Relaxation Phenomenology

Diego Redigolo
10/08/2018
Relaxion = New Playground for Naturalness

new theoretical challenges ↔ new phenomenological probes
Relaxion = New Playground for Naturalness

new theoretical challenges

hopefully another example after Nate's talk

new phenomenological probes
Relaxion = New Playground for Naturalness

Setting the stage
The Relaxion rolling

(Graham, Kaplan & Rajendran)

\[ V(\phi) \]

\[ \mu^2(\phi) > 0 \]
The Relaxion rolling

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\[ V(\phi) \]

\[ \mu^2(\phi) > 0 \]

\[ \phi \text{ rolling potential:} \]

\[ \Lambda_{\text{roll}}^4 \cos \frac{\phi}{F} \]
The Relaxion rolling

(Graham, Kaplan & Rajendran)

\[ \phi \text{ rolling potential:} \]

\[ \Lambda_{\text{roll}}^4 \cos \frac{\phi}{F} \]
The Relaxion rolling

(phi-dependent Higgs mass)

\[ \Lambda_H^2 \left( \kappa - \cos \frac{\phi}{F} \right) H^\dagger H \]

\[ \mu^2(\phi) \]

(phi rolling potential):

\[ \Lambda_{\text{roll}}^4 \cos \frac{\phi}{F} \]
The Relaxion rolling

(Graham, Kaplan & Rajendran)

\[ V(\phi) \]

rolling down the Higgs mass goes down

\[ \mu^2(\phi) > 0 \]

\[ \phi - \text{dependent Higgs mass} \]

\[ \Lambda_H^2 (\kappa - \cos \frac{\phi}{F}) H^\dagger H \approx (\kappa \Lambda_H^2 - g\phi) H^\dagger H \]

\[ \mu^2(\phi) \]

\[ \phi \text{ rolling potential:} \]

\[ \Lambda_{\text{roll}}^4 \cos \frac{\phi}{F} \approx g \Lambda_H^3 \phi \]
The Relaxion rolling

\[ V(\phi) \]

\[ \phi \text{ rolling potential:} \]

\[ \phi_{\text{roll}} \sim \frac{\Lambda_{\text{roll}}^4}{3H_IF} \]

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\[ \phi_{\text{rolling potential:}} \]

\[ \Lambda_{\text{roll}}^4 \cos \frac{\phi}{F} \sim g\Lambda_H^3 \phi \times r_{\text{roll}}^2 \]

\[ \frac{g}{\Lambda_H} \ll 1 \]

\[ \text{the pace of the scanning:} \quad r_{\text{roll}} \equiv \frac{\Lambda_{\text{roll}}^2}{\Lambda_H^2} \geq \frac{1}{4\pi} \]

\[ \phi_{\text{-dependent Higgs mass}} \]

\[ \frac{\Lambda_H^2 (\kappa - \cos \frac{\phi}{F}) H^\dagger H}{\mu^2(\phi)} \sim (\kappa \Lambda_H^2 - g\phi) H^\dagger H \]

\[ \mu^2(\phi) > 0 \]

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The Relaxion wiggles

\( V(\phi) \)

\[ \mu^2(\phi) > 0 \quad \mu^2(\phi) < 0 \]

\( \phi \) gets a "backreaction" potential after EWSB

Periodicity of this potential smaller than the "rolling"

\[ \Lambda_{\text{br}}^4 \cos \frac{\phi}{f} \]
The Relaxion wiggles

\[ V(\phi) \]

\[ \phi \sim \phi_c \]

\( \mu^2(\phi) > 0 \quad \mu^2(\phi) < 0 \)

\[ \phi \] gets a "backreaction" potential after EWSB

\[ \Lambda_{br}^4 \cos \frac{\phi}{f} \]

\( \Lambda_{br} \) model dependent

Periodicity of this potential smaller than the "rolling"

\[ f/F \approx Q \ll 1 \]
$I + II = \text{rolling} + \text{wiggles}$

Stopping condition

$\mu^2(\phi_0) = m_h^2$

$\phi \sim \phi_c$

EW scale
\[ I + II = \text{rolling} + \text{wiggles} \]

\[ \mu^2(\phi_0) = m_h^2 \]

