Leptogenesis in Cosmological Relaxation with Particle Production

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Outline

• Introduction
• Relaxion models
• Leptogenesis during reheating in relaxion models
• Summary
Introduction

• Higgs was discovered in 2012. Particle contents seem to be complete.

• Unsolved: dark matter (DM), baryon asymmetry (BA), neutrino mass, etc

• Naturalness
Introduction

**Baryon asymmetric universe (BAU)**

Also known as matter asymmetry

- Why slightly more matter over antimatter?

- Observation

  From the acoustic peaks in the CMB spectrum (WMAP), assuming Friedmann universe

  \[ \frac{n_B - n_{\bar{B}}}{n_Y} \sim 10^{-10} \]

From http://www.triumf.ca/experiments
Introduction

Baryon asymmetric universe (BAU)

- 3 Sakharov’s conditions to get BAU from initially baryon symmetric universe:
  - (i) B-violation: Sphaleron
  - (ii) C, CP-violation: Chiral gauge theory, CP phase, etc
  - (iii) Departure from thermal equilibrium: e.g. strong 1st order electroweak (EW) phase transition (PT), out-of-eq decay of heavy particles, dynamics of topological defects

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]
Introduction

• Why the Higgs mass/VEV is so small (compared to Planck mass or other cutoff scale)?

• $m_h = O(100) \text{ GeV}$, $M_P = 10^{19} \text{ GeV}$
Introduction

Naturalness

- Solutions: (i) + symmetry, e.g. SUSY

Higgs mass: sensitive to large UV corrections

SUSY near EW scale solves hierarchy prob.

However, null results in the search of SUSY/other new physics @ LHC may imply that the underlying theory is decoupled at higher energies.

=> how to naturally obtain a little hierarchy b/t EW scale and this intermediate scale which represents SM EFT cutoff, w/o new phy. in b/t

•
Introduction

- Solutions: (i) + symmetry, e.g. SUSY; (ii) via dynamics: e.g. relaxion

- Relaxion: axion-like particle (ALP) whose periodic symmetry is softly and explicitly broken by a small coupling to Higgs (and also small self-coupling)

- Smallness of Higgs mass: cosmological evolution of relaxion
GKR’s relaxion models

- Relaxion potential: many minima + coupling to Higgs

\[ V(\phi) = (-\Lambda^2 + \epsilon\phi)|h|^2 + \Lambda^2 \epsilon\phi + \Lambda^4_c \cos \frac{\phi}{f'} \]

Try to realize baryogenesis in a relaxion model

EW unbroken -> EW broken

cutoff

Propto to Higgs vev \(<h>\)

small mass-dim parameter
GKR’s relaxion models

- **QCD relaxion**: $O(f')$ shift of the local min of the QCD part $\Rightarrow O(1)$ theta parameter! $\Rightarrow$ Sol: + additional mech. (e.g. a separate inflaton)

- **Non-QCD relaxion**: barrier height propto $<h>$ $\Rightarrow$ need condensate of new gauge group $\Rightarrow$ new physics near EW scale

- **Large amounts of inflation**
  - Tiny coupling $\sim 10^{-31}$ GeV
  - $\Rightarrow$ severe fine-tuning
  - Quantum information: $N \gtrsim M_p^2/H^2$ always leads to eternal inflation

- **Super-Planckian field excursions by relaxion**
  - Giddings and Strominger
  - A free periodic scalar w/ period f has gravitational instantons $S \sim M_P/f$
    - non-negligible NP effects if $f \geq M_P$
  - Whether this applies to interacting scalars: open question
HMT relaxion models

• Different initial conditions than the original relaxion models

• **Particle production** as a friction force

• Barrier height no longer depends on $<h>$

• **$v$-dependence** of the back reaction resides in the **EW gauge boson production**

• Sub-Planckian field excursions

• Allow **inflation dynamics** to be **decoupled from the relaxation**: can work before, during or after inflation

• **Avoid large e-folds**: $O(100)$

• Focus on **relaxation after inflation**: allow **high-scale inflation**, easier to tie to generating baryon asymmetry

Others using particle production: e.g. Choi, Kim and Sekiguchi 1611; Tangarife, Tobioka, Ubaldi and Volansky 1706; Fonseca, Morgante and Servant 1805

Sufficient Higgs production contradicts w/ Higgs tracking potential min
HMT relaxion models

- $T=0$ potential

\[ V(\phi) = (\Lambda^2 - \epsilon \phi)|h|^2 + \Lambda^2 \epsilon \phi + \Lambda^4 \cos \frac{\phi}{f^i} - \frac{\phi}{f}(B\tilde{B} - WW), \]

via hidden strong dynamics, indep of $\langle h \rangle$

linear combination not containing photon

- Initial: very large field value of relaxion, very negative Higgs mass-squared, relatively fast speed to pass through many minima

- Relaxion scans the Higgs mass-squared when rolling down the potential

  “quasi slow roll”

- Tachyonic sol. to EOM of Abelian gauge boson -> exponential production of Abelian gauge bosons

\[ A_\pm + \omega_A A_\pm = 0 \quad A_\pm(k) \propto e^{i\omega_A t} \quad \omega^2 = k^2 + m^2 \pm \frac{k^2}{f} \]

- Correct $\langle h \rangle$ $\iff$ $f \sim \frac{\phi_s}{v}$ (Right before being trapped)

  Relaxion-photon coupling induced from loops must be suppressed
  \[ f_\gamma \gtrsim \frac{vf}{H} \]

- Exponential production quickly drains the kinetic energy of relaxion and the relaxion gets trapped in the nearest local minimum
HMT relaxion models

• **Finite-T** case

• \( T > v \)

• System in a plasma state \( \Rightarrow \) Charged particles screen electric fields and slow the tachyon growth

• Tachyon modes always in high \( T \) modes

\[
|\Omega| \ll |k| \ll T.
\]

\[
\omega = i\Omega, \quad \Omega \sim \frac{|\phi|}{f^2 m_D^3}, \quad k \sim \dot{\phi}/f
\]

• Will higher loops remove the tachyon as \( T \) is parametrically larger than the size of the tachyon? No, for Abelian gauge field. Yes, for non-Abelian gauge field.

