i)$$

New strongly-interacting gauge sectors

Warped Relaxion

NF, Harling, Lima, Machado, Servant; working in progress.

After canonical normalization:

$$\frac{A_5^0(x)}{f_{\rm UV}} G\tilde{G}; \quad f_{\rm UV} \approx k\, e^{kL}$$

$$\frac{A_5^0(x)}{f_{\rm IR}} G'\tilde{G}'; \quad f_{\rm IR} \approx k\, e^{-kL}$$

$$\tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma,a}$$

The warp factor can explain the large hierarchy between the decay constants in the relaxion potential

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- **From Warped Space:** NF, Harling, Lima, Machado, Servant; working in progress.

3. Concluding Remarks

Concluding Remarks & Outlook

- UV sensibility to the Higgs mass: one of the leading motivation for new physics at the LHC;

- No compelling evidence of BSM at the LHC current data! 

Why is
this stable?

Concluding Remarks & Outlook

- UV sensibility to the Higgs mass: one of the leading motivation for new physics at the LHC;
- No compelling evidence of BSM at the LHC current data!

- Relaxation models: proof of concept. If self-consistent, then the hierarchy problem cannot be an argument for new physics at the TeV scale.

Chiricahua National Monument, Arizona

Concluding Remarks & Outlook

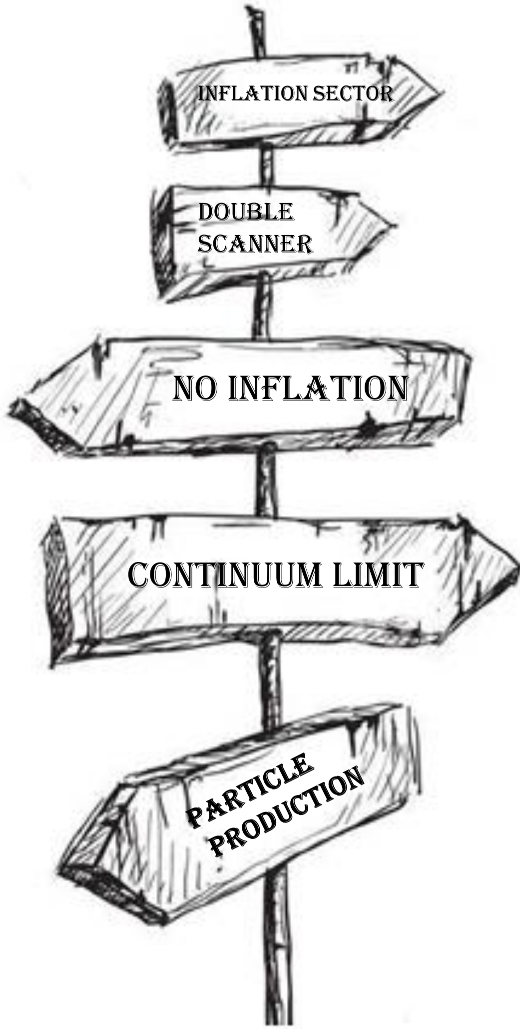
- *N*-Relaxion: *N*-site model generating a large-scale hierarchy; ✓

NF, Lima, Machado, Matheus, Phys. Rev. D 94, 015010 (2016).

  - pNGB as the relaxion;
  - Oscillations with hierarchical periods.

- Warped Relaxion: a continuum limit;

NF, Harling, Lima, Machado, Servant; working in progress.



Concluding Remarks & Outlook

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  - pNGB as the relaxion;
  - Oscillations with hierarchical periods.

- Warped Relaxion: a continuum limit;

  NF, Harling, Lima, Machado, Servant; working in progress.