Stopping condition

EW scale

\[ \phi \sim \phi_c \]

CP violating phase

\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim \mathcal{O}(1) \]
\[ \mathbf{I} + \mathbf{II} = \text{rolling} + \text{wiggles} \]

**Stopping condition**

**EW scale**

\[ \mu^2(\phi_0) = m_h^2 \]

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**CP violating phase**

\[ \sin \left( \frac{\phi_0}{f} \right) \sim \sin \left( \frac{\phi_0}{F} \right) \sim \mathcal{O}(1) \]

**Ratio of scales**

**Ratio of vevs**

\[ \frac{\Lambda_{\text{roll}}}{\Lambda_{\text{br}}} \sim \left( \frac{F}{f} \right)^{1/4} \]
\[ \mathbf{I} + \mathbf{II} = \text{rolling + wiggles} \]

CP violating phase
\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim O(1) \]

Stopping condition
EW scale
\[ \mu^2(\phi_0) = m_h^2 \]

Ratio of scales = Ratio of vevs
\[ \frac{\Lambda_{\text{roll}}}{\Lambda_{\text{br}}} \sim \left( \frac{F}{f} \right)^{1/4} \approx \frac{1}{Q} \gg 1 \]
\[ \text{\upshape I} + \text{\upshape II} = \text{rolling} + \text{wiggles} \]

\[ \Delta \phi \sim \frac{\phi_{\text{roll}}}{H_I} N_e \]

\[ N_e \sim \left( \frac{F H_I}{\Lambda_{\text{roll}}^2} \right)^2 \gg 1 \]

\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim \mathcal{O}(1) \]

Price to pay:

Stopping condition

EW scale

\[ \mu^2(\phi_0) = m_h^2 \]

\[ \phi \sim \phi_c \]

Huge number of e-folds

CP violating phase

Ratio of scales = Ratio of vevs

\[ \frac{\Lambda_{\text{roll}}}{\Lambda_{\text{br}}} \sim \left( \frac{F}{f} \right)^{1/4} \approx 1/Q \gg 1 \]
\[ I + II = \text{rolling + wiggles} \]

**Price to pay:**

\[ N_e \sim \left( \frac{F H_I}{\Lambda_{roll}^2} \right)^2 \gg 1 \]

**Stopping condition**

EW scale

\[ \mu^2(\phi_0) = m_h^2 \]

**Ratio of scales** = **Ratio of vevs**

\[ \frac{\Lambda_{roll}}{\Lambda_{br}} \sim \left( \frac{F}{f} \right)^{1/4} \approx \frac{1}{Q} \gg 1 \]

**CP violating phase**

\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim \mathcal{O}(1) \]

there is a price to pay for too large pace

\[ \frac{\Lambda_H}{\Lambda_{br}} \sim 1/\sqrt{r_{roll}} \cdot 1/Q \]
\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim \mathcal{O}(1) \]
THE RELAXION CP PROBLEM

\[
\sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim O(1)
\]

\textit{if classical rolling + Hubble friction set the Cosmo}

\[
\dot{\phi}_{\text{roll}} \gtrsim H_I^2 
\]

\[
V_{\text{infl}} \gtrsim \Delta V_{\text{roll}}
\]
THE RELAXION CP PROBLEM

- if classical rolling + Hubble friction set the Cosmo
  \[ \dot{\phi}_{\text{roll}} \gtrsim H_I^2 \quad V_{\text{infl}} \gtrsim \Delta V_{\text{roll}} \]

- if QCD anomaly generates the wiggles
  \[ \frac{\phi}{f} \tilde{G} \tilde{G} \quad \longleftrightarrow \quad m_\pi^2 f_\pi^2 \cos \frac{\phi}{f} \quad \longleftrightarrow \quad \theta_{\text{QCD}} \sim O(1) \]
THE RELAXION CP PROBLEM

\[ \sin \frac{\phi_0}{f} \sim \sin \frac{\phi_0}{F} \sim \mathcal{O}(1) \]

- if classical rolling + Hubble friction set the Cosmo
  \[ \dot{\phi}_{\text{roll}} \gtrsim H_I^2 \quad V_{\text{infl}} \gtrsim \Delta V_{\text{roll}} \]

