New Developments in Relaxion Models

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DESY

Axions at the crossroads: QCD, dark matter, astrophysics

ECT*, Trento
Outline

1. Relaxation idea
2. Concerns and some solutions
3. Relaxation after inflation
4. Conclusions
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Not the QCD axion!

Please don’t leave 😊
SM hierarchy problem: New physics at the weak scale

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

- **The problem and its importance**: 170 of the 226 search channels at LHC tied to naturalness (Craig PPC ‘16)

- We need BSM at $\geq 1$ TeV scale (Eg.: SUSY & Composite Higgs Models)

- No compelling evidence of BSM at the LHC current data!
SM hierarchy problem: Relaxation mechanism of the EW scale

Warming up...

\[ V(h, \phi) = \frac{1}{2} m^2_H(\phi) h^2 + \cdots = \frac{1}{2} (-\Lambda^2 + g\Lambda \phi) h^2 + \cdots \]

- $\phi$ scans $m^2_H(\phi)$ during the cosmological evolution;
- Arrange a mechanism so that $\phi$ stops where we want, precisely at the EW scale:

\[ m^2_H(\phi_c) = -\Lambda^2 + g\Lambda \phi_c \ll \Lambda^2 \]
The Relaxion Idea (Graham-Kaplan-Rajendran; 1504.07551 [hep-ph]) inspired by Abbott's attempt to solve the CC problem, '85

**SM hierarchy problem: Relaxation mechanism of the EW scale**

Warming up...

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

- \( \phi \) scans \( m_H^2(\phi) \) during the cosmological evolution;
- Arrange a mechanism so that \( \phi \) 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 (Graham-Kaplan-Rajendran; 1504.07551 [hep-ph])

Closer look: relaxion potential

\[ V(h, \phi) \supset \Lambda^2 \left( \frac{g\phi}{\Lambda} - 1 \right) H^2 + \lambda H^4 + g\Lambda^3 \phi + \varepsilon \Lambda^4_c \left( \frac{\langle H \rangle}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]
The Relaxion Idea (GKR'15)

\[ V(h, \phi) \supset \Lambda^2 \left( \frac{g \phi}{\Lambda} - 1 \right) H^2 + \lambda H^4 + g \Lambda^3 \phi + \epsilon \Lambda_c^4 \left( \frac{\langle H \rangle}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]
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- \( m_H^2(\phi) < 0 \) \( \langle H \rangle \neq 0 \)
- \( m_H^2(\phi) > 0 \) \( \langle H \rangle = 0 \)

\( \langle H \rangle \) is the Higgs vev

\[ \phi_c = \Lambda/g \]

- evolution starts in the symmetric phase
  \( \phi_{\text{ini}} > \Lambda/g \)
The Relaxion Idea (GKR'15)

\[ V(h, \phi) \supset \Lambda^2 \left( \frac{g\phi}{\Lambda} - 1 \right) H^2 + \lambda H^4 + g\Lambda^3 \phi + \epsilon\Lambda^4 \left( \frac{\langle H \rangle}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]

EW scale:
\[ \langle H \rangle \sim \Lambda_c \left( \frac{g\Lambda^3 f}{\epsilon\Lambda^4_c} \right)^{1/n} \]

Interplay between barriers and \( \phi \) slope;

\( \phi \) gets stuck near: \( m_H^2(\phi) \approx 0 \)

\( \phi \) stops at \( V'(\phi) = 0 \) \( \Rightarrow \)

"Slope term"

"Stopping term"
The Relaxion Idea (GKR’15)

\[ V(h, \phi) \supset \Lambda^2 \left( \frac{g \Lambda}{\Lambda} - 1 \right) H^2 + \lambda H^4 + g \Lambda^3 \phi + \epsilon \Lambda^4 \left( \frac{H}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]

**EW scale:**

- \( \phi \) gets stuck near: \( m_H^2(\phi) \approx 0 \)
- \( \phi \) stops at \( V'(\phi) = 0 \) ⇒
  - \( \langle H \rangle \sim \Lambda_c \left( \frac{g \Lambda^3 f}{\epsilon \Lambda_c^4} \right)^{1/n} \)
  - \( \Lambda \sim 10^8 \text{ GeV} \)
  - \( \Lambda_c \sim \mathcal{O}(1) \text{ TeV} \)

- \( \langle H \rangle \) in terms of fundamental parameters;
- \( \langle H \rangle \ll \Lambda \) is technically natural.
Typical constraints

Espinosa-Grojean-Panico-Pomarol-Pujolàs-Servant; 1506.09217 [hep-ph]

cosmologically stable

\( \phi \) decays after BBN

\( \phi \) cosmologically stable

\( \sigma \)

