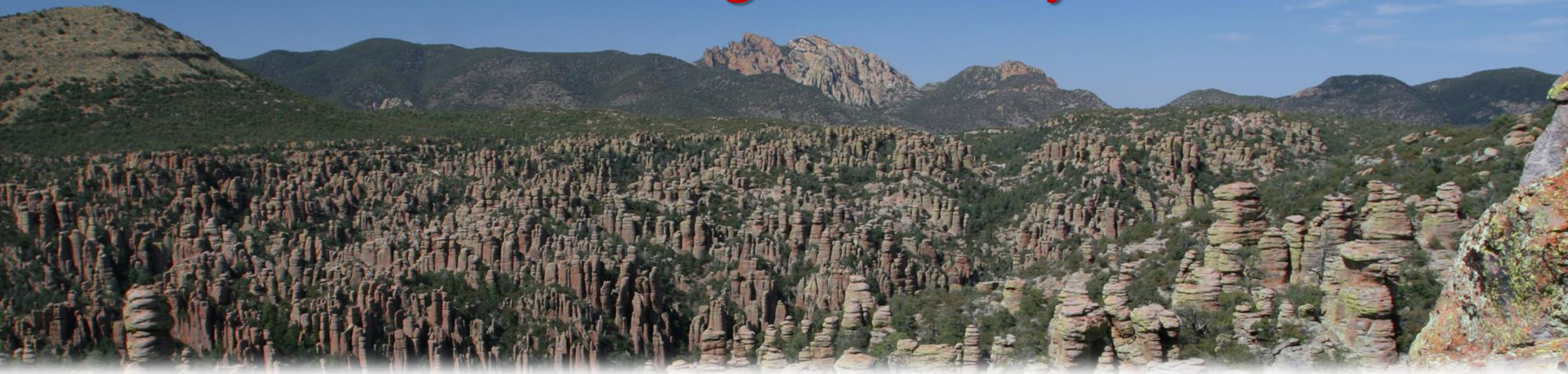
Theories with Large Hierarchy of Scales



Nayara Fonseca

DESY Fellow Meeting
November 29th, 2016

Retrospective

- **Composite Dark Matter**

  N. F., R. Z. Funchal, A. Lessa and L. Lopez-Honorez, JHEP 1506, 154 (2015).

- **Asymmetric Dark Matter**

  N. F., L. Necib and J. Thaler, JCAP 1602, no. 02, 052 (2016).

  N. Bernal, C. S. Fong and N. F, JCAP 1609 (2016) no.09, 005

- ***N*-site models & Dimensional Deconstruction framework**

I. Full-hierarchy quiver theories;
   G. Burdman, N.F. and L. de Lima, JHEP 1301, 094 (2013).

II. Their phenomenology at the LHC;
   G. Burdman, N.F. and G. Lichtenstein, Phys. Rev. D 88, 116006 (2013).

III. Realizing the relaxion with *N*-site models;
   N. F., L. de Lima, C. S. Machado and R. D. Matheus, Phys. Rev. D 94, 015010 (2016).

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15 min talk ⇨ Relaxion Idea

The Relaxion Idea

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;**

E.gs.: SUSY & Composite Higgs Models & Warped Scenarios.

2. **Anthropics** !?

3. Another option: The Relaxation Mechanism

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

Warming up…

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

3. Another option: The Relaxation Mechanism

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

Warming up…

high scale

the new field

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

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:

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

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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 initial value of ϕ is such that $m_H^2(\phi) > 0$;
- We can already see why large field excursions are crucial here: $\phi > \Lambda/g$.