• Constraints + sub-Placnkian: cutoff \( \leq 10^5 \text{ GeV} \)
Leptogenesis

- Leptogenesis: relatively easy to realize
- Generate L asymmetry
- (B-L)-conserving sphaleron transitions convert L asymmetry to B asymmetry
- The relatively low reheating temperatures in HMT relaxation models restrict possible scenarios if we don’t want to reintroduce new physics below the cutoff.
Leptogenesis

- **Reheating-era leptogenesis**: Hamada, Kawana, 1510.05186

- L asymmetry is produced not by the decay of a heavy particle, but by the scattering b/t SM particles (via higher dimensional LNV operators)

\[
\mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \frac{c^{(5)}}{\Lambda_5} \mathcal{O}^{(5)} + \sum_i \frac{c^{(6)}_i}{\Lambda_{6,i}^2} \mathcal{O}^{(6)} + \sum_i \frac{c^{(7)}_i}{\Lambda_{7,i}^3} \mathcal{O}^{(7)} + \ldots
\]

- Also have L-conserving dim-6 operators with complex coefficients

\[
\mathcal{O}^{(6)} = (L_a \gamma^\mu L_b) (\bar{e}_c \gamma_\mu e_d)
\]

- **CPV**: interference b/t tree-level and 1-loop LNV scatterings

- One of the scattering leptons is **out of equilibrium** (OOE), e.g. right after from inflaton decay

- **B asymmetry** is obtained via sphaleron transitions

\[
\frac{n_B}{s} \sim \frac{28}{79} \frac{n_L}{s} \sim \mathcal{O}(10^{-10})
\]

All 3 Sakharov’s conditions are satisfied!
Leptogenesis

- **Reheating-era leptogenesis**: Hamada, Kawana, 1510.05186

- L asymmetry is produced not by the decay of a heavy particle, but by the scattering b/t SM particles (via higher dimensional LNV operators)

\[ \mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \frac{c^{(5)}}{\Lambda_5} \mathcal{O}^{(5)} + \sum_i \frac{c^{(6)}_i}{\Lambda^2_{6,i}} \mathcal{O}^{(6)}_i + \sum_i \frac{c^{(7)}_i}{\Lambda^3_{7,i}} \mathcal{O}^{(7)}_i + \ldots \]

- Lowest LNV operator: dim-5, Weinberg operator

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_1} \lambda_{1,ij} HH \bar{L}_j L_i + \frac{1}{\Lambda_2} \lambda_{2,ijkl} (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma_\mu L_l) + \lambda_{1,ij} \frac{\nu^2}{2\Lambda_1} (\bar{\nu}e + \bar{\nu}\nu^c), \]

\[ + \frac{1}{\Lambda^3_3} \lambda_{3,ijkl} (\bar{L}_i \gamma^\mu L_j)(\bar{E}_k \gamma_\mu E_l) + h.c. \]

LNV interaction rate is suppressed by the operator scale.

Light neutrino mass requires \( O(10^{14}) \) GeV scale of dim-5 LNV operator.

The contribution to the baryon asymmetry from this operator is negligible.
Leptogenesis

• **Reheating-era leptogenesis**: Hamada, Kawana, 1510.05186

• L asymmetry is produced not by the decay of a heavy particle, but by the **scattering b/t SM particles (via higher dimensional LNV operators)**

\[ \mathcal{L}_{SMEFT} \supset \mathcal{L}_\text{SM} + \frac{c^{(5)}}{\Lambda_5} \mathcal{O}^{(5)} + \sum_i \frac{c^{(6)}_i}{\Lambda^{2,6}_i} \mathcal{O}^{(6)}_i + \sum_i \frac{c^{(7)}_i}{\Lambda^{3,7}_i} \mathcal{O}^{(7)}_i + \ldots \]

• Focus on dim-7 LNV operators

• Example:

\[ \mathcal{O}^{(7)} = L_h \bar{e}^c \bar{u}^d c^e \]

\[ \mathcal{O}^{(6)} = (L_a \gamma^\mu L_b) (\bar{e}_c \gamma_\mu e_d) \]

with complex coefficient \( c^{(6)}_{abcd} \) and scale \( \Lambda_6 \).
Leptogenesis

• Constraints

• Loop-induced light neutrino mass < 0.1 eV
  \[ \frac{y_e^c y_d y_u}{(16\pi)^2} \frac{v^2}{\Lambda} \]
  for the operator we’re considering

• Neutrinoless double beta decay
  \[ T_{1/2}^{Ge} \geq 5.3 \times 10^{25} \text{ y} \]

• For the example we’re considering, such constraints are weak (negligible). Other operators have stricter bounds.
Leptogenesis

