Relaxation from Particle Production

Anson Hook
Stanford

1607.01786:
A.H. & G. Marques-Tavares
Ultra Fast Relaxion Review

\[
\mathcal{L} \supset (\Lambda^2 - \epsilon \phi) h h^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} G \tilde{G}
\]

- Relaxion field scans Higgs mass during inflation
- QCD generates a cosine potential for the relaxion whose magnitude is approximately linear in H
- Choose parameters such that minima start appearing when Higgs vev is 100 GeV
Ultra Fast Relaxion Review

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon \phi) hh^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} G \tilde{G} \]

FIG. 1: Here is a characterization of the 's potential in the region where the barriers begin to become important. This is the one-dimensional slice in the field space after the Higgs is integrated out, effectively setting it to its minimum. To the left, the Higgs vev is essentially zero, and is \( \mathcal{O}(m_W) \) when the barriers become visible. The density of barriers are greatly reduced for clarity.

We will now examine the dynamics of this model in the early universe. We take an initial value for such that the effective mass-squared of the Higgs, \( m^2_h \), is positive. During inflation, \( \epsilon \) will slow-roll, thereby scanning the physical
Ultra Fast Relaxion Review

- Relaxion has generated much controversy
- Many aesthetically (theoretically?) unappealing aspects
  - Super Planckian field excursions
  - Large Monodromy
  - Low scale inflaton
  - Large amount of inflation
  - … (c.c./why early time rather than late time)
Downsides

\( \Lambda \sim 10^7 \text{ GeV} \)

- Field excursions of relaxion are extremely super Planckian

\[ \Delta \phi \sim \frac{\Lambda^2}{\epsilon} \sim 10^{22} M_p \]

- Super Planckian periodicity theoretically suspect
  - Giddings and Strominger showed gravitational instantons exist whose actions scale as \( M_p/\text{period} \)
  - Inherently untestable

Downsides

- Super large number of e-foldings of inflation
  
  \[ N_e \gtrsim \frac{H^2}{\epsilon^2} \sim 10^{44} \]

- Requiring that you stop

  \[ N_e \gtrsim \frac{\Lambda^4}{m^2 \pi f^2} \]
Downsides

\[ N_e \lesssim \frac{M_p^2}{H^2} \sim 10^{44} \]

- If number of e-foldings is too large inflaton sector is automatically eternally inflating

\[ n_s - 1 \sim 1/N_e \]

Downsides

- Small scale inflation

\[ H \sim \frac{\Lambda^2}{M_p} \sim 10^{-4} \text{ GeV} \]

- Model building is difficult
  - Tends to be fairly fine tuned
  - Hard to reproduce density perturbations
Relaxion

- Have a minima with the correct Higgs vev
  - Large monodromy
- Select 100 GeV
- Friction
  - Inflation
  - This is why most of the downsides emerge
Relaxion

- Have a minima with the correct Higgs vev
  - Large monodromy
- Select 100 GeV
- Friction

Relaxion in the infinite Mp limit

- Inflation
- This is why most of the downsides emerge
Relaxation with Particle Production

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}G\tilde{G} + \frac{\phi}{f'} (W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos \frac{\phi}{f'} \]

Removes all previous problems!
Relaxation with Particle Production

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon \phi) h h^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} (W W' - B B') + \Lambda_c^4 \cos \frac{\phi}{f'} \]

Initially relaxation has enough kinetic energy to fly over Higgs independent bumps.
Relaxation with Particle Production

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos \frac{\phi}{f'} \]

When \( h \sim v \) exponential production of electroweak gauge bosons occurs
Relaxation with Particle Production

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon \phi) h h^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} (W \tilde{W} - B \tilde{B}) + \Lambda_c^4 \cos \frac{\phi}{f'} \]

Can happen before/during/after inflation
Particle Production

\[ \mathcal{L} \supset -\frac{\phi}{4f} F \tilde{F} \]

- Consider an axion-like coupling
- Gauge boson equation of motion

\[ \dddot{A}_\pm + \left( k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f} \right) A_\pm = 0 \quad \quad |\dot{\phi}| \gtrsim 2f m_A \]

- A tachyon for one of the transverse polarizations of the gauge boson!
Particle Production

\[ \mathcal{L} \supset -\frac{\phi}{4f} F \tilde{F} \]