- if QCD anomaly generates the wiggles
  \[ \frac{\dot{\phi}}{\dot{f}} G \tilde{G} \quad \text{-----} \quad m_\pi^2 f_\pi^2 \cos \frac{\phi}{f} \quad \text{-----} \quad \theta_{\text{QCD}} \sim \mathcal{O}(1) \]

Then the relaxion is excluded by neutron EDM

\[ d_n = \frac{e}{m_\rho} \frac{g_{\pi NN} \tilde{g}_{\pi NN}}{4\pi^2} \log \frac{m_\rho}{m_\pi} \approx \theta \cdot 10^{-15} \text{ e cm} \]

\[ d_n < 10^{-26} \text{ e cm} \quad \text{Pendlebury '15} \]
POSSIBLE SOLUTIONS
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• changing the Cosmo:

★ particle production: no slope vs wiggles  Hook & Tavares

★ relaxing the vev  Graham, Kaplan & Rajendran

★ inflation between EW & QCD PT  Nelson & Prescod-Weinstein
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● changing the Field Theory:

★ ignoring CP: no QCD anomaly   (Gupta, Komargodski, Perez, Ubaldi)
★ solving CP: Nelson-Barr relaxion   (Davidi, Gupta, Perez, DR, Shalit)
POSSIBLE SOLUTIONS

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  - particle production: no slope vs wiggles  
    Hook & Tavares
  - relaxing the vev  
    Graham, Kaplan & Rajendran
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  - ignoring CP: no QCD anomaly  
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  - solving CP: Nelson-Barr relaxion  
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see Nayara’s talk

if we have time…
Relaxion = New Playground for Naturalness

How do we test the relaxion paradigm?
The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles

wiggles + relaxion VEV
The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles

\[ m_a \simeq \frac{M_{\text{br}}^2}{f} \]
The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles

\[ f (\text{GeV}) \]

\[ m_a (\text{eV}) \]

\[ 10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 1 \quad 10^5 \quad 10^{10} \]

\[ 10^{20} \quad 10^{16} \quad 10^{12} \quad 10^8 \quad 10^4 \]

\[ \sin \theta \]

\[ 10^{-43} \quad 10^{-38} \quad 10^{-33} \quad 10^{-28} \quad 10^{-23} \quad 10^{-18} \quad 10^{-13} \]

\[ 10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 1 \quad 10^5 \quad 10^{10} \]

\[ M^2_{\text{br}} / f \]

\[ m_a \approx \frac{M^2_{\text{br}}}{f} \]

\[ \sin \theta \approx \frac{v}{f} \cdot \frac{M^2_{\text{br}}}{m^2_h} \]

Flacke, Gupta, Frugiuele, Fuchs, Perez
Choi and Im
The relaxation parameter space

Model-independent boundaries

\[ \Lambda_{\text{br}} > \sqrt{4\pi v} \]

\[ f < 4\pi v \]

\[ \Lambda_H < 4\pi v \]

\[ \Lambda_{\text{roll}} \lesssim H_I^2 M_{\text{Pl}}^2 \]

\[ \phi \gtrsim H_I^2 \]
The relaxion parameter space

Model-independent boundaries

\[
\Lambda_H < 4\pi v
\]

\[
\Lambda_{br} > \sqrt{4\pi v}
\]

\[
\Lambda_{roll} \lesssim H_I^2 M_{Pl}^2
\]

\[
\phi \gtrsim H_I^2
\]

\[
\frac{4\pi v}{\Lambda_H} \lesssim \left( \frac{M_{Pl}}{r_{roll}} \right)^{1/2} \left( \frac{\Lambda_{br}^4}{f} \right)^{1/6}
\]

\[
\sqrt{\frac{M_{Pl}}{f}} \cdot 10^{-18} \text{ eV} \lesssim m_a \lesssim v
\]
The relaxion parameter space