- Efficiency factor for the asymmetry in the scattering

\[ \epsilon_a = \frac{\sigma(L_a e_a \rightarrow h\bar{u}d) - \sigma(L_a \bar{e}_a \rightarrow h\bar{u}d)}{\sigma(L_a e_a \rightarrow h\bar{u}d) + \sigma(L_a \bar{e}_a \rightarrow h\bar{u}d)} \]

\[ \mathcal{M}(L_a \bar{e}_a \rightarrow h\bar{u}d) \propto \frac{c_a^{(7)}}{\Lambda_7} + \sum_b \frac{c_b^{(7)}}{\Lambda_7} \frac{2c_{ab}^{(6)}}{\Lambda_6} I. \]

\[ \text{Im} I = \frac{p^2}{(8\pi)} \]

Loop function

Square of 4-momentum sum of initial leptons

\[ \epsilon_a \simeq \frac{4}{\Lambda_6^2} \text{Im} I \sum_b \frac{c_b^{(7)} \text{Im} c_{ab}^{(6)}}{c_a^{(7)}} \]
Leptogenesis

\[ \epsilon_a \approx \frac{4}{\Lambda_6^2} \text{Im}I \sum_b \frac{c_b^{(7)} \text{Im}c_{ab}^{(6)}}{c_a^{(7)}} \]

where \( \text{Im}I = p^2/(8\pi) \), and \( p^2 \) is the square of the four-momentum sum of the initial state leptons. After perturbative decay of the relaxion with mass \( m_\phi \), and before reaching a thermal distribution, the out-of-equilibrium leptons will have energies distributed from \( m_\phi/2 \) to \( T \) as they are upscattered by the thermal bath, corresponding to \( 6m_\phi T \lesssim p^2 \lesssim T^2 \). Since the dominant contribution to the asymmetry will come from the higher energy non-thermal leptons we mainly use \( p_{\text{max}}^2 \approx T^2 \) as an upper bound in our estimates, while also showing the \( p_{\text{min}}^2 \approx 6m_\phi T \) points as a conservative lower bound case.

Inflaton -> hidden sector: Need some mech. to decrease the hidden energy density (via a faster scaling) s.t. eventually the asy won’t be diluted
Leptogenesis

- Sources of OOE leptons

- Perturbative decay of relaxion after it has been trapped

\[ m_\phi > H \]

Relaxion oscillation in its local min: redshift as non-relativistic matter

\[ n_\phi \sim \Lambda^4_c / m_\phi. \]

Pert. decay rate

\[ \Gamma_D \sim m_\phi^3 / f_L^2. \]

To avoid intro. coupling to Abelian gauge field and to evade astro. bound on electron coupling @ tree

\[ J^{5\mu} = J^{5\mu}_\phi - J^{5\mu}_T \]

In the thermal bath with temperature \( T >> v \), **condensate scattering with the thermal bath** ("Landau damp") is the dominate way of dissipating energy from the oscillating field. The corresponding rate is

\[ \Gamma_S \sim T^2 m_\phi / f_L^2. \]

Have included a suppression factor \( m_\phi / T \) due to Bose enhancement

- The available number density for producing OOE leptons

\[ n_{\phi}^{\text{min.}} \sim \frac{\Gamma_D}{\Gamma_S} n_\phi \sim \left( \frac{m_\phi}{T} \right)^2 n_\phi \]

Loop induced electron coupling has to be bounded by astro. constraints.
Leptogenesis

• Sources of OOE leptons

• Lepton pair production from the classically rolling relaxion

Classical production $\frac{\partial \mu \phi}{f_L} J^{\mu}$

Although the occupation number of fermions can’t be exponentially enhanced due to Pauli blocking, the generation of fermions from a rolling classical field has been shown to give large effects.

Expect this to give a large contribution to OOE leptons whose typical energy $\sim \frac{\phi_0}{f_F} \lesssim v$.

• Effective number density for OOE leptons $n_\phi'$ should include both contributions. For simplicity and to get a preliminary result, allow the effective number density to range in

$$\left( \frac{m_\phi}{T} \right)^2 \lesssim \frac{n_\phi'}{n_\phi} \lesssim 1$$
Leptogenesis

- Solve Boltzmann eq. (w/ washout) \( \Rightarrow \) Lepton asymmetry

\[
\frac{n_L}{s} \approx \frac{n'_\phi}{s} \sum_a 2\epsilon_a B_a \frac{\Gamma_{\text{LNV}a}}{\Gamma_{\text{th.}}}
\]

LNV interaction rate

Thermal scattering rate

Fraction of the effective number density converted into OOE lepton pairs

\[
\Gamma_{\text{LNV}a} \approx \frac{3\xi(3)}{512\pi^5} p^4 \left( \frac{c^{(7)}_a}{\Lambda^3} \right)^2 T^3 \quad , \quad \Gamma_{\text{th.}} \approx \alpha_2 T
\]
Leptogenesis

• Benchmark points w/ OOE leptons from relaxion perturbative decays

## Table I

<table>
<thead>
<tr>
<th>$\Lambda, \Lambda_c, \Lambda_{6,7}, T$</th>
<th>$f'$</th>
<th>$m_\phi$</th>
<th>$f$</th>
<th>$f_\nu$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{max}}^2$</td>
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<td>$10^8$</td>
<td>$100$</td>
<td>$10^7$</td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td>$p_{\text{min}}^2$</td>
<td>$10^5$</td>
<td>$5 \times 10^6$</td>
<td>$2 \times 10^3$</td>
<td>$10^9$</td>
<td>$5 \times 10^7$</td>
</tr>
</tbody>
</table>