- Many possible directions:

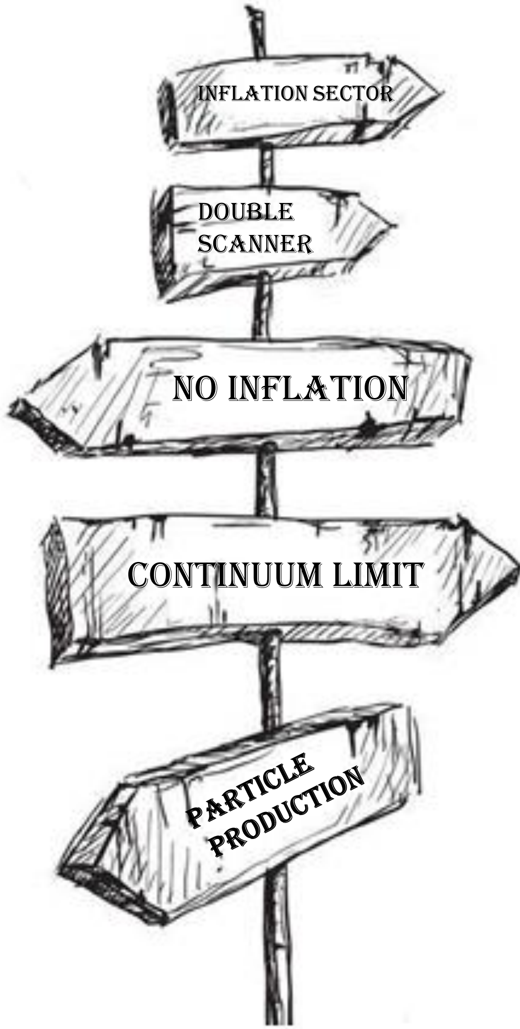
  - Alternatives to <u>inflation</u>?

    Eg.: Hook, Marques-Tavares JHEP 1612 (2016) 101

  - Can we apply this mechanism to generate other <u>large-scale hierarchies</u>?

    Abbott's attempt to solve the CC problem; Phys. Lett. B 150 , 427 (1985)

  - ...



Thanks!

QCD Relaxion

P. W. Graham, D. E. Kaplan, S. Rajendran; Phys. Rev. Lett. 115, 221801 (2015)

ϕ **is the QCD axion,** $\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{\phi}{f} G_{\mu\nu}\tilde{G}^{\mu\nu}$

Instanton effects generate: $V(\phi, H) \sim m_u(H)\langle q\bar{q}\rangle \cos(\phi/f)$

$\Lambda_c = \Lambda_{QCD}$ $\quad \epsilon = Y_u$ $\quad V_{\text{stop}} = \epsilon\Lambda_c^4 \left(\frac{\langle h\rangle}{\Lambda_c}\right)^n \cos\frac{\phi}{f}$ $\quad n = 1$

$$\Lambda < 10^7 \text{ GeV} \left(\frac{10^9 \text{ GeV}}{f}\right)^{1/6}$$

10^9 **GeV** $< f <$ 10^{12} **GeV**

Star cooling — DM abundance

QCD Relaxion

P. W. Graham, D. E. Kaplan, S. Rajendran; Phys. Rev. Lett. 115, 221801 (2015)

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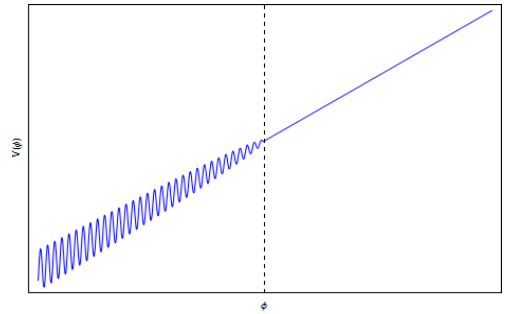
Instanton effects generate: $V(\phi, H) \sim m_u(H) \langle q\bar{q} \rangle \cos(\phi/f)$

- **But this model spoils the axion solution to the strong CP problem ($\theta_{\rm QCD} < 10^{-10}$);**

- **If the relaxion is the QCD axion, its vev determines the QCD theta parameter.**