Model-independent boundaries

\[ \Lambda_{br} > \sqrt{4\pi v} \]
\[ f < 4\pi v \]
\[ \Lambda_H < 4\pi v \]
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\[ \Lambda_{roll} \lesssim H_I^2 M_{Pl}^2 \]
\[ \phi \gtrsim H_I^2 \]
\[ 4\pi v \lesssim \Lambda_H \lesssim \left( \frac{M_{Pl}}{r_{roll}} \right)^{1/2} \left( \frac{\Lambda_{br}^4}{f} \right)^{1/6} \]
\[ \sqrt{\frac{M_{Pl}}{f}} \cdot 10^{-18} \text{ eV} \lesssim m_a \lesssim v \]

inflation OK

small quantum spread

maximal gain in cut-off
The relaxation parameter space

Model-independent boundaries

\[ f < 4\pi v \]

\[ \Lambda_{\text{br}} > \sqrt{4\pi v} \]

\[ \Lambda_H < 4\pi v \]

\[ \Lambda_{\text{roll}} \lesssim H_I^2 M_{\text{Pl}}^2 \]

\[ \dot{\phi} \gtrsim H_I^2 \]

\[ 4\pi v \lesssim \Lambda_H \lesssim \left( \frac{M_{\text{Pl}}}{r_{\text{roll}}} \right)^{1/2} \left( \frac{\Lambda_{\text{br}}^4}{f} \right)^{1/6} \]

\[ \sqrt{\frac{M_{\text{Pl}}^3}{f}} \cdot 10^{-18} \text{ eV} \lesssim m_a \lesssim v \]

inflation OK

small quantum spread

maximal gain in cut-off

minimal mass
The relaxion parameter space

**Highest cut-off** ↔ **Highest mixing**

**Testable Setup**
The relaxion parameter space

Highest cut-off $\leftrightarrow$ highest mixing

TESTABLE SETUP
The Phenomenology is the one of a light Higgs portal

Frugiuele, Fuchs, Perez, Schlaffer
Can the Relaxion be a relic?

If produced cold (misalignment, during inflation etc..) it would be a classical background

\[ m_\phi \lesssim 10 \text{ eV} \]
Can the Relaxion be a relic?

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\( m_\phi \lesssim 10 \text{ eV} \)
Can the Relaxion be a relic?

if produced cold (misalignment, during inflation etc..) it would be a classical background

\[ m_\phi \lesssim 10 \text{ eV} \]

\[ \Lambda_{\text{br}} > \sqrt{4\pi} \text{ eV} \]

\[ \Lambda_{\text{H}} < 4\pi \text{ eV} \]

\[ m_a \text{ (eV)} \]

\[ \omega \text{ [Hz]} \]

\[ \sin \theta \]

\[ 10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 1 \quad 10^5 \quad 10^{10} \]

\[ 10^{-4} \quad 10^{-9} \quad 10^{-14} \quad 10^{-19} \quad 10^{-24} \]

\[ 10^{-43} \quad 10^{-38} \quad 10^{-33} \quad 10^{-28} \quad 10^{-23} \quad 10^{-18} \quad 10^{-13} \quad 10^{-8} \quad 10^{-3} \]

\[ f > M_{\text{Pl}} \]

\[ < \text{ gravity} \]

\[ > \text{ gravity} \]

this might enhance detectability in the near future

bullet atomic clock experiments

bullet absorption

bullet ...

if produced cold (misalignment, during inflation etc..) it would be a classical background

\[ m_\phi \lesssim 10 \text{ eV} \]
Can the Relaxion be a relic?

*if produced cold (misalignment, during inflation etc..) it would be a classical background*

\[ m_\phi \lesssim 10 \text{ eV} \]

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**Diagram**

- Classical region
- \( \Lambda_{\text{br}} > \sqrt{4\pi} v \)
- \( \Lambda_{H} < 4\pi v \)
- Various lines indicating different conditions

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**Text**

- *this might enhance detectability in the near future*

- **bullet points**
  - atomic clock experiments
  - absorption
  - ...

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**References**

Perez, DR, Safronova, Ubaldi, Zupan

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**Graph**

- Log scale for \( m_\phi \) and \( \log_{10}[m_\phi/\text{eV}] \)
- Various lines indicating different limits and conditions
- Points and regions indicating different values and conditions
The Nelson Barr relaxion

\[ \phi_0 \sim \delta_{\text{CKM}} \]  (see Gilad's talk)

narrows down the relaxion parameter space

(certainly not the only way but it is one well motivated way)
The Nelson Barr relaxion

\( \phi_0 \sim \delta_{\text{CKM}} \) (see Gilad’s talk)

narrowed down the relaxion parameter space
(certainly not the only way but it is one well motivated way)
Can we formulate a no-lose theorem for other states?

(see Hinchliffe's rule)
Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant

Komargodski, Gupta, Perez, Ubaldi

\[ V_{br} = -M_{br}^2 H^\dagger H \cos \frac{\phi}{f} + r_{br} M_{br}^4 \cos \frac{\phi}{f} \]
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\[ \Lambda_{br} \gtrsim M_{br} \text{ to make it work} \]

(coincidence problem)
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\[
V_{br} = -M_{br}^{2} H^\dagger H \cos \frac{\phi}{f} + r_{br} M_{c}^{4} \cos \frac{\phi}{f}
\]

\[
\Lambda_{br} \equiv \sqrt{\nu M_{br}}
\]

\[
\Lambda_{br} \lesssim M_{br} \quad \text{to make it work}
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(coincidence problem)

\[
\text{no loose theorem}
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New states @ the EW scale \[ \mathcal{L}_{\text{NP}} \supset H f^{SM} f^{NP} \]
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Generically these states are EW-charged
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(coincidence problem)

no loose theorem

New states @ the EW scale: \( \mathcal{L}_{NP} \supset H f^{SM} f^{NP} \)

\[ \uparrow \text{Generically these states are EW-charged} \]

\[ \uparrow \text{We can test them @ collider} \]
We use sterile neutrinos $\mathcal{L}_{NP} \supset Y_N \tilde{H} L N^c$
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Froggatt-Nielsen texture to ensure

$$\begin{cases} \Lambda_{br} \gtrsim M_{br} & \text{(where } M_{br} \text{ is the scale of sterile neutrinos)} \\ \text{neutrino masses for free} \end{cases}$$
We use sterile neutrinos  \[ \mathcal{L}_{\text{NP}} \supset Y_N \tilde{H} L N^c \]

Froggatt-Nielsen texture to ensure \[ \Lambda_{\text{br}} \gtrsim M_{\text{br}} \quad (\text{where } M_{\text{br}} \text{ is the scale of sterile neutrinos}) \]

\{ neutrino masses for free \}

The relaxion is the PNGB of a \( U(1) \) flavor symmetry acting on leptons
Counter-Example
(Davidi, Gupta, Perez, DR, Shalit)

We use sterile neutrinos \( \mathcal{L}_{NP} \supset Y_N \tilde{H} L N^c \)

Froggatt-Nielsen texture to ensure \( \Lambda_{br} \gtrsim M_{br} \) (where \( M_{br} \) is the scale of sterile neutrinos)

neutrino masses for free

The relaxion is the PNGB of a \( U(1) \) flavor symmetry acting on leptons

\[
\mathcal{L}_\phi \supset \frac{i v \phi}{f} (L^c_j + e^c_k) e_j e^c_k
\]
Counter-Example
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The relaxion is the PNGB of a U(1) flavor symmetry acting on leptons

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\mathcal{L}_\phi \supset \frac{i v \phi}{f} (L_j + e^c_k) e_j e^c_k
\]

\[ \Gamma(\mu \to e\phi) \sim \frac{m_e^2 m_\mu}{16\pi f^2} \]

\( FV \) lepton decays VS star cooling

\begin{itemize}
\item Compton
\item Pair Annihilation
\item Electromagnetic Bremsstrahlung
\end{itemize}
Star cooling gives the most stringent bound!
Can we increase the sensitivity of future experiments?

Learning from the past...

TRIUMF (1988) $\approx 10^7 \mu$  \hspace{1cm} BR($\mu \rightarrow e + a$) $\lesssim 3 \cdot 10^{-6}$  \hspace{1cm} $f_a \gtrsim 10^7$ GeV

The signal is a line at $E_e \approx \frac{m_\mu}{2}$

The background comes from

The peak of the Michel spectrum depend on the muon polarization

IT IS ZERO in the OPPOSITE direction to the muon polarization!
More recent experiments...

| CRYSTAL BOX (1988) | $10^{12} \mu$ | $\text{BR}(\mu \rightarrow e + a + \gamma) \lesssim 1 \cdot 10^{-9}$ | $f_a \gtrsim 10^6 \text{ GeV}$ |
More recent experiments...