The Relaxion Idea

Closer Look

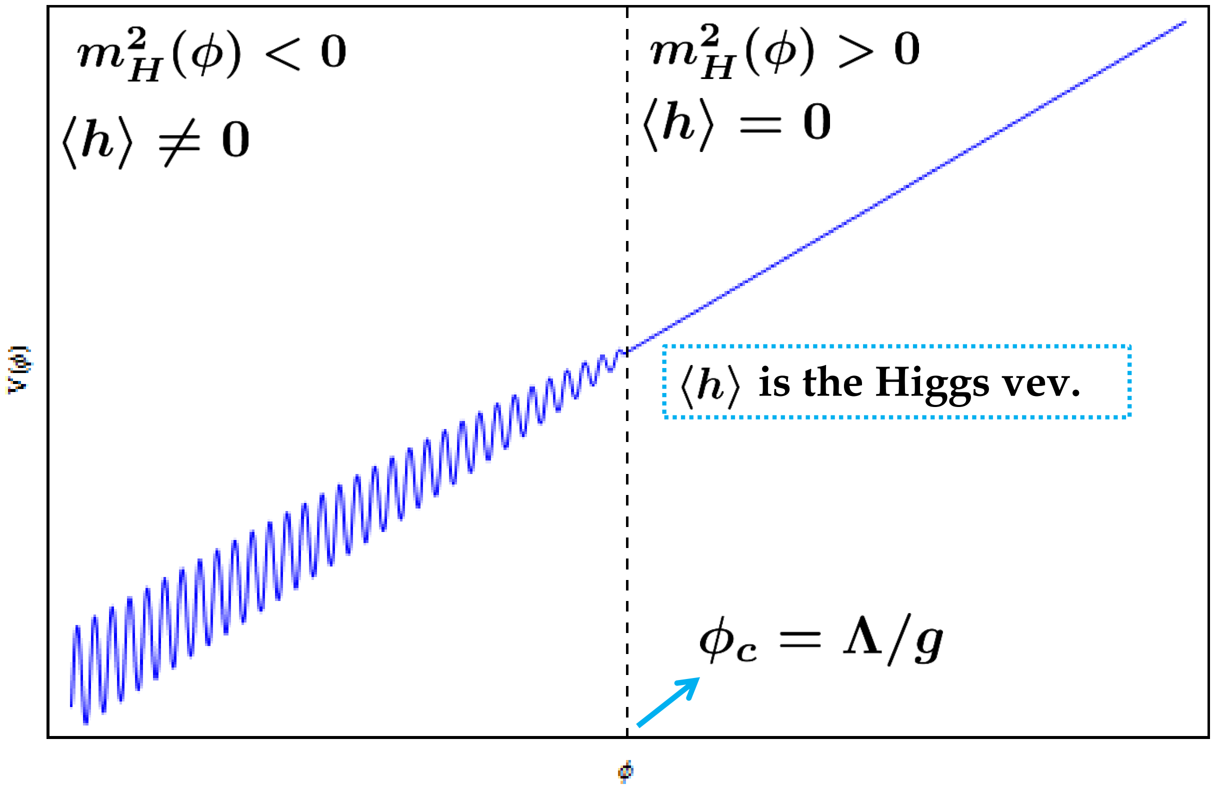
$$V(h,\phi) = \frac{1}{2}\Lambda^2\left(\frac{g\phi}{\Lambda} - 1\right)h^2 + g\Lambda^3\phi + \epsilon\Lambda_c^4\left(\frac{\langle h\rangle}{\Lambda_c}\right)^n \cos\left(\frac{\phi}{f}\right) + \cdots$$

The Relaxion Idea

Closer Look

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

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



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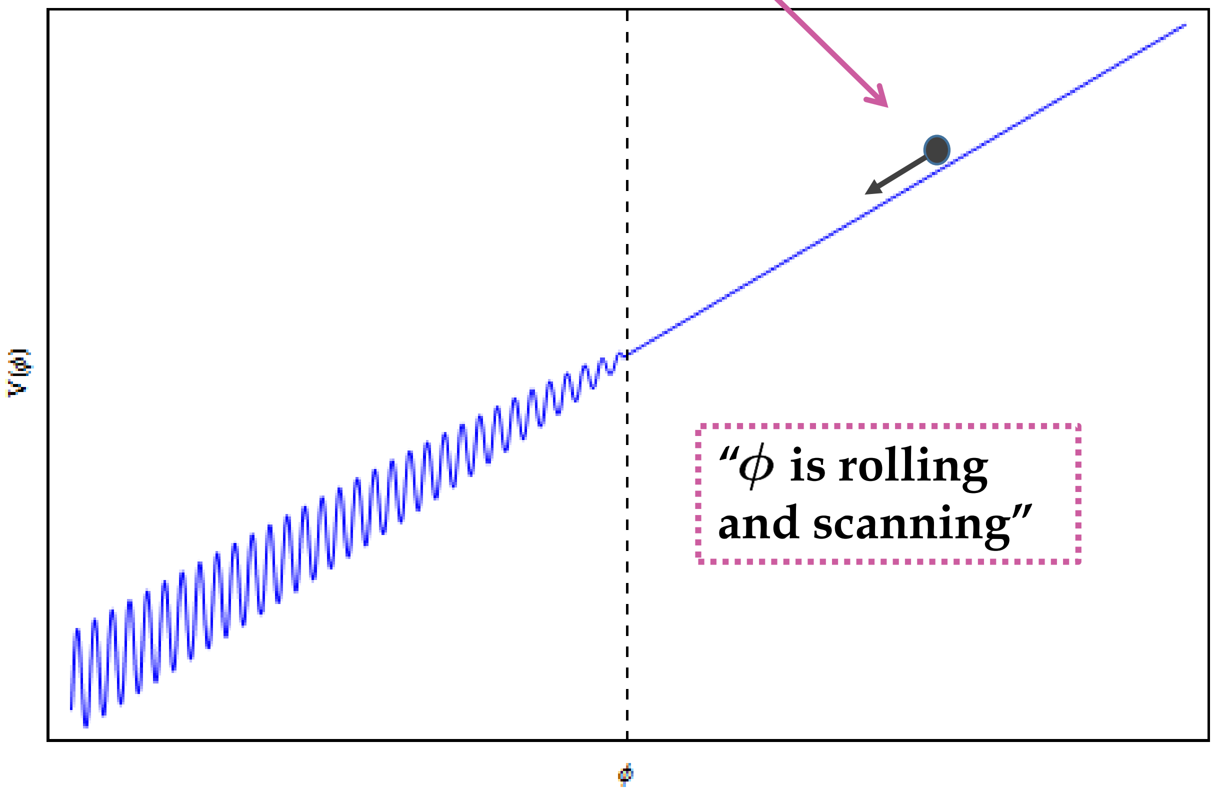