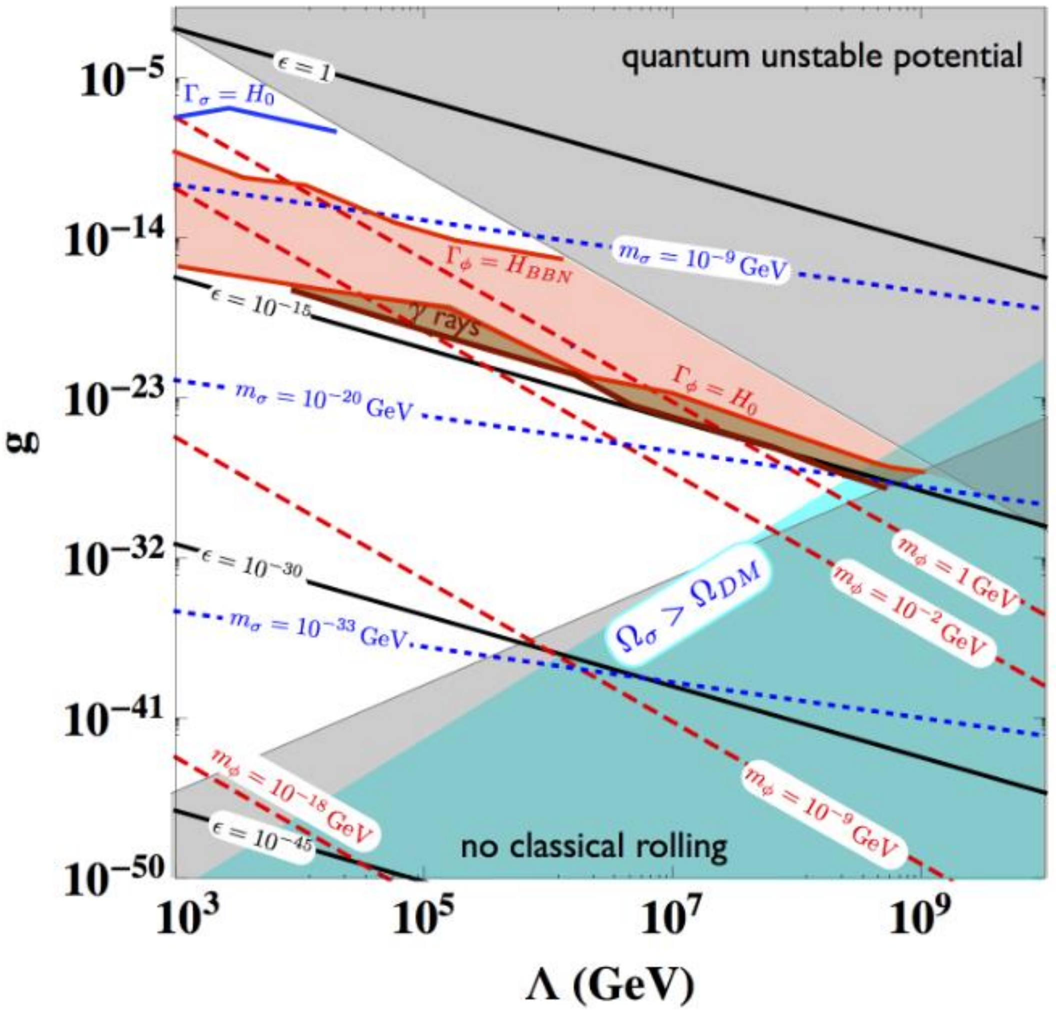
$$\Rightarrow \theta_{\rm QCD} = \langle \frac{\Delta\phi}{f} \rangle \sim \mathcal{O}(1) \quad !?$$

(Due to the tilt of the potential)



Ways to solve this: adding dynamics at the end of inflation (removes the slope of the potential). Cutoff scale at most ~ 30 TeV.