- Time scale for particle production is inverse tachyon frequency

\[ t \sim \frac{f}{\dot{\phi}} \quad \dot{\frac{\phi}{f}} \gtrsim m_A \]
Particle Production

- Particle production gives a thermal bath
- Repeat calculation at finite temperature
  - Use finite temperature self energy

$$\omega^2 - k^2 \pm \frac{k\phi}{f} = \Pi_t(\omega, k)$$

$$\Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots$$

- In order for there to be a tachyon, first term must vanish. i.e. no mass term
Particle Production

\[ \Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots \]

- First term is called magnetic mass
  - Unlike Debye mass, NOT a mass term!
- Vanishes for U(1) gauge fields
  - Solve gap equation : \( m = 0 \) consistent solution
  - Experimentally verified
Particle Production

$$\Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots$$

- Non-zero for non-abelian gauge fields
  - Results from quartic couplings of gauge bosons
  - Perturbation theory fails if it doesn’t exist
  - Existence confirmed via lattice

- Particle production occurs at finite T only for couplings to U(1) gauge fields
Particle Production

\[ w^2 - k^2 \pm \frac{k \dot{\phi}}{f} = \frac{m_D^2}{2} \frac{w}{k} \left[ \frac{1}{2} \left( 1 - \frac{w^2}{k^2} \right) \log \left( \frac{w + k}{w - k} \right) + \frac{w}{k} \right] \]

\[ \approx \frac{|i \pi w| m_D^2}{4k} \]

- Written in terms of gauge fields, this is literally Ohm’s law
  - 1-loop calculation of the conductivity
- Time scale associated with tachyon slower

\[ t \sim \frac{f \dot{\phi}}{\dot{\phi}} \left( \frac{fm_D}{\dot{\phi}} \right)^2 \]
During Inflation

<table>
<thead>
<tr>
<th>Values in GeV</th>
<th>$\Lambda$</th>
<th>$H$</th>
<th>$\epsilon$</th>
<th>$N_c$</th>
<th>$f$</th>
<th>$f'$</th>
<th>$\Lambda_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^5$</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^2$</td>
<td>$3 \times 10^6$</td>
<td>$10^9$</td>
<td>$1.5 \times 10^4$</td>
</tr>
</tbody>
</table>

$$
\mathcal{L} \supset (\Lambda^2 - \epsilon \phi) hh^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} (W \tilde{W} - B \tilde{B}) + \Lambda_c^4 \cos \frac{\phi}{f'}$$

- Start in the attractive slow roll solution
- Higgs mass is large and negative
During Inflation

\[ V(\phi) \]

\[ \phi \]
During Inflation

\[ \dot{\phi} \sim \frac{\epsilon \Lambda^2}{3H} + \delta(t) \]

- Dimensional analysis
  - Small high frequency bumps cannot disrupt slow roll
- There still exists a pseudo slow roll attractive solution

\[ \text{Values in GeV} \]

\[ 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \]

\[ 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \]
During Inflation

- Attractive slow roll solution exists when
- Slow roll velocity has enough kinetic energy to go over the bumps
- Time scale to go over a bump fast compared to Hubble so they can be averaged away
- Second weaker than first due to the requirement that minima exist

\[
\frac{\varepsilon \Lambda^2}{3H} \gtrsim \Lambda_c^2
\]

\[
H < \sqrt{\frac{\varepsilon \Lambda^2}{f'}}
\]
During Inflation

- Slow roll until Particle production kicks in

\[ 100 \text{ GeV} \sim \frac{\dot{\phi}}{f} \lesssim m_W \lesssim v \]

- Zero temperature Higgs mass is the correct measured value

- As gauge bosons are produced, finite temperature/density effects decrease their mass
During Inflation

\[ \mathcal{L} \supset (\Lambda^2 - \epsilon \phi) hh^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f} (W \tilde{W} - B \tilde{B}) + \Lambda_c^4 \cos \frac{\phi}{f'} \]

- Exponential production occurs until relaxion has lost enough kinetic energy that it is stuck
- \( T = 0 \)
  - EW gauge bosons produced
  - No couplings to photon
- \( T \neq 0 \)
  - B gauge boson being exponentially produced
Constraints

- Particle production happens much faster than Hubble
- Hubble $< v$
- Classical beats quantum
- Higgs mass does not change much in the time it takes for relaxion to get stuck
- SM fermion particle production from changing Higgs vev
- Higgs tracks minimum efficiently
- ...
During Inflation