Decays leading to distortion in the galactic and extra-galactic diffuse X-ray or gamma-ray background

\[ \rho_i(T) \sim \rho_{ini,i}(T/T_{osc,i})^3 \]

misalignment
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Concerns about the original idea

- QCD relaxation?
- UV completion
- Dissipation: Hubble friction during inflation
Concerns about the original idea

• **QCD relaxation**

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

○ **Relaxion parameters**

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

Naively, \[ V(\phi, H) \sim m_u(H) \langle q\bar{q} \rangle \cos(\phi/f) \]

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

\[ 10^9 \text{ GeV} < f < 10^{12} \text{ GeV} \]
Concerns about the original idea

• **QCD relaxion**

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

- But this model spoils the axion solution to the strong CP problem;
- If the relaxion is the QCD axion, its vev determines the QCD theta parameter.

\[
\Rightarrow \theta_{QCD} = \langle \frac{\Delta \phi}{f} \rangle \sim \mathcal{O}(1)
\]

(Due to the tilt of the potential)

\[ \theta_{QCD} \lesssim 10^{-10} \]
Concerns about the original idea

- **QCD relaxion**
  
  (GKR ’15)

  \[ \phi \text{ is the QCD axion}, \quad \mathcal{L} \supset \frac{g_s^2}{32\pi^2} \frac{\phi}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

  - \textbf{But} this model spoils the axion solution to the strong CP problem;
  - \textbf{If} the relaxion is the QCD axion, \textbf{its vev determines the QCD theta parameter.}

  \[ \Rightarrow \theta_{\text{QCD}} = \langle \frac{\Delta \phi}{f} \rangle \sim \mathcal{O}(1) \]

  (Due to the tilt of the potential)

  \[ \theta_{\text{QCD}} \lesssim 10^{-10} \]

  \[ \text{Ways out} \]

  - \textbf{adding dynamics at the end of inflation} (removes the slope of the potential) \textbf{Cutoff scale} \( \lesssim 30 \text{ TeV} \)
  - \textbf{QCD'} relaxion
Concerns about the original idea

- QCD relaxation?
- UV completion
- Dissipation: Hubble friction during inflation
Let's check the symmetries

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \Lambda^2 \left( \frac{g\phi}{\Lambda} - 1 \right) H^2 - \lambda H^4 - g \Lambda^3 \phi - \epsilon \Lambda_4^4 \left( \frac{\langle H \rangle}{\Lambda_4} \right)^n \cos \left( \frac{\phi}{f} \right)$$

- $g = 0, \epsilon = 0$ → continuous shift symmetry: $\phi \rightarrow \phi + c$
  Nambu-Goldstone boson

- $\epsilon \neq 0$ → breaks the continuous shift symmetry to: $\phi \rightarrow \phi + 2\pi n f$
  Pseudo Nambu-Goldstone boson

- $g \neq 0$ → breaks the discrete shift symmetry!
Concerns about the original idea

Let’s check the symmetries

\[ \mathcal{L} \supset \frac{1}{2} (\partial_\mu \phi)^2 - \Lambda^2 \left( \frac{g \phi}{\Lambda} - 1 \right) H^2 - \lambda H^4 - g \Lambda^3 \phi - \epsilon \Lambda^4_c \left( \frac{\langle H \rangle}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]

- \( \epsilon \) term \( \Rightarrow \) Breaks the continuous shift symmetry to: \( \phi \rightarrow \phi + 2\pi n f \)

- \( g \) terms \( \Rightarrow \) Break the discrete shift symmetry!

\( \Rightarrow \phi \) is a pNGB (periodicity)

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

Gupta-Komargodski-Perez-Ubaldi ’15
Concerns about the original idea

Let's check the symmetries

\[ \mathcal{L} \supset \frac{1}{2} (\partial_\mu \phi)^2 - \Lambda^2 \left( \frac{g\phi}{\Lambda} - 1 \right) H^2 - \lambda H^4 - g \Lambda^3 \phi - \epsilon \Lambda_c^4 \left( \frac{H}{\Lambda_c} \right)^n \cos \left( \frac{\phi}{f} \right) \]

- \( \epsilon \) term \( \Rightarrow \) Breaks the continuous shift symmetry to: \( \phi \rightarrow \phi + 2\pi nf \)
- \( g \) terms \( \Rightarrow \) Break the discrete shift symmetry!