Typical predictions



J.R. Espinosa, C. Grojean, G. Panico, A. Pomarol O. Pujolàs, G. Servant; Phys.Rev.Lett. 115 (2015) no.25, 251803

N-Relaxion

NF, L. de Lima, C. S. Machado, R. D. Matheus; Phys.Rev. D94 (2016) no.1, 015010

- pNGB as the relaxion;
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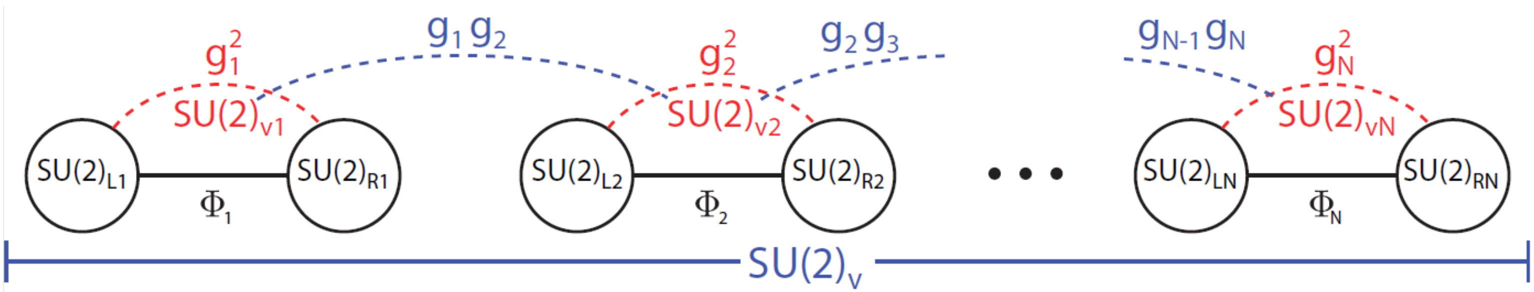


$$\Phi_j \to L_j \Phi_j R_j^\dagger$$

- Φ_j gets a vev $\langle \Phi_j \rangle = \frac{f}{2}$, spontaneously breaking $\boxed{SU(2)_{L_j} \times SU(2)_{R_j} \to SU(2)_{V_j};}$
- $g_j g_{j+1}$ terms break $\boxed{SU(2)_{V_j} \times SU(2)_{V_{j+1}} \to SU(2)_{V_{j,j+1}};}$

Small symmetry breaking terms

$$\mathcal{L}_\Phi = \sum_{j=1}^{N} \mathrm{Tr}\left[\partial_\mu \Phi_j^\dagger \partial^\mu \Phi_j + \frac{f^3}{2}(2 - \delta_{j,1} - \delta_{j,N}) g_j^2 \left(\Phi_j + \Phi_j^\dagger\right)\right] - \frac{f^2}{2} \sum_{j=1}^{N-1} g_j g_{j+1} \mathrm{Tr}\left[(\Phi_j - \Phi_j^\dagger)(\Phi_{j+1} - \Phi_{j+1}^\dagger)\right]$$

N-Relaxion

NF, L. de Lima, C. S. Machado, R. D. Matheus; Phys.Rev. D94 (2016) no.1, 015010

Mass Matrix

$$\mathcal{L}_\Phi = \sum_{j=1}^{N} \mathrm{Tr}\left[\partial_\mu \Phi_j^\dagger \partial^\mu \Phi_j + \frac{f^3}{2}(2-\delta_{j,1}-\delta_{j,N}) g_j^2 \left(\Phi_j + \Phi_j^\dagger\right)\right] - \frac{f^2}{2}\sum_{j=1}^{N-1} g_j g_{j+1} \mathrm{Tr}\left[(\Phi_j - \Phi_j^\dagger)(\Phi_{j+1} - \Phi_{j+1}^\dagger)\right]$$

Writing in terms of the $\vec{\pi}_j{}'s$, we obtain the mass matrix for the pNGBs:

$$\vec{\pi}^T \cdot M_\pi^2 \cdot \vec{\pi} \equiv \sum_{j=1}^{N-1} f^2 (g_j \vec{\pi}_j - g_{j+1}\vec{\pi}_{j+1})^2$$