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MEG with $10^{14} \mu$? no analysis but naively: $\text{BR}(\mu \to e + a + \gamma) \lesssim 1 \cdot 10^{-9} \cdot \frac{1}{\sqrt{100}}$
More recent experiments...

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| MEG II ? | Mu3e ? |

They could use the TRUMF trick only with an electron only trigger + detector upgrade
More recent experiments...

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MEG II? Mu3e?

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GENERAL LESSON HERE:

- Flavor experiment can be extremely good at probing light new states
- They compete/complement with astro in some region of the par. space
- Optimised searches on many motivated final states need still to be done

(I have more examples @ NA62 and LHCb)
Relaxion = New Playground for Naturalness

- Switches the focus to very light weakly coupled states
- Worst case we would have ameliorated our sensitivity on light weakly coupled scalars
- Many cosmological and UV problems to be taken more seriously
Thanks everyone for the amazing Workshop
BACKUP
Rolling generated by Nelson-Barr sector

(see Gilad's talk)

$V(\phi)$

$\phi$ rolling potential:

$V_{\text{roll}} = \frac{g_{u,d} \tilde{g}_{u,d} f^4}{16\pi^2} \cos \frac{\phi}{F}$

$\phi$-dependent Higgs mass:

$\Lambda_H^2 (\kappa - \cos \frac{\phi}{F}) H^\dagger H$

$\mu^2(\phi)$

$\Lambda_H^2 = \frac{g_{u,d} \tilde{g}_{u,d} (Y_u)^T Y_u}{16\pi^2} f^2$
Rolling generated by Nelson-Barr sector

(see Gilad's talk)

**φ rolling potential:**

\[
V_{\text{roll}} = \frac{g_{u,d} \tilde{G}_{u,d} f^4}{16\pi^2} \cos \frac{\phi}{F}
\]

**φ-dependent Higgs mass:**

\[
\Lambda_H^2 \left( \kappa - \cos \frac{\phi}{F} \right) H^\dagger H
\]

\[
\mu^2(\phi)
\]

**hard-breaking**

\[
\Lambda_H^2 = \frac{g_{u,d} \tilde{G}_{u,d} (Y_u)^T Y_u f^2}{16\pi^2}
\]
Rolling generated by Nelson-Barr sector
(see Gilad's talk)

\( V(\phi) \)

\[ V_{\text{roll}} = \frac{g_{u,d} \tilde{g}_{u,d} f^4}{16\pi^2} \cos \frac{\phi}{F} \]

**\( \phi \) rolling potential:**

**\( \phi \)-dependent Higgs mass:**

\[ \Lambda_H^2 (\kappa - \cos \frac{\phi}{F}) H^\dagger H \]

\[ \mu^2(\phi) \]

\( \Lambda_H^2 = \frac{g_{u,d} \tilde{g}_{u,d} (Y_u)^T Y_u f^2}{16\pi^2} \]

hard-breaking

small NB couplings

to avoid \( \theta_{QCD} \)
Rolling generated by Nelson-Barr sector
(see Gilad's talk)

φ rolling potential:

\[ V_{\text{roll}} = \frac{g_{u,d} \tilde{g}_{u,d} f^4}{16\pi^2} \cos \frac{\phi}{F} \]

φ-dependent Higgs mass:

\[ \Lambda_H^2 (\kappa - \cos \frac{\phi}{F}) H^\dagger H \]

\[ \Lambda_H^2 = \frac{g_{u,d} \tilde{g}_{u,d} (Y_u)^T Y_u \tilde{f}^2}{16\pi^2} \]

hard-breaking

small NB couplings to avoid \( \theta_{QCD} \)

\[ \sqrt{g_{u,d} \tilde{g}_{u,d}} \lesssim 10^{-3} \]

(depends on the flavor structure)

see M. Dine & P. Draper and L. Vecchi