Rewrite the \( \phi \) terms as periodic functions
Effectively, it is enough to have a hierarchy of decay constants: \( F = n f \gg f \)

\[
V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left( c_F + \frac{H^2}{M_F^2} \right) \cos \left( \frac{\phi}{F} \right) + \Lambda_f^4 \left( c_f + \frac{H^2}{M_f^2} \right) \cos \left( \frac{\phi}{f} \right)
\]
Concerns about the original idea

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

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left( c_F + \frac{H^2}{M_F^2} \right) \cos \left( \frac{\phi}{F} \right) + \Lambda_f^4 \left( c_f + \frac{H^2}{M_f^2} \right) \cos \left( \frac{\phi}{f} \right)$$

$V(\phi) \sim g\Lambda^3 \phi$

expanding $(\Phi - \pi F/2) \ll F$
How to generate large-scale hierarchies?
Model building front

4D site models

- Clockwork constructions
  Choi, Im '16; Kaplan, Rattazzi '16

No exponential hierarchies in fundamental parameters

\[ U(1)^{N+1} \rightarrow U(1) \ (N+1 \ NGBs \ with \ the \ same \ decay \ constant \ \lambda): \]

\[ \mathcal{L} \supset \frac{f^2}{2} \sum_{j=0}^{N} |\partial_{\mu} U_j|^2 - \frac{\epsilon f^2}{2} \sum_{j=0}^{N-1} (U_j^\dagger U_{j+1} + h.c.) \]

\[ U_j(x) = e^{i\pi_j(x)/f} \]

For the zero mode:

\[ \frac{F}{f} \sim q^N, \quad q > 1 \]
4D site models

- **Clockwork constructions**
  Choi, Im ’16; Kaplan, Rattazzi ’16

No exponential hierarchies in fundamental parameters

\[ U(1)^{N+1} \rightarrow U(1) \quad (N+1 \text{ NGBs with the same decay constant } f) \]

\[ \mathcal{L} \supset \frac{f^2}{2} \sum_{j=0}^{N} |\partial_{\mu} U_j|^2 - \frac{e f^2}{2} \sum_{j=0}^{N-1} (U_j^{\dagger} U_{j+1}^q + \text{h.c.}) \]

\[ U_j(x) = e^{i \pi_j(x)/f} \]

For the zero mode:

\[ \frac{F}{f} \sim q^N, \quad q > 1 \]

Clockwork 5D continuum limit

- Linear dilaton metric: Giudice, McCullough ’16
- Or not? Craig, Garcia Garcia, Sutherland [1704.07831]
- Or yes? Giudice-McCullough [1705.10162]
4D site models

- Deconstruction inspired
  NF, Lima, Machado, Matheus ‘16

  - Site-dependent couplings or vevs (hierarchy built in);
  - motivated by deconstruction of AdS$_5$ models (5D analogues).
Model building front

4D site models

- Deconstruction inspired
  
  NF, Lima, Machado, Matheus ‘16

  - Site-dependent couplings or vevs (hierarchy built in);
  - motivated by deconstruction of AdS₅ models (5D analogues).

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

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

For the zero mode: \[ \frac{F}{f} \sim \frac{1}{q'^{N-1}}, \quad q' < 1 \]
Concerns about the original idea

- QCD relaxation?
- UV completion
- Dissipation: Hubble friction during inflation
Concerns about the original idea

- **Dissipation mechanism: Hubble friction during inflation**
  
  - **Inflation sector:** largely unspecified, but at least:
    
    I. $V(\phi)$ is subdominant (an extra field, i.e. the inflaton, provides the required $N_e$)
    
    
    $$V_I \sim H_I^2 M_{Pl}^2 > V(\phi) \sim \Lambda^4$$
    
    II. Relaxion classical rolling $>$ quantum fluctuations;
    
    $$(\Delta \phi)_{\text{class}} \sim H_I^{-1} \frac{d\phi}{dt} \sim H_I^{-2} V'$$
    
    $$(\Delta \phi)_{\text{quant}} \sim H_I$$
    
    $\rightarrow \quad H_I^3 < V'$$

\begin{align*}
\ddot{\phi} + 3H_I \dot{\phi} + \frac{\partial V}{\partial \phi} &= 0 \\
\phi = \phi(t) \quad |\dot{\phi}| \ll H|\phi| \\
\frac{dV}{d\phi} &\sim g\Lambda^3
\end{align*}
Concems about the original idea