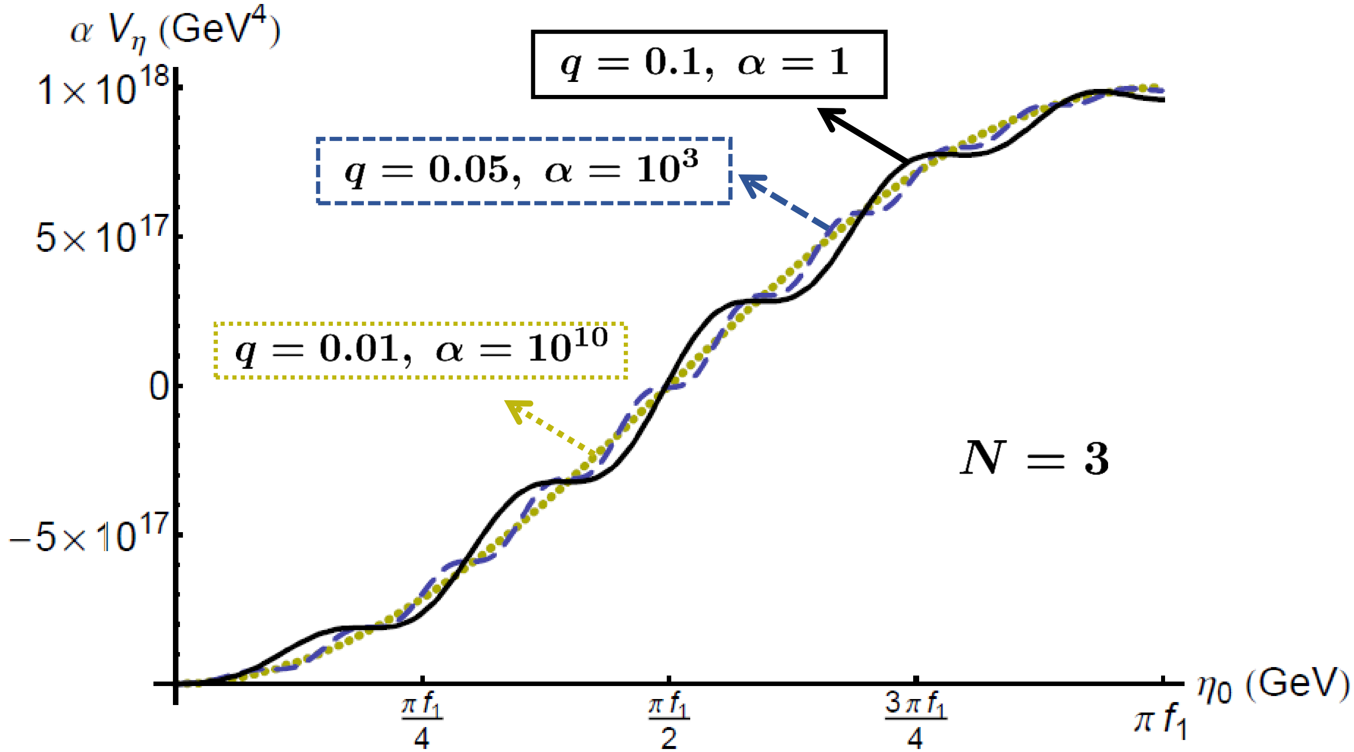
$$\vec{\pi}^T \equiv \{\vec{\pi}_1, \cdots, \vec{\pi}_N\}$$

$$M_\pi^2 = f^2 \begin{pmatrix} q^2 & -q^3 & 0 & \dots & 0 & 0 \\ -q^3 & 2q^4 & -q^5 & \dots & 0 & 0 \\ 0 & -q^5 & 2q^6 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 2q^{2(N-1)} & -q^{2N-1} \\ 0 & 0 & 0 & \dots & -q^{2N-1} & q^{2N} \end{pmatrix}$$

✓ The parametrization $g_j \to q^j,\ 0 < q < 1$ results in a mass matrix that is identical to the one obtained for a pNGB Wilson line in the deconstruction of AdS_5.

N-Relaxion

NF, L. de Lima, C. S. Machado, R. D. Matheus; Phys.Rev. D94 (2016) no.1, 015010



- Quite large values of q to exaggerate the features of the potential;
- the slope quickly gets smooth;
- before the inclusion of the Higgs the relaxion is able to roll down.