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Closer Look

$m_H^2(\phi)$

"Slope term"

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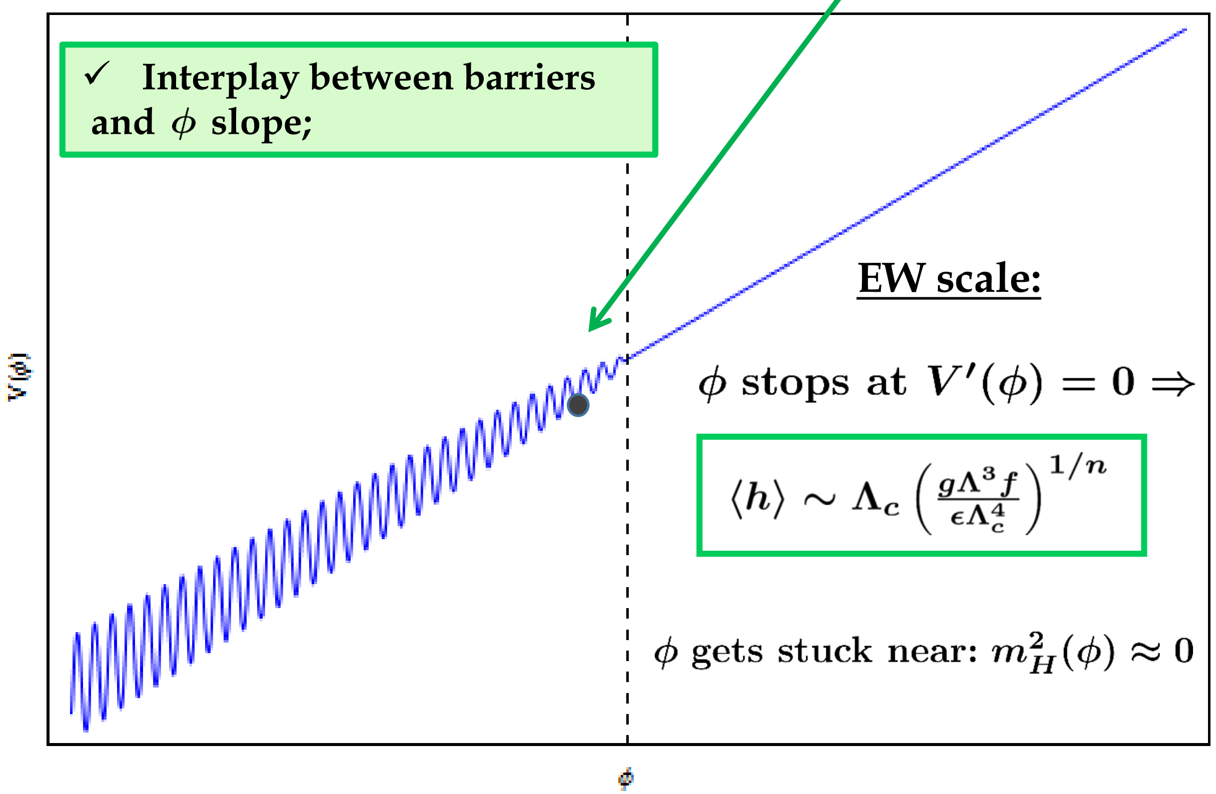