A benchmark point in GeV for our relaxion leptogenesis mechanism in which the baryon asymmetry is generated entirely from the relaxion decaying perturbatively into leptons with $n'_\phi = n_{\phi,\text{min}}$ and branching ratio $B = 10^{-2}(1)$ for the upper (lower) row.

\[
\frac{n_B}{s}\bigg|_{\text{pert.}} \sim 10^{-10} \left( \frac{B}{10^{-2}} \right) \left( \frac{T}{10^5 \text{ GeV}} \right)^3 \left( \frac{m_\phi}{100 \text{ GeV}} \right) \\
\times \left( \frac{\Lambda_c}{10^5 \text{ GeV}} \right)^4 \left( \frac{10^5 \text{ GeV}}{\Lambda_7} \right)^6 \left( \frac{10^5 \text{ GeV}}{\Lambda_6} \right)^2
\]

\[
p_{\text{min}}^2 \approx 6m_\phi T,
\]

\[
p_{\text{max}}^2 \approx T^2
\]

\[
n_\phi \approx \Lambda_c^4/m_\phi
\]

\[
n_{\phi,\text{min}} \approx \frac{\Gamma_D}{\Gamma_S} n_\phi \approx \left( \frac{m_\phi}{T} \right)^2 n_\phi
\]
Leptogenesis

- Benchmark points w/ OOE leptons from relaxion perturbative decays and other source

<table>
<thead>
<tr>
<th>$\Lambda, \Lambda_c, \Lambda_6, T$</th>
<th>$\Lambda_7$</th>
<th>$f'$</th>
<th>$m_{\Phi}$</th>
<th>$f, f_\nu$</th>
<th>$g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{max}}^2$</td>
<td>$10^5$</td>
<td>$10^7$</td>
<td>$5 \times 10^{11}$</td>
<td>0.02</td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td>$p_{\text{min}}^2$</td>
<td>$5 \times 10^6$</td>
<td>$10^7$</td>
<td>$4 \times 10^9$</td>
<td>$6 \times 10^3$</td>
<td>$2 \times 10^{11}$</td>
</tr>
</tbody>
</table>

TABLE II. A benchmark point in GeV for our relaxion leptogenesis mechanism in which the baryon asymmetry is generated from leptons produced by the relaxion with $n'_{\Phi} = n_{\Phi}$ and branching ratio $\mathcal{B} = 1$.

$$n_{\Phi} \sim \Lambda_c^4 / m_{\Phi}.$$
Summary

• Proposed a model of cosmological relaxation of the EW scale w/ particle production that generates the BAU while reheating the universe after inflation.

• EFT cutoff \(10^5\) GeV (higher when slightly relaxing sub-Planckian condi.)

• The model allows for high-scale inflation, has no extremely small parameters, introduces no new physics below the cutoff, and achieves leptogenesis @ low reheating temperatures.

• 2 approaches combined to understand the smallness of EW scale: a dynamic selection and a censorship approach.

• Used OOE leptons: from relaxion pert. decay and classical rolling.

  Details of thermalization needs further investigation

• Lack of new phys @ EW scale to solve the hierarchy prob. -> Sol. may be postponed to higher scales. Worthwhile to explore ways of obtaining a hierarchy.
Thank you!
Backup
Introduction

Baryon asymmetric universe (BAU)

• 3 Sakharov’s [Sakharov, 1967] conditions to get BAU from initially baryon symmetric universe:

• (i) B-violation: Sphaleron

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]

- Spatially localized, unstable finite energy classical sol
- Conserve B-L, but break B+L
- Saddle points, or max
- (convert baryon to anti-lepton)
- \[ T \sim O(100) \text{ GeV} \]

Figure from 0910.0464
Introduction

3 Sakharov’s conditions to get BAU from initially baryon symmetric universe:

(i) B-violation: Sphaleron

(ii) C, CP-violation:

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]
Introduction

Baryon asymmetric universe (BAU)

- 3 Sakharov’s conditions to get BAU from initially baryon symmetric universe:
  
  (i) B-violation: Sphaleron
  
  (ii) C, CP-violation: Chiral gauge theory, CP phase, etc

  Sometimes can be studied in a separate sector

  e.g. in SM, the CKM matrix is a course of CPV: complexity of some elements

  But CPV in SM is too small to provide sufficient baryon asymmetry

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]
Introduction

Baryon asymmetric universe (BAU)

• (iii) Departure from thermal equilibrium: e.g. strong 1st order electroweak (EW) phase transition (PT), out-of-eq decay of heavy particles, dynamics of topological defects

• 1st order EWPT: discrete change of Higgs VEV at PT

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]

• Whether SM has strongly 1st order EWPT is an open question.
Baryon asymmetric universe (BAU)

• (iii) Departure from thermal equilibrium: e.g. strong 1st order electroweak (EW) phase transition (PT), out-of-eq decay of heavy particles, dynamics of topological defects

\[ \frac{n_B}{s} \sim 8.6 \times 10^{-11} \]

need extra pieces
Monodromy induced potential

\[ F_4 = dC_3 \text{ in 4-dimensional spacetime} \]

\[ \mathcal{L} = -\frac{1}{2}(da)^2 - V_{KS}(a) - V_{NP}(a), \]

\[ V_{KS}(a) \equiv \frac{1}{2} F_4 \wedge \ast_4 F_4 - m F_4 a \Rightarrow V_{KS}(a) = \frac{1}{2}(f_0 + ma)^2. \]

\[ \ast_4 F_4 = f_0 + ma, \quad f_0 = n \Lambda_k^2, \quad n \in \mathbb{Z}. \]

Dirac quantization of a gauge field

Consistency condi.

