Leptogenesis in Cosmological Relaxation with Particle Production

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1804.06599[hep-ph], w/ Minho Son and Tevong You

COSMO18

Introduction

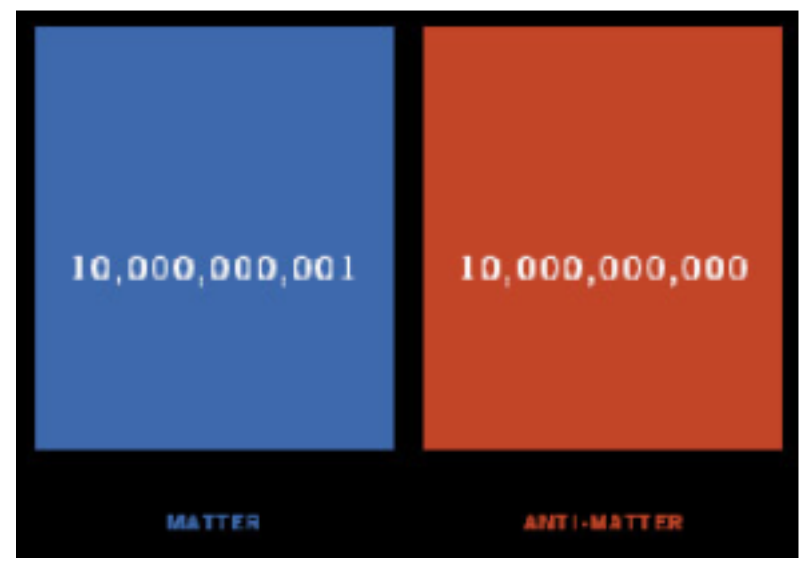
- Higgs was discovered in 2012. Particle contents seem to be complete.
- Unsolved: dark matter (DM), baryon asymmetry (BA), neutrino mass, etc
- Naturalness

Introduction

Baryon asymmetric universe (BAU)

Also known as matter asymmetry

- Why slightly more matter over antimatter?



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

- Observation $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$

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

Introduction

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

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

Introduction

Naturalness

- Why the Higgs mass/VEV is so small (compared to Planck mass or other cutoff scale)?
- $m_h = O(100)$ GeV, $M_P = 10^{19}$ GeV

Introduction

Naturalness

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

Higgs mass: sensitive to large UV corrections

SUSY near EW scale solves hierarchy prob.

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Introduction

Naturalness

- Solutions: (i) + symmetry, e.g. SUSY; (ii) via **dynamics**, e.g. **cosmological relaxation** of EW scale

decoupled new phys w/o fine-tuning

Due to the null result @ LHC, this is an increasingly motivated scenario

Nontrivial to include baryogenesis in a realistic relaxation model due to relaxion conditions => a main hinderance to further developments

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Introduction

- 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

Cosmological Relaxation of the Electroweak Scale

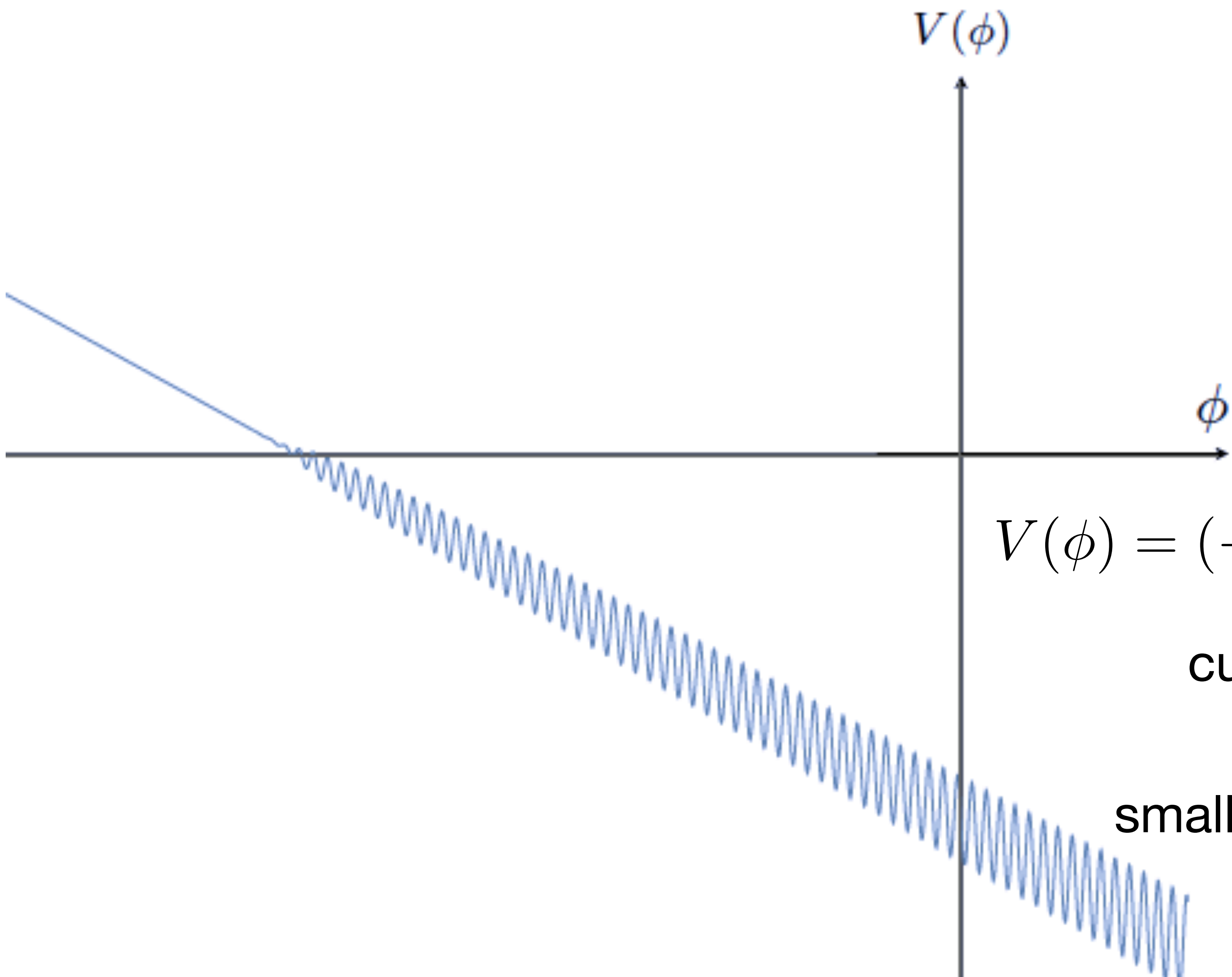
Peter W. Graham (Stanford U., ITP & Stanford U., Phys. Dept.), David E. Kaplan (Stanford U., ITP & Johns Hopkins U. & Stanford U., Phys. Dept. & UC, Berkeley & Tokyo U., IPMU), Surjeet Rajendran (UC, Berkeley)

Apr 28, 2015 - 9 pages

Phys.Rev.Lett. 115 (2015) no.22, 221801
(2015-11-23)
DOI: 10.1103/PhysRevLett.115.221801
e-Print: arXiv:1504.07551 [hep-ph] | PDF

GKR's relaxions

- Relaxion potential: many minima + coupling to Higgs



EW unbroken -> EW broken

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

cutoff

Propto to Higgs vev <h>

small mass-dim parameter

Problems w/ GKR

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

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

- **Large amounts of inflation** Tiny coupling ~ 10^-31 GeV

  -> **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 ~ M_P/f

non-negligible NP effects if f >= M_P

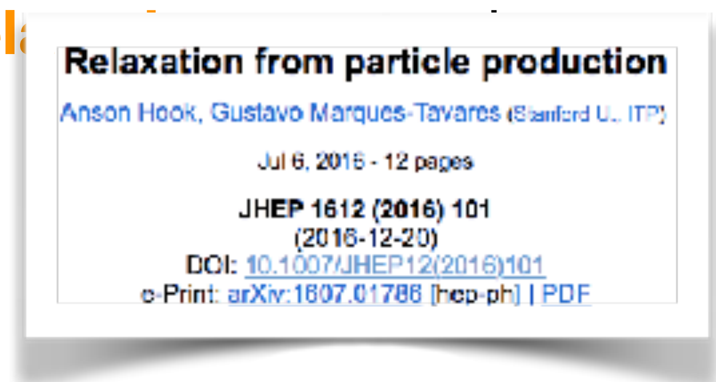
Whether this applies to interacting scalars: open question

HMT’s relaxions

- 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 rel**
  before, during or after inflation
- **Avoid large e-folds**: O(100)
- Focus on **relaxation after inflation:** easier to tie to baryogenesis

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


Relaxation from particle production
Anson Hook, Gustavo Marques-Tavares (Stanford U., ITP)
Jul 6, 2016 - 12 pages
JHEP 1612 (2016) 101
(2016-12-20)
DOI: 10.1007/JHEP12(2016)101
e-Print: arXiv:1607.01786 [hep-ph] | PDF

HMT's relaxions

- T=0 potential

via hidden strong dynamics, indep of <h>

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

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

$$\dot{\phi}_0 \gtrsim \Lambda_c^2.$$

- 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**

$$\ddot{A}_\pm + \omega_\pm^2 A_\pm = 0 \quad A_\pm(k) \propto e^{i w_\pm t} \quad w_\pm^2 = k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}$$

$\dot{\phi} \gtrsim f m_A$ $\quad$ $m_A \sim < h >$

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

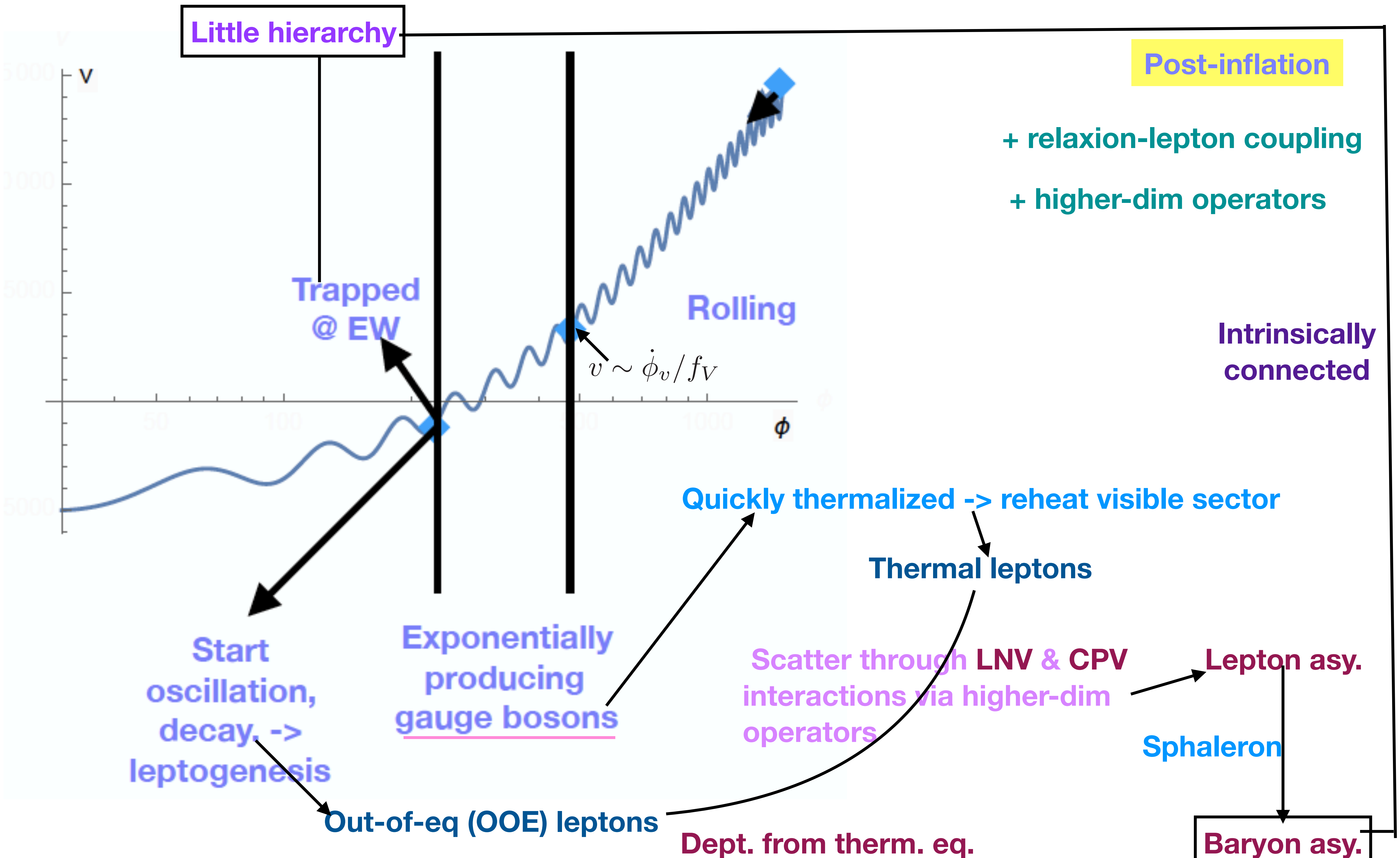
Relaxion-photon coupling induced from loops must be suppressed $f_\gamma \gtrsim \frac{vf}{H}$

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

Gauge bosons => quickly thermalize the visible sector **T ~ cutoff** **restrict possible baryogenesis**

Relaxion conditions => EFT cutoff <~ 10^5 GeV ***Relatively low reheating temperature!***

Our scenario



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)**

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

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

$$\mathcal{O}^{(6)} = \left(\bar{L}_a \gamma^\mu L_b\right)\left(\bar{e}_c \gamma_\mu e_d\right) \qquad \text{with complex coefficient } c_{abcd}^{(6)} \text{ and scale } \Lambda_6$$

- **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
- $$\frac{n_B}{s} \simeq \frac{28}{79}\frac{n_L}{s} \sim \mathcal{O}(10^{-10})$$

All 3 Sakharov's conditions are satisfied!

Leptogenesis

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- Lowest LNV operator: dim-5, Weinberg operator $\mathcal{O}^{(5)} = LhLh$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\lambda_{1,ij} H H \bar{L}_j^c L_i + \frac{1}{\Lambda_2^2}\lambda_{2,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{L}_k\gamma_\mu L_l) \quad \ni \lambda_{1,ij}\frac{v^2}{2\Lambda_1}(\bar{\nu^c}\nu + \bar{\nu}\nu^c)$$

$$+ \frac{1}{\Lambda_3^2}\lambda_{3,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{E}_k\gamma_\mu E_l) + h.c.$$

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

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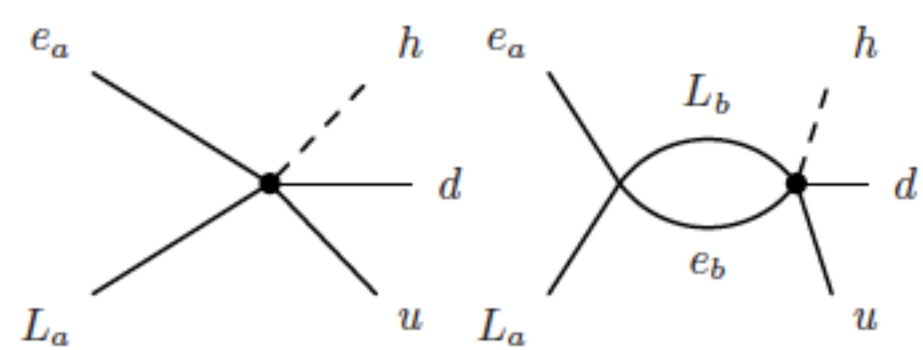
- Focus on dim-7 LNV operators

- Example: $\mathcal{O}^{(7)} = Lh\bar{e}^c\bar{u}^c d^c$

- $\mathcal{O}^{(6)} = \left(L_a\gamma^\mu L_b\right)\left(\bar{e}_c\gamma_\mu e_d\right)$

with complex coefficient $c^{(6)}_{abcd}$ and scale Λ_6



Leptogenesis

- Constraints

- Loop-induced light neutrino mass < 0.1 eV

  → $\frac{y_e^{\rm ex} y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$ for the operator we're considering

- Neutrinoless double beta decay $T_{1/2}^{\rm Ge} \geq 5.3 \times 10^{25}$ y

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

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

Leptogenesis

- Efficiency factor for the asymmetry in the scattering

$$\epsilon_a = \frac{\sigma(\bar{L}_a e_a \to \bar{h} u \bar{d}) - \sigma(L_a \bar{e}_a \to h \bar{u} d)}{\sigma(\bar{L}_a e_a \to \bar{h} u \bar{d}) + \sigma(L_a \bar{e}_a \to h \bar{u} d)}$$

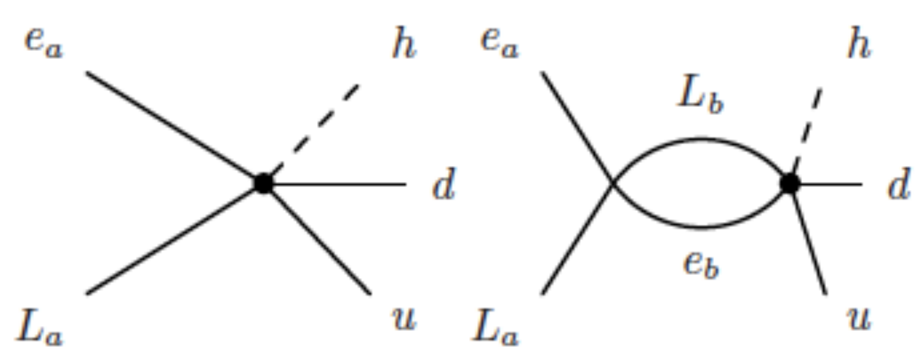
$$\mathcal{M}(L_a \bar{e}_a \to h \bar{u} d) \propto \frac{c_a^{(7)}}{\Lambda_7} + \sum_b \frac{c_b^{(7)}}{\Lambda_7} \frac{2 c_{ab}^{(6)}}{\Lambda_6} I \, .$$

$$\mathrm{Im} I = p^2/(8\pi)$$

Loop function

Square of 4-momentum sum of initial leptons

- $$\epsilon_a \simeq \frac{4}{\Lambda_6^2} \mathrm{Im} I \sum_b \frac{c_b^{(7)} \mathrm{Im} c_{ab}^{(6)}}{c_a^{(7)}}$$



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

$n_\phi \sim \Lambda_c^4/m_\phi$ Pert. decay rate $\Gamma_D \sim m_\phi^3/f_L^2$ $\frac{\partial_\mu \phi}{f_L} J^{5\mu}$

$\Gamma_D > H$ —> upper bound on f_L $J^{5\mu} = J_\mu^{5\mu} - J_\tau^{5\mu}$

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

- 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

$$\Gamma_S \sim T^2 m_\phi / f_{L,V}^2$$

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

- The available number density for producing OOE leptons

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

$$n_\phi^{\text{min.}} \simeq \frac{\Gamma_D}{\Gamma_S} n_\phi \simeq \left(\frac{m_\phi}{T}\right)^2 n_\phi$$

Leptogenesis

- Solve Boltzmann eq. (w/ washout) => Lepton asymmetry

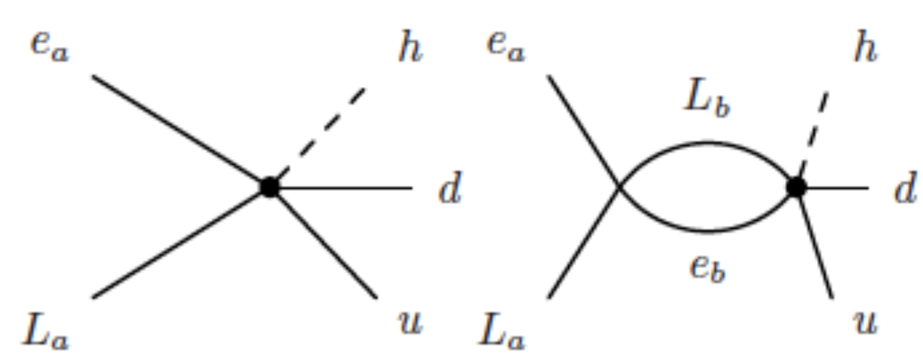
$$\frac{n_L}{s} \simeq \frac{n'_\phi}{s} \sum_a 2\epsilon_a \mathcal{B}_a \frac{\Gamma_{\mathrm{LNV}\,a}}{\Gamma_{\mathrm{th.}}}$$

LNV interaction rate

Thermal scattering rate

Fraction of the effective number density converted into OOE lepton pairs

$$\Gamma_{\mathrm{LNV}\,a} \simeq \frac{3\xi(3)}{512\pi^5} p^4 \left(\frac{c_a^{(7)}}{\Lambda_7^3}\right)^2 T^3 \quad , \quad \Gamma_{\mathrm{th.}} \simeq \alpha_2 T$$

- 

Leptogenesis

A bench mark point that generates O(10^-10) baryon asy.

In GeV (except B)

	$\Lambda, \Lambda_c, \Lambda_{6,7}, T$	f_P	m_ϕ	f_L	f_V	g	B
$p_{\rm min}^2 = 6 m_\phi T$	$10^{3.5}$	10^5	10^2	10^7	10^6	10^{-12}	0.1

One lepton from thermal bath, the other right after being produced (relaxion decay)

$$\frac{n_B}{s} \sim O(10^{-10}) \left(\frac{B}{0.1}\right) \left(\frac{m_\phi}{10^2\,\mathrm{GeV}}\right)^4 \left(\frac{\Lambda_c}{10^{3.5}\,\mathrm{GeV}}\right)^4 \left(\frac{10^{3.5}\,\mathrm{GeV}}{\Lambda_7}\right)^6 \left(\frac{10^{3.5}\,\mathrm{GeV}}{\Lambda_6}\right)^2$$

Signals/Detection:
Axionic couplings;
Photophobic ALP;
T & N_eff

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 up to 10^5 GeV

- **Minimal setup**

- The model has **no extremely small parameters**, introduces **no new physics below the cutoff**, and achieves **leptogenesis @ low reheating temperatures**.

- ***Thank you!***

The relaxation mech. ensures its evolution naturally selects a min. << cutoff, whereaa tying its particle production back reaction to reheating and leptogenesis gives a cosmological censorship criteria for us living in the corner of the universe where the relaxation happened to have the right initial conditions for sufficient scanning-if not, the universe would be empty.

Backup

Constraints

For relaxation to work:

1. Relaxion must roll past the Higgs mass scale before being trapped
2. Higgs field tracks the min of its potential
3. g~H (Hubble) during relaxation (post-inflationary)
4. Relaxion potential < the vacuum energy
5. Multiple minima exist
6. Each minimum is separated by less than O(v)
7. Energy loss due to particle production is faster than energy gain from the linear slope
8. When relaxion is losing energy, change in Higgs mass < O(v)
9. Loop-induced photon coupling will not ruin the mech.
10. Loop-induced fermion coupling should be allowed by the astro constraints etc

For leptogenesis to work:

1. Relaxion mass > H when it's trapped (s.t. relaxion starts oscillating @ the vac)
2. Relaxion decay rate > H
3. Relaxion mass > 0.1 GeV to decay to muons
4. Light neutrino mass < 0.1 eV
5. Lifetime of the inverse neutrinoless double beta decay > 1.9 * 10^25 years
6. Lepton asy. @ leptogenesis won't be diluted

Introduction

Baryon asymmetric universe (BAU)

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

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

- (i) B-violation: Sphaleron

saddle points, or max

↑

Spatially localized, unstable finite energy classical sol

Conserve B-L, but break B+L

(convert baryon to anti-lepton)

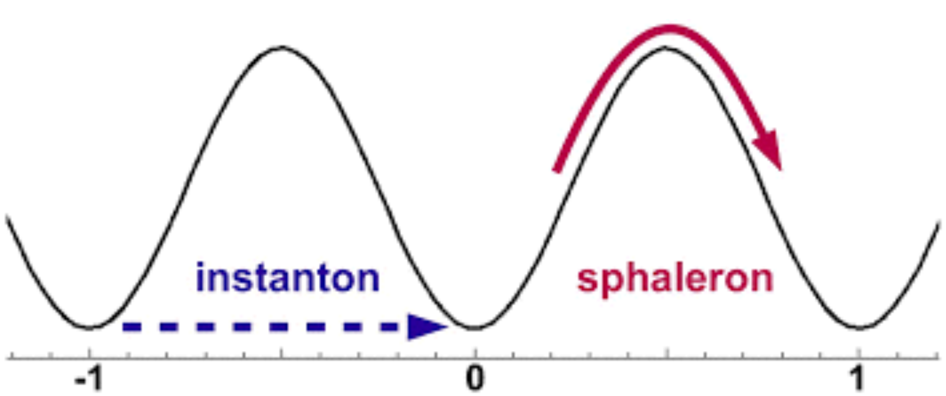


Figure from 0910.0464

T >~ O(100) GeV for unsuppressed sphaleron rate (classically allowed thermal activation instead of tunneling)

Introduction

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

Baryon asymmetric universe (BAU)

- 3 Sakharov's conditions to get BAU from initially baryon symmetric universe:
- (i) B-violation: Sphaleron
- (ii) C, CP-violation:
-

Introduction

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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

$V_{ub} = |V_{ub}|e^{-i\gamma}$

Quarks $$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V_{td} = |V_{td}|e^{-i\beta}$

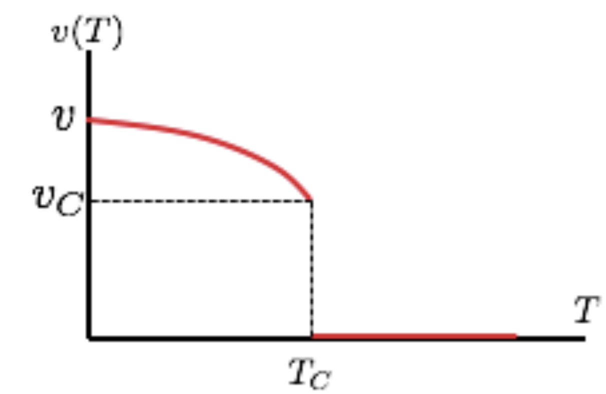
But CPV in SM is too small to provide sufficient baryon asymmetry

Introduction

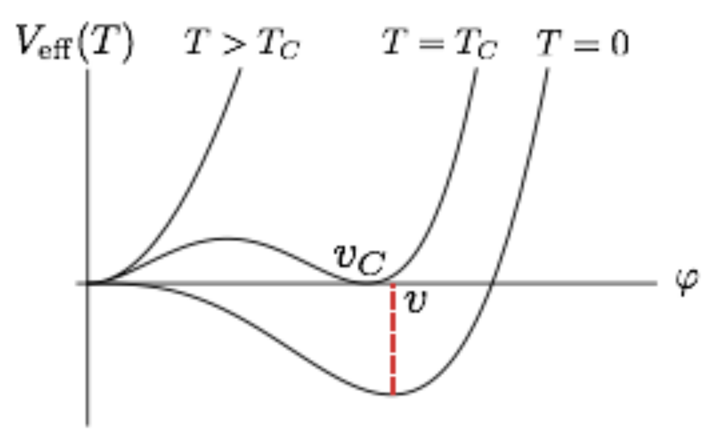
$$\frac{n_B}{s} \sim 8.6 \times 10^{-11}$$

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



- Whether SM has strongly 1st order EWPT is an open question.

Introduction

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

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

need extra pieces

-

Monodromy induced potential

$F_4 = dC_3$ in 4-dimensional spacetime not dynamic

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

$$V_{KS}(a) \equiv \frac{1}{2}F_4 \wedge \star_4 F_4 - mF_4 a \Rightarrow V_{KS}(a) = \frac{1}{2}(f_0 + ma)^2.$$

$$\star_4 F_4 = f_0 + ma,$$

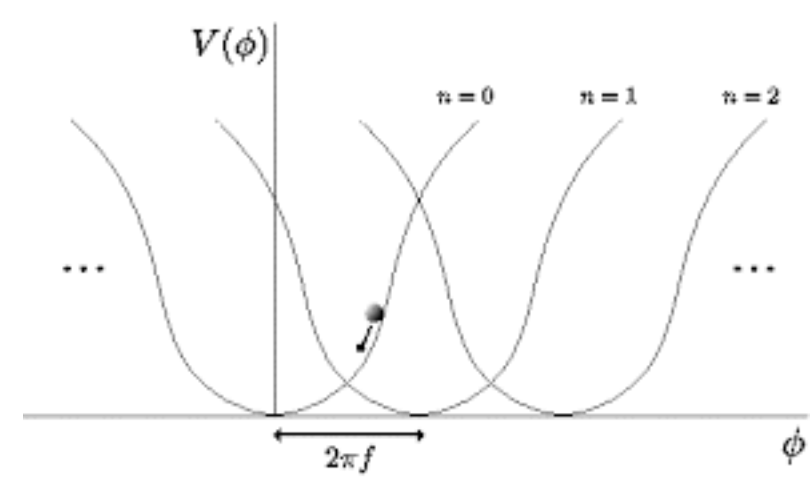
Dirac quantization of a gauge field $f_0 = n\Lambda_k^2, \quad n \in Z,$

where Λ_k is of mass dimension and the index k is associated with a combined discrete shift symmetry of the lagrangian:

$$a \to a + 2\pi f, \quad f_0 \to f_0 - 2\pi m f.$$

consistency condi. $2\pi m f = k\Lambda_k^2, \quad k \in Z.$

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 Δa 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 => **O(1) theta parameter!**

Near $\mu_h^2 \equiv -\Lambda^2 + \epsilon\phi = 0$, $\phi \sim \Lambda^2/\epsilon$

$V \sim \epsilon\phi\Lambda^2 + \Lambda_c^4 \cos\frac{\phi}{f'}$

stopping cond: $\epsilon\Lambda^2 \sim \frac{\Lambda_c^4}{f'}$

Local min $\downarrow$ $