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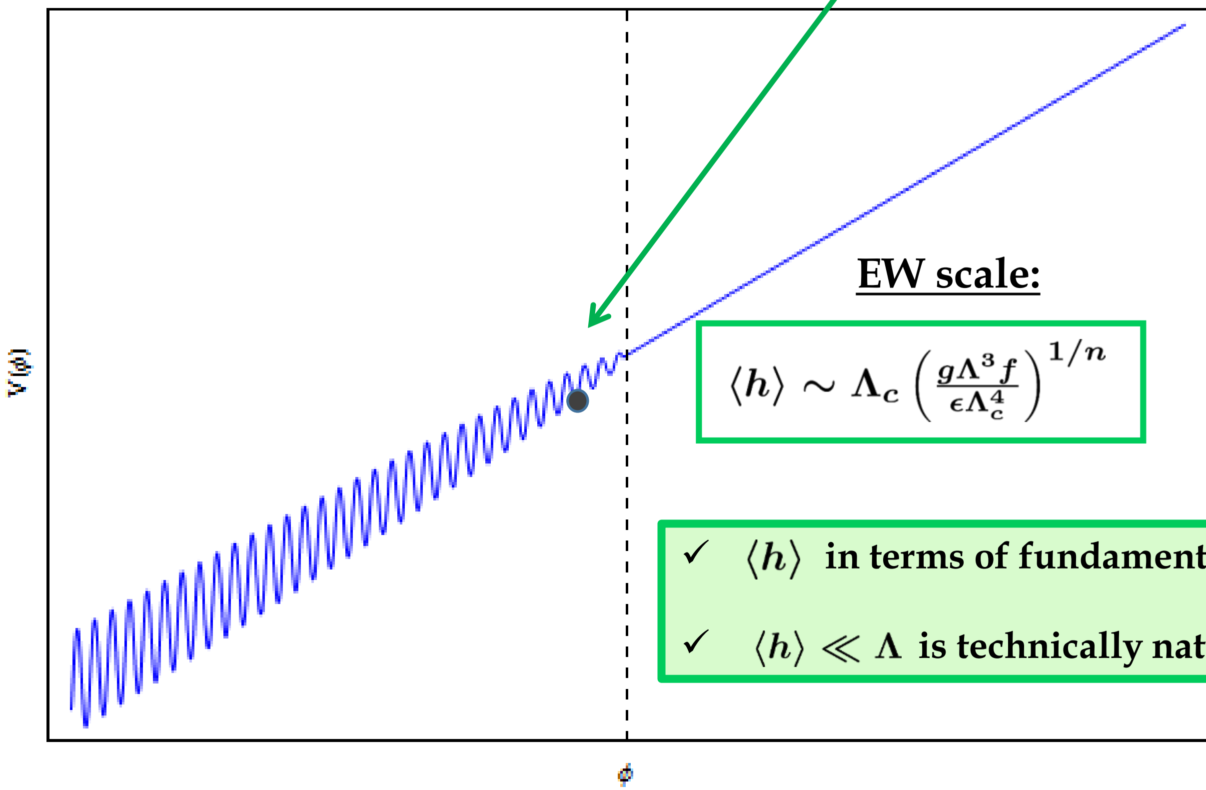


EW scale:

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

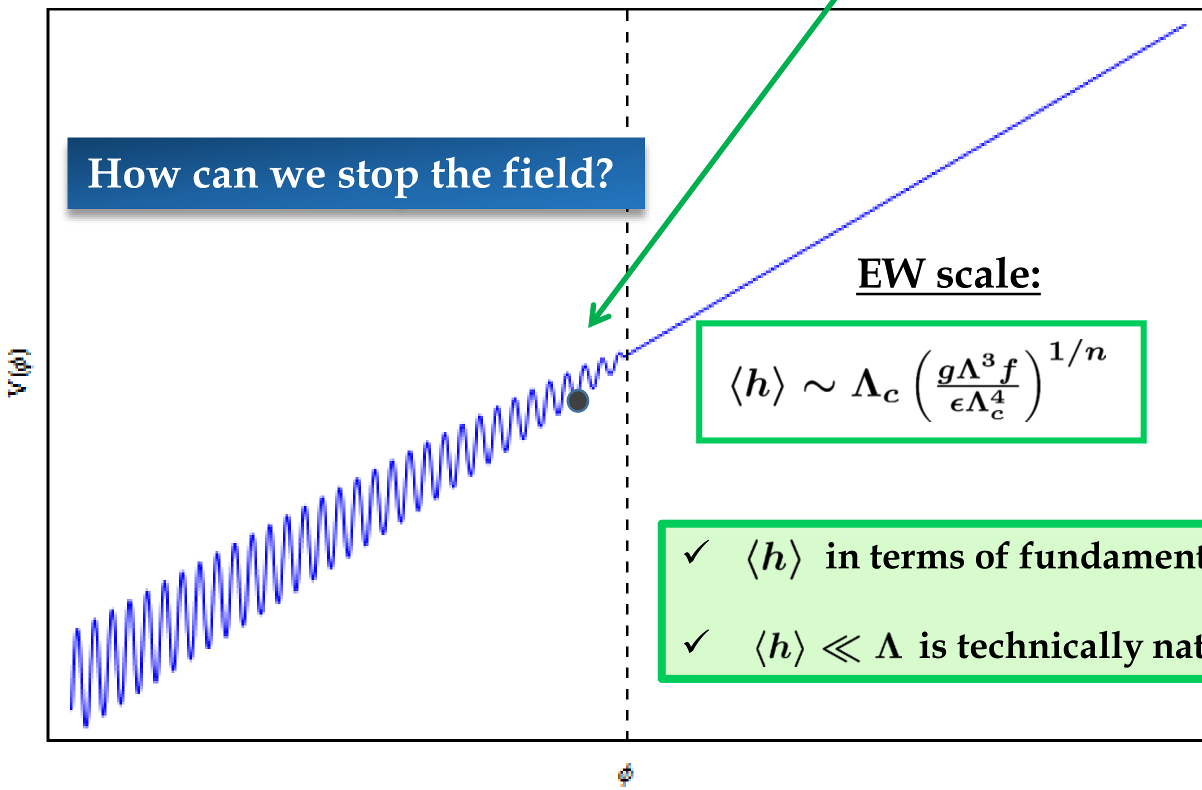
- ✓ $\langle h\rangle$ in terms of fundamental parameters;
- ✓ $\langle h\rangle \ll \Lambda$ is technically natural.

The Relaxion Idea

Closer Look

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

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



How can we stop the field?

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The Relaxion Idea

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

How can we stop the field? ⇨ **We need dissipation!**

The Relaxion Idea

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How can we stop the field? ⇒ **We need dissipation!**

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

- **The relaxion dynamical evolution requires energy transfer that should be dissipated, so the field can stop.**

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. Large parameter space allowed.**

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.

Nothing special! ?

Chiricahua National Monument, Arizona

Concluding Remarks & Outlook

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

N. F., Lima, Machado and Matheus, Phys. Rev. D 94, 015010 (2016).

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

- Many possible directions:

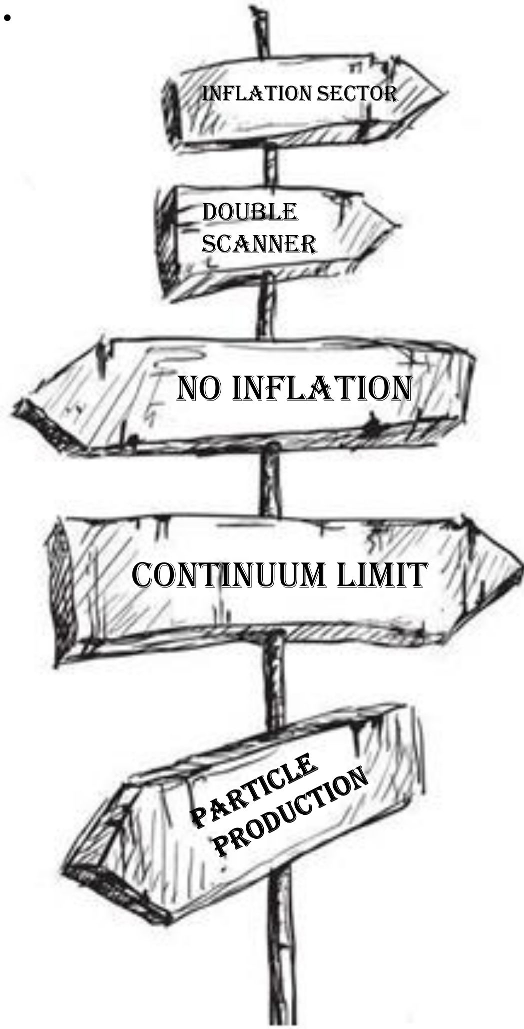
  - **Alternatives to inflation? How can we generate the <u>friction term</u>?**

    Eg.: Relaxation from particle production; A. Hook & G. Marques-Tavares; 1607.01786

  - **<u>Continuum limit</u>? Which theory do we get in AdS_5?**

  - **Can we apply this mechanism to <u>solve other problems</u>?**

    Eg.: Relaxing the Cosmological Constant: a Proof of Concept; Creminelli et al.; 1608.05715



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

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

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

$$10^9\ \text{GeV} < f < 10^{12}\ \text{GeV}$$

Star cooling — DM abundance

- **<u>But</u> this model is ruled out by the strong CP problem (**$\theta_{\rm QCD} < 10^{-10}$**)**

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

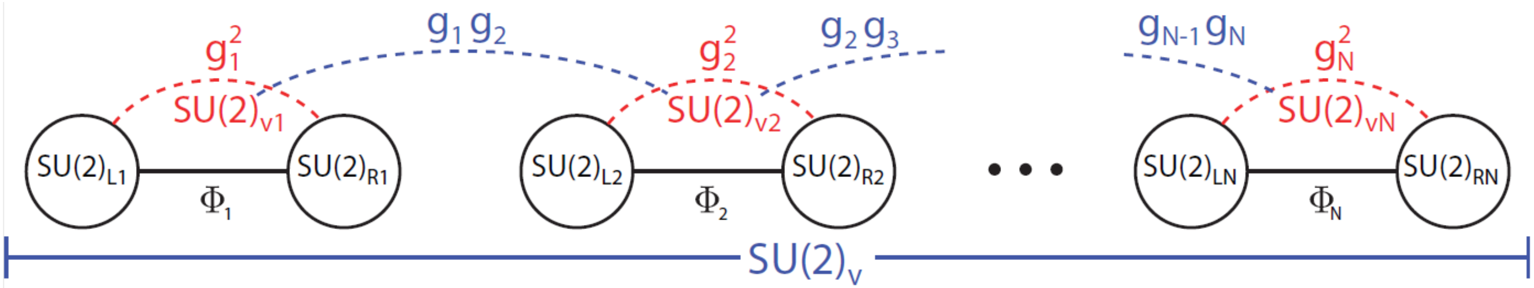
$$\Rightarrow \theta_{\rm QCD} = \langle\frac{\Delta\phi}{f}\rangle \sim \mathcal{O}(1)$$!? **(Due to the tilt of the potential)**

Ways to solve this: result in new physics close to the TeV (even if it is not there to solve the hierarchy problem)

N-Relaxion

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

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



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

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

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

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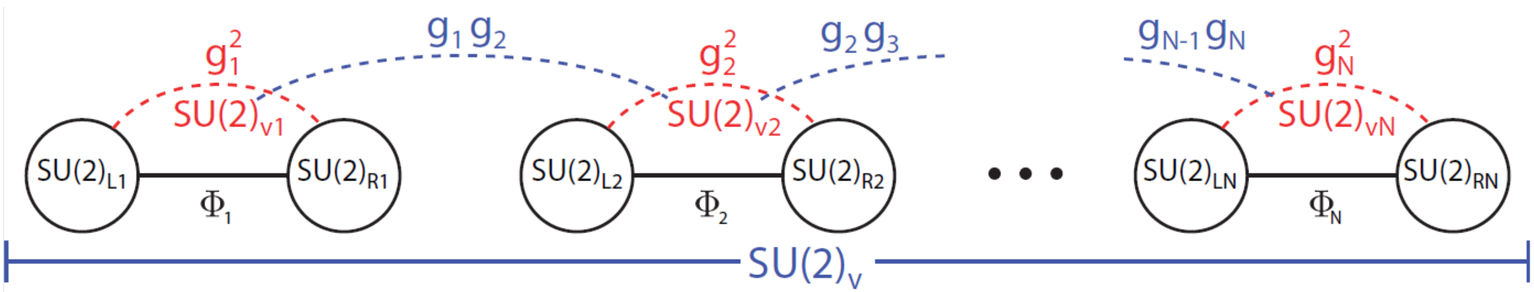

$$\Phi_j \to L_j \Phi_j R_j^\dagger$$

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

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