• Dissipation mechanism: Hubble friction during inflation
  
  o Inflation sector: largely unspecified, but at least:

    i. $V(\phi)$ is subdominant (an extra field, i.e. the inflaton, provides the required $N_e$)

    $$V_I \sim H_I^2 M_{Pl}^2 > V(\phi) \sim \Lambda^4$$

    ii. Relaxion classical rolling > quantum fluctuations;

    $$(\Delta\phi)_{\text{class}} \sim H_I^{-1} \frac{d\phi}{dt} \sim H_I^{-2} V'$$

    $$(\Delta\phi)_{\text{quant}} \sim H_I$$

    $\implies H_I^3 < V'$$

    $I \& II:$

    $$\frac{\Lambda^2}{M_{Pl}} < H_I < (g\Lambda^3)^{1/3}$$
Concerns about the original idea

- **Dissipation mechanism:** Hubble friction during inflation
  
  - **Inflation sector:** largely unspecified, but at least:
    
    \[
    \frac{\Lambda^2}{M_{Pl}} < H_I < (g\Lambda^3)^{1/3}
    \]
    
  - \( V(\phi, H) \supset \frac{1}{2}(g\Lambda\phi - \Lambda^2)H^2 \)
    
    \( \phi_{ini} > \Lambda/g \) (large field excursions)

III. Inflation: long enough to scan a typical field range

\[
\Delta \phi \gtrsim \frac{\Lambda}{g} \implies
\]

large field excursion
Concerns about the original idea

- **Dissipation mechanism: Hubble friction during inflation**

  - **Inflation sector:** largely unspecified, but at least:

    \[
    \frac{\Lambda^2}{M_{Pl}} < H_I < (g\Lambda^3)^{1/3}
    \]

    \[
    V(\phi, H) \supset \frac{1}{2}(g\Lambda \phi - \Lambda^2)H^2
    \]

    \[
    \phi_{\text{ini}} > \Lambda/g \quad \text{(large field excursions)}
    \]

  - **III. Inflation:** long enough to scan a typical field range

    \[
    \Delta \phi \gtrsim \frac{\Lambda}{g} \implies N_e H_I^{-2} V' \gtrsim \frac{\Lambda}{g}
    \]

    large field excursion \quad \text{Inflation should last long enough}

    \[
    N_e \gtrsim \left(\frac{H_I}{g\Lambda}\right)^2
    \]
Concerns about the original idea

• Dissipation mechanism: Hubble friction during inflation
  
  o Inflation sector: largely unspecified, but at least:

  \[
  \frac{\Lambda^2}{M_{Pl}} < H_I < (g\Lambda^3)^{1/3}
  \]
  
  \[
  N_e \gtrsim \left( \frac{H_I}{g\Lambda} \right)^2
  \]

  ➢ Low inflation scale

  ➢ Super-Planckian field excursions

  ➢ Large number of e-folds: fine-tuning in the inflation sector
Concerns about the original idea

• Dissipation mechanism: Hubble friction during inflation
  
  o Inflation sector: largely unspecified, but at least:

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  \frac{\Lambda^2}{M_{Pl}} < H_I < (g\Lambda^3)^{1/3}
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  ➢ Low inflation scale

  ➢ Super-Planckian field excursions

  ➢ Large number of e-folds: fine-tuning in the inflation sector

Alternative to Inflation: Particle production friction
Concerns about the original idea

• QCD relaxion ?
• UV completion
• Dissipation: Hubble friction during inflation
• ...

An incomplete list of relaxion possibilities
Cosmological Relaxation of the Electroweak Scale, GKR ’15
inspired by Abbott’s attempt to solve the CC problem, ’85

Cosmological Constant
• Graham, Kaplan, Rajendran; 1709.01999
• Alberete, Creminelli, Khmelnitsky, Pirtshelfova, Trincherini ’16

Dynamics during Inflation
• Non-constant Hubble;
  Patil, Schwaller ’15

Observational Constraints
• Higgs-relaxion coupling;
  Flacke, Frugiuele, Fuchs, Gupta, Perez; ‘16

• New strongly coupled sector;
  Beauchesne, Bertuzzo, di Cortona; 1705.06325

Double scanner mechanism
Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant ’16

Model building front
• 4D site models;
  Choi, Im ’16
  Kaplan, Rattazzi ’16
  NF, Lima, Machado, Matheus ’16

• 5D continuum limit;
  Giudice, McCullough ’16

• String theory (Monodromy);
  McAllister, Schwaller, Servant, Stout, Westphal ’16