Thus the axion potential \( V_{KS}(a) \) is multi-branched, with each branch (namely, a membrane) labelled by a value of \( f_0 \). When crossing a membrane, \( f_0 \) shifts by an integer times the charge of the membrane. Therefore, starting from a specific branch, the axion can go up in the potential away from its minimum and travel a distance \( \Delta a \) in its field space greater than the intrinsic periodicity \( f \).
GKR’s relaxion models

Constraints

• Hubble friction drives slow-roll

• Slow-roll is long enough s.t. the relaxion can scan the its whole field space

• During inflation, total vacuum energy > vacuum energy change along the relaxion potential

• Barriers are within the Hubble sphere s.t. barriers form in the first place

• Classical rolling beats quantum spreading
GKR’s relaxion models

Problems

- QCD relaxion: $O(f')$ shift of the local min of the QCD part
  $\Rightarrow O(1)$ theta parameter!
GKR's relaxion models

- Sol: e.g. + separate inflaton, or consider non-QCD relaxion

During inflation, + inflaton $\sigma$:

\[ V(\phi) \sim k \sigma^2 \phi + \epsilon \phi^4 + \ldots \]

$\sigma \approx \text{const. at least for most of inflation}$

$\gamma \approx k \sigma^2$

$\theta = \frac{\Delta \sigma^2}{k \sigma \phi / e} = \frac{\epsilon^2}{g^2}$

$\theta \sim 10^{-10}$ to be consistent w/ strong CP.

Stopping condi. (evaluated @ $\phi$ not far from $\lambda^2 / e$):

\[ \frac{\theta^2 \Delta \sigma^2}{\epsilon} \sim \frac{\Delta \phi^2}{f} \Rightarrow \frac{\epsilon \lambda^2}{\theta} \sim \frac{\Delta \phi^2}{f} \]

After inflation, $\sigma$ drops to 0:

\[ V(\phi) \sim \epsilon \phi^2 + \ldots \]

The slope of $\phi$ potential drops by a factor of

\[ \frac{\epsilon \lambda^2}{\gamma \phi / e} = \frac{\epsilon^2}{g^2} = \theta \]
GKR’s relaxion models

- Non QCD relaxion: barrier height propto $\langle h \rangle$ -> need condensate of new gauge group -> new physics near EW scale
GKR’s relaxion models

Other problems

- Large amounts of inflation
  
  - severe fine-tuning

  Additionally, argument from Quantum information:

  \[ N \gtrsim \frac{M_P^2}{H^2} \] always leads to eternal inflation

- Super-Planckian field excursions by relaxion

  \[ \text{Giddings and Strominger} \]

  A free periodic scalar w/ period f has gravitational instantons \( S \sim M_P/f \)

  
  non-negligible NP effects if \( f \geq M_P \)

  Whether this applies to interacting scalars: open question

Tiny coupling \( \sim 10^{-31} \) GeV
HMT relaxion models

- Finite T: $\langle h \rangle = 0$, time scale asso. w/ tachyon longer due to thermal plasma effects

  $$\Omega \sim \left( \frac{|\phi|}{f} \right)^3 \frac{\phi}{m_D^2}.$$  

  Process of losing energy: dominated by IR

  \[ \text{the time it takes for } \dot{\phi} \text{ to fall below } \phi_c \]  

  \[ t \sim \frac{T^2 f^3}{\phi_c^3} \]

- Hook’s relaxion: starting at $T = 0$ or very low $T (<< v)$ s.t. it is scanning the vac, not thermal Higgs mass
HMT relaxion models

- **Initial:** \( \phi_0 \) s.t. Higgs has a very large negative mass-squared

\[
V(\phi) = (\Lambda^2 - \epsilon \phi)|\phi|^2 + \Lambda^2 \epsilon \phi + \Lambda_c^4 \cos \frac{\phi}{f'} - \frac{\phi}{f'} (B\tilde{B} - W\tilde{W}).
\]

Or start from rest, if exists 10% coincidence in the scales of the slope and periodic potential

assume that the Higgs is at its minimum with a vev \( \langle \hat{h} \rangle \) and that the temperature of the universe is negligible

- Setting nonzero velocity after exiting high-scale inflation: 1) **inflaton reheats into hidden sector** which the relaxion couples to could temporarily act as a background source in its EOM; 2) inflaton-relaxion coupling \( \kappa\sigma\phi \) acts as a faster effective slow-roll slope during inflation s.t. it exits w/. \( \dot{\phi} \sim \kappa\sigma/H_I \).
HMT relaxion models

- **Initial**: \( \phi_0 \) s.t. Higgs has a very large negative mass-squared

\[ \phi_0 \gtrsim \frac{\Lambda^2}{\Lambda_c} \]

- Or start from rest, if exists 10% coincidence in the scales of the slope and periodic potential

Assume that the Higgs is at its minimum with a vev \( \langle h \rangle \) and that the temperature of the universe is negligible

Very large \( <h> \) s.t. tachyonic condi. not satisfied

- As relaxion rolls down the potential, starting from one pt., tachyonic condi. is satisfied and particle exponential productions starts.