<table>
<thead>
<tr>
<th>Values in GeV</th>
<th>$\Lambda$</th>
<th>$H$</th>
<th>$\epsilon$</th>
<th>$N_e$</th>
<th>$f$</th>
<th>$f'$</th>
<th>$\Lambda_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^5$</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^2$</td>
<td>$3 \times 10^6$</td>
<td>$10^9$</td>
<td>$1.5 \times 10^4$</td>
<td></td>
</tr>
</tbody>
</table>

- Can satisfy all constraints
- Field excursion sub Planckian
- Number of e-folds small
- Hubble is still small
After Inflation

- Generic initial conditions after inflation
  - Relaxion at a random point in the potential
  - Relaxion at rest (slow roll)
  - $T = 0$
- Energy in matter (inflaton) or dark radiation (inflaton decay product)
After Inflation

- Scanning of Higgs mass requires that relaxion does not get stuck in a minimum in the early universe
  - Exit inflation with pseudo-slow roll initial conditions
  - Coincidence of scales

\[
\begin{align*}
 f &\gg f_0^c \\
\text{Values in GeV} &\sim 10^4
\end{align*}
\]

TABLE III: A sample point for relaxation after inflation, which saturates many of the inequalities.

\[\begin{align*}
\text{FIG. 1: A plot of the potential for when Eq. 35 is satisfied. By eye, one can see that a generic starting point on the potential could result in traveling past all of the subsequent minima.}
\end{align*}\]
After Inflation

- After inflation, sitting at a random point in the potential
- $H \sim \epsilon$ then the relaxion is able to scan $O(1)$ of field space
- Only operational difference between during and after inflation is the speed

$$\dot{\phi} \sim \frac{\epsilon \Lambda^2}{H} \quad \dot{\phi} \sim \Lambda^2$$
After Inflation

- As this happens after inflation, completely insensitive to details of inflation
- High scale inflation allowed
- Arbitrary number of e-folds
- Sub-Planckian field excursions
- SM reheated by relaxion particle production

<table>
<thead>
<tr>
<th>Values in GeV</th>
<th>$\Lambda$</th>
<th>$\epsilon$</th>
<th>$f$</th>
<th>$f'$</th>
<th>$\Lambda_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$10^{-10}$</td>
<td>$10^6$</td>
<td>$10^{14}$</td>
<td>$10^3$</td>
<td></td>
</tr>
</tbody>
</table>
After Inflation

\[ V(\phi) \Lambda \]

\[ \langle h \rangle \sim 100 \text{ GeV} \quad \phi \]
• Higgs mass evolves to 100 GeV
• SM reheated by relaxion
After Inflation

- Higgs mass evolves to 100 GeV
- SM reheated by relaxion
- Higgs mass squared larger than \(-100^2\) GeV
- Relaxion stops right away
- Much lower reheat temperature
Three interpretations

• If Higgs vev 100 GeV, reheat temperature much larger than if Higgs vev is not 100 GeV
  • Put Baryogenesis, Dark Matter … in between these two temperatures
• Three interpretations of the same model!
Three interpretations

• Relaxion approach
  • Initial conditions after inflation result in a large number of initial conditions giving the correct Higgs vev

• Attractor solution

• Makes things better by an amount that depends on your bias towards initial conditions
Three interpretations

- Anthropic approach
- Reheating/Baryogenesis/Dark matter tied to Higgs vev
- Presence of matter necessary for any anthropic arguments: Thus Higgs vev is 100 GeV
Three interpretations

\[ P(\langle h \rangle = 100 \text{ GeV} | \text{matter existing}) = 1 \]

- Conditional approach
  - Observed fact: Baryogenesis/Dark matter/Reheating has occurred
  - Higgs vev being 100 GeV is not a surprise
- Initially two questions
  - Why is Higgs vev 100 GeV? Why is the universe reheated?
- After model, one question
  - Why is the universe reheated?
Conclusion

• Relaxion mechanism can be implemented completely separately from inflation
  • Solves several of the theoretically annoying issues
  • Super Planckian field excursions
  • Small Hubble
  • Huge amounts of inflation

• Reheating tied with obtaining correct Higgs vev

• Multiple conceptually different interpretations of the same model