• Relaxion from Warped Space
  NF, von Harling, Lima, Machado ’in preparation

Alternatives to Inflation
• Friction from particle production;
  Hook, Marques–Tavares; ’16
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Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares ‘16

\[ \mathcal{L} \supset \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi + \frac{1}{2} \partial_{\mu} h \partial^{\mu} h - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\phi}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\pi \alpha}{2} A_{\mu} A^{\mu} h^2 - V(\phi, h) \]

\[ V \supset \frac{1}{2} (-\Lambda^2 + g \Lambda \phi) h^2 - g \Lambda^3 \phi + \frac{\lambda}{4} h^4 + \Lambda_c^4 \cos \left( \frac{\phi}{f'} \right) \]

\[ \tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} \]

\[ \alpha = g_{U(1)}^2 / (4\pi) \]
Alternatives to Inflation

Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares ‘16

\[ \mathcal{L} \supset \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi + \frac{1}{2} \partial_{\mu} h \partial^{\mu} h - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\phi}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\pi \alpha}{2} A_{\mu} A^{\mu} h^2 - V(\phi, h) \]

\[ V \supset \frac{1}{2} \left( -\Lambda^2 + g \Lambda \phi \right) h^2 - g \Lambda^3 \phi + \frac{\lambda}{4} h^4 + \Lambda^4 \cos \left( \frac{\phi}{f} \right) \]

\[ (m_H)^2 < 0 \]

- the evolution starts in the broken phase, i.e. the vev is large: \( \Phi_{\text{ini}} < \Lambda/g \).
Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares '16

the evolution starts in the broken phase, i.e. the vev is large: $\Phi_{\text{ini}} < \Lambda/g$.

the relaxion is coupled to a massive SM vector field:

$-g\Lambda^3\Phi$ makes the relaxion roll to larger values, decreasing the Higgs vev.
Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares ‘16

\[ \mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - \frac{\phi}{4f} F_{\mu \nu} \tilde{F}^{\mu \nu} + \frac{\pi \alpha}{2} A_\mu A^\mu h^2 - V(\phi, h) \]

- Higgs vev is sufficiently \( \leftrightarrow \) \( A_\mu \) experiences a **tachyonic instability**

\[ \ddot{A}_\pm + (k^2 + m_A^2 \mp k \frac{\dot{\phi}}{f}) A_\pm = 0 \quad m_A^2 = \pi \alpha h^2 \]

- When \( A_+ \) grows exponentially, the \( \tilde{F} \) term slows down the field \( \phi \)

\[ \ddot{\phi} - g \Lambda^3 + g \Lambda h^2 + \frac{\Lambda^4}{f'} \sin \frac{\phi}{f'} + \frac{1}{4f} \langle F \tilde{F} \rangle = 0 \]

\[ \langle F \tilde{F} \rangle = \frac{1}{4\pi^2} \int_0^\Lambda dk \frac{d}{dt} (|A_+|^2 - |A_-|^2) \]
Alternatives to Inflation

Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares ’16

\[
\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - \frac{\phi}{4f} F_{\mu \nu} \tilde{F}^{\mu \nu} + \frac{\pi \alpha}{2} A_\mu A^\mu h^2 - V(\phi, h)
\]

- Higgs vev is sufficiently ↔ A_\mu experiences a tachyonic instability

\[(\omega_k)^2 < 0\]

\[\ddot{A}_\pm + (k^2 + m_A^2 \mp k \frac{\phi}{f}) A_\pm = 0 \quad m_A^2 = \pi \alpha h^2\]

- When A_+ grows exponentially, the \(\tilde{F}\) term slows down the field \(\phi\)

\[
\ddot{\phi} - g \Lambda^3 + g \Lambda h^2 + \frac{\Lambda^4}{f^2} \sin \frac{\phi}{f'} + \frac{1}{4f} \langle F \tilde{F} \rangle = 0
\]

\[
\langle F \tilde{F} \rangle = \frac{1}{4\pi^2} \int_0^\Lambda dk \frac{d}{dt} (|A_+|^2 - |A_-|^2)
\]

\[
\tilde{F}^{\mu \nu} = \epsilon^{\mu \nu \rho \sigma} F_{\rho \sigma}
\]

\[
\alpha = g^2 U(1)/(4\pi)
\]
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Concluding Remarks and Outlook

- **Relaxation models**: the hierarchy problem might not be an argument for new physics at the TeV scale.
Concluding Remarks and Outlook

- **Relaxation models:** the hierarchy problem might not be an argument for new physics at the TeV scale.

- **Challenges & possibilities:**
  - CC;
  - dynamics during inflation;
  - alternatives to inflation;
  - observational constraints;
  - model building;
  - pheno;
  - ...
Concluding Remarks and Outlook

- Relaxation models: the hierarchy problem might not be an argument for new physics at the TeV scale.

- Challenges & possibilities:
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Thank you!