- Correct \( <h> \) \( \iff \) \( f \sim \frac{\dot{\phi}_s}{v} \) (Right before being trapped)

\[ \dot{\phi} \gtrsim f m_A \]

No or suppressed relaxion-photon coupling

- The produced gauge bosons quickly reach thermal eq. really satisfied once the cutoff \( \gg v \)

\[ m_A \sim <h> \]
HMT relaxion models

- Thermal back reaction is critical for the relaxion to lose all its kinetic energy once the exponential production starts.

- Higgs receives positive contribution to its mass-squared due to thermal and finite density effects.

- As $\langle h \rangle$ decreases, tachyonic conditions are satisfied to a better and better degree.

- Eventually, energy density in the gauge field $\sim v^4$, Higgs mass-squared turns positive $\rightarrow$ always exist tachyon sol. for massless gauge boson.

- Once the relaxion loses all its kinetic energy, it gets trapped in a local min of the periodic potential.
HMT relaxion models

Constrains

- Relaxation energy is not greater than the vac energy
- Relaxation can pass through many minima
- The scan of Higgs mass has enough precision
- The energy loss due to exponential production is faster than the energy gain from the linear slope
- Relaxation does not overshoot the correct Higgs mass
- Relaxation abundance from thermal and non-thermal production will not over close the universe

\[ V(\phi) = (\Lambda^2 - \epsilon \phi)|h|^2 + \Lambda^2 \epsilon \phi + \Lambda_4^4 \cos \frac{\phi}{f'} - \frac{\phi}{f} (B\tilde{B} - W\tilde{W}). \]

\[ H_{MP} \gtrsim \Lambda^4. \]

\[ \epsilon f' \Lambda^2 \lesssim \Lambda_4^4. \]

\[ \epsilon f' < v^2 \]

\[ \Lambda_4^8 > \frac{\epsilon \Lambda^2}{v^3} \phi_s^4 \sim \epsilon \Lambda^2 f^4 v. \]

\[ \frac{\epsilon f^3 m_D^2}{v \Lambda_4^4} \lesssim v \Rightarrow \epsilon f^4 \sim v \Lambda_4^4 \]

\[ m_D \sim g'T \sim \sqrt{\phi} \sim \sqrt{fv}. \]

For high reheating temperature \( T_{reh} \sim \Lambda \) above the EW scale, we must also ensure that the thermal production of the relaxion via scattering with weak gauge bosons is not too much. This can be done, e.g., by imposing that the fermion current coupled to the relaxion does not reintroduce a coupling to \( B\tilde{B} \quad W\tilde{W} \).
HMT relaxion models

Constrains

- The particle production from a changing $\langle h \rangle$ is negligible, and thermal effects on the Higgs mass are small. Thermalization of the particles produced by the relaxion is fast.

\[ V(\phi) = (\Lambda^2 - \epsilon \phi)|h|^2 + \Lambda^2 \epsilon \phi + \Lambda_c^4 \cos \frac{\phi}{f} - \frac{\phi}{f}(B\tilde{B} - W\tilde{W}). \]

- The hidden sector is not to equilibrate w/ the visible sector s.t. barriers formed by hidden strong dynamics will not be erased when the visible sector is in thermal bath

\[ \frac{\dot{\phi}^5/2}{f^2 f^2} \lesssim H. \]

- Photons won’t be non-negligibly produced

- Some conservative constraints:

\[ \Lambda \gg \Lambda_c, \quad \dot{\phi}_s \sim f v \lesssim \Lambda^2. \]
HMT relaxion models

Constrains

- The above constraints + sub-Planckian field excursion ->
  Upper bound on the cutoff

\[ \Lambda \lesssim (M_p v^5)^{1/6} \sim 5 \times 10^4 \text{ GeV}. \]

This bound can be relaxed (e.g. 10^8 GeV) if slightly super-Planckian field excursion of relaxion is allowed.
Leptogenesis

- Standard leptogenesis: via out-of-equilibrium decay of the lightest RH neutrino at least $10^9$ GeV, much above our EFT cutoff $10^5$ GeV $\rightarrow$ require reheating above the cutoff or adding new physics below it.

- The relatively low reheating temperatures in Hook’s relaxion models restrict possible scenarios if we don’t want to reintroduce new physics below the cutoff.
Leptogenesis

• Via other dim-7 LNV operators

• Same mech., different parameter space

• The particular choice of an operator may be theoretically motivated. e.g. focusing operators w/ 2 leptons and no quarks + requiring LNV operators to induce neutrino-less double beta decay at lowest order -> dim of the LNV is correlated w/ the chiralities of electron pairs in neutrino-less double beta decay: LL <-> dim-5; LR <-> dim-7; RR <-> dim-9

\[ \mathcal{O}^{(7)} = \bar{L} \gamma^{\mu} e^{\nu} h (h^\dagger D_\mu \tilde{h}) \]

Neutrinoless double beta decay
1-loop induced light neutrino mass

\[ \Lambda_7 \gtrsim 10^5 \text{ GeV for } c^{(7)} \sim \mathcal{O}(1) \]
\[ \Lambda_7 \gtrsim 10^7 \text{ GeV} \]

Larger phase space suppression in LNV rate

Need to raise \( T_{\text{reh}} \) (cutoff) to \( 10^6 \text{ GeV} \) (slightly super-Planckian)

\[ \text{del Aguila, Aparici, Bhattacharya, Santamaria, Wudka, 1204.5986} \]
Baryogenesis in relaxion models

- Electroweak baryogenesis (EWBG)
- Relaxion-Higgs coupling is too small to provide strong 1st order EWPT
- Need to add additional particles with sizable couplings with Higgs
- The relaxation and EWBG are sort of decoupled
Baryogenesis in relaxion models

- Really impossible for the relaxion to be involved more in a EWBG model?
- One possibility: clockwork
Baryogenesis in relaxion models

- Other baryogenesis (BG)? Spontaneous BG, decay BG…
Baryogenesis in relaxion models

- **Spontaneous BG (SBG):** can happen when CPT is violated in the early, evolving universe, e.g. via a classically moving scalar (*thermion*) derivatively coupled to a current

  \[ \mathcal{L}_\varphi \equiv -\frac{1}{f_0} \partial_\mu \varphi j_B^\mu, \quad n_B = j_B^0, \quad \mu = \langle \varphi \rangle / f_0 \]

  Effective chemical potential as a shift to the energy
  -> particles/antiparticles have different number densities when in eq

  When temperature drops below the decoupling temperature,
  B violating processes fall out of eq, and baryon number density gets frozen.

- Another possibility of SBG: baryon number density oscillation after decoupling

  \[ \dot{n}_B = -\Gamma f_0 \dot{\varphi}, \]
Baryogenesis in relaxion models

- SBG: identify relaxion as thermion?
  - No

- Relaxion has no classical motion after being trapped

- Baryon number density oscillation: relaxion (slope) constraint inconsistent with baryon isocurvature bound

- $\rightarrow$ SBG can’t be realized in a minimal relaxion model
Baryogenesis in relaxion models

- **Decay BG**: out-of-eq decay of heavy particle $X$ in expanding universe

- If at some high temperature ($> M_X$), $X$'s are so weakly coupled that they can’t catch up the expansion of the universe, $X$’s remain in their initial abundance and decouple from the thermal bath.

In eq.

\[
\begin{align*}
    n_X &= n_X \simeq n_\gamma \quad \text{for} \quad T \gtrsim M_X, \\
    n_X &= n_X \simeq (M_X T)^{3/2} e^{-M_X / T} \ll n_\gamma \quad \text{for} \quad T \lesssim M_X
\end{align*}
\]
Baryogenesis in relaxion models

• Realizing decay BG in a Hook’s model: *relaxion provides the thermal bath for the visible sector*, with a sufficiently high *reheating temperature ~ cutoff*; inflaton reheats the hidden sector

• Decay BG usu. requires very heavy states

• Examples of decay BG: GUT BG, leptogenesis, etc

• GUT BG: heavy particle at least $10^{10}$ GeV (scalar) or $10^{15}$ GeV (gauge boson)

• Standard leptogenesis: the lightest RH neutrino at least $10^9$ GeV

  Too high for a relaxion model with a low cutoff

\[ \Lambda \lesssim (M_p v^5)^{1/6} \sim 5 \times 10^4 \text{ GeV} \]
Baryogenesis in relaxion models

- Realizing decay BG in a Hook’s model
- Sol.: (i) removing sub-Planckian constraint; (ii) low-scale leptogenesis, e.g. resonant leptogenesis
Baryogenesis in relaxion models

- Removing sub-Planckian constraint:
- Hook: want to avoid possible non-negligible non-perturbative gravitational instanton effects for super-Planckian field excursion
  
  Such large NP effects occur in free periodic scalar case. Same story in the interacting scalar case?

- If super-Planckian field excursions allowed, the upper bound of cutoff can be relaxed to $10^9$ GeV (w/ large e-folds) or $10^6$ GeV (with at least $O(10^8)$ e-folds)
  
  still satisfies $N_e < M_P^2/H^2$ and may not lead to eternal inflation.
Baryogenesis in relaxion models

- Resonant leptogenesis: When the lightest RH neutrinos have near degenerate masses, the asymmetry from self-energy diagrams dominates and can be enhanced. Lower bounds on the lightest RH neutrino mass can be significantly lowered (to TeV)

$$m_{N_i} - m_{N_j} \sim \frac{\Gamma_{N_{ij}}}{2} , \quad \frac{|\text{Im} (h^{\nu \nu})_{ij}|}{(h^{\nu \nu})_{ii} (h^{\nu \nu})_{jj}} \sim 1 ,$$

Enhancement condi
Cubic terms from periodic potential

Hook's: \( \Lambda^4 \) indep of \( h \)

GRK's: \( \Lambda^4 \sim h^n v^{4-n} \quad 0 \leq n \leq 3 \)

\[ e.g. \quad h^2 v^2 \cos \frac{\phi}{f} \gg h^2 v^2 \left( \frac{\phi}{f} \right)^2 \]

\[ \frac{1}{16\pi^2} \left( \frac{v^3}{f^2} \right)^3 \frac{1}{\Lambda^2} \]

\[ m_\phi \sim \Lambda^2 / f' \sim v^2 / f' \]

\[ f' > 10^9 \text{ GeV} \]

\[ \Lambda \lesssim 0(10^9) \text{ GeV} \]
Other LNV operators

- LNV dim-6 operators involve quarks and violate baryon number by +, - one unit; they conserve B-L and don’t contribute to neutrino-less double beta decay.

- LNV dim-7 operators involving two derivatives do contribute to neutrino-less double beta decay, but also necessarily generate tree-level LNV dim-5 operator. The dim-5 LNV operator will dominate over the dim-7 one in all processes we are interested in.

\[
\begin{align*}
O^{(7-I)} &= (D_\mu \ell_L \phi)(\phi^\dagger D^\mu \tilde{\ell}_L) \\
O^{(7-II)} &= (\ell_L D_\mu \tilde{\ell}_L)(\phi^\dagger D^\mu \tilde{\phi}) \\
O^{(7-III)} &= (\bar{\ell}_L \tilde{\phi}) \partial_\mu (\phi^\dagger D^\mu \tilde{\ell}_L)
\end{align*}
\]

•
Tree-level dim-7 LNV from renormalizable theory

• Many renormalizable models can give rise to tree-level dim-7 LNV (no tree-level dim-5 LNV). They are classified in 1204.5986. Some external Higgs legs may be replaced with non-SM doublet scalars. In these models, the constraints on the LNV operator scale from neutrino-less double beta decay and light neutrino mass can be relaxed.

• One example

<table>
<thead>
<tr>
<th>$SU(2)_L$</th>
<th>$L_{La}$</th>
<th>$L_{Ra}$</th>
<th>$\chi$</th>
<th>$\phi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U(1)_Y$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>$-\frac{1}{2}$</td>
<td>$-\frac{1}{2}$</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
</tr>
</tbody>
</table>

- $e_R$ $L^{(-)}$ $L^{(0)}$ $\chi^{(0)}$
- $W$
- $\phi^{(0)}$
- $\phi^{(0)}$
- $\chi^{(0)}$

- $\nu_L$ $e_R$ $L^{(-)}$ $\nu_L$
- $\langle \phi^{(0)} \rangle$
- $\phi^{(-)}$
- $\chi^{(-)}$
- $\langle \phi^{(0)} \rangle$
# Baryogenesis in relaxion models

<table>
<thead>
<tr>
<th>Baryogenesis</th>
<th>Work in the minimal model?</th>
<th>Connection to relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>X</td>
<td>N/A</td>
</tr>
<tr>
<td>Spontaneous</td>
<td>X</td>
<td>N/A</td>
</tr>
<tr>
<td>Decay</td>
<td>TeV-scale resonant leptogenesis</td>
<td>Weak</td>
</tr>
<tr>
<td>Reheating-era leptogenesis</td>
<td>V</td>
<td>Strong</td>
</tr>
</tbody>
</table>
Connecting B to L

• @ high temperature (> EW scale): in a weakly coupled plasma w/ temperature T and volume V, a chemical potential can be assigned to each of the quark, lepton and Higgs fields.

• Thermodynamics

\[
Z(\mu, T, V) = \text{Tr}[e^{-\beta(H - \Sigma_i \mu_i Q_i)}] \\
\Omega(\mu, T) = -\frac{T}{V} \ln Z(\mu, T, V)
\]

\[
n_i - \overline{n}_i = -\frac{\partial \Omega(\mu, T)}{\partial \mu_i}
\]

\[
n_i - \overline{n}_i = \frac{1}{6} g T^3 \left\{ \beta \mu_i + \mathcal{O}((\beta \mu_i)^3), \right. \\
\left. 2\beta \mu_i + \mathcal{O}((\beta \mu_i)^3), \quad \text{fermions} \right. \\
\left. \beta \mu_i \ll 1 \right. \\
\left. \text{bosons} \right.
\]

• In the plasma, quarks, leptons and Higgs interact via gauge and Yukawa couplings. In additions, there are N.P sphaleron processes. All these processes give rise to constraints among chemical potentials in thermal equilibrium.
Connecting B to L

(1) The effective 12-fermion interactions $O_{B+L}$ induced by the sphalerons give rise to the following relation,

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

(2) The SU(3) QCD instanton processes lead to interactions between LH and RH quarks. These interactions are described by the operator, $\prod_i (q_L^i q_L^i u_{R_i}^c d_{R_i}^c)$. When in equilibrium, they lead to,

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0$$

(3) Total hypercharge of the plasma has to vanish at all temperatures. This gives,

$$\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f} \mu_H) = 0$$
Connecting B to L

(4) The Yukawa interactions yield the following relations among chemical potential of the LH and RH fermions,

\[ \mu_{q_t} - \mu_H - \mu_{d_j} = 0, \]
\[ \mu_{q_t} + \mu_H - \mu_{u_j} = 0, \]
\[ \mu_{\ell_t} - \mu_H - \mu_{e_j} = 0, \]

\[ B = \sum_i (2\mu_{q_t} + \mu_{u_t} + \mu_{d_t}) \]
\[ L = \sum_i L_i, \quad L_i = 2\mu_{\ell_t} + \mu_{e_t}. \]
Connecting B to L

- Assume all Yukawa interactions are in equilibrium and equilibrium exists among different generations

- Together w/ sphaleron, hyper charge constrains

\[
\begin{align*}
\mu_e &= \frac{2N_f + 3}{6N_f + 3} \mu_\ell, \\
\mu_d &= -\frac{6N_f + 1}{6N_f + 3} \mu_\ell, \\
\mu_u &= \frac{2N_f - 1}{6N_f + 3} \mu_\ell \\
\mu_q &= -\frac{1}{3} \mu_\ell, \\
\mu_H &= \frac{4N_f}{6N_f + 3} \mu_\ell.
\end{align*}
\]

\[
B = -\frac{4}{3} N_f \mu_\ell, \\
L = \frac{14N_f^2 + 9N_f}{6N_f + 3} \mu_\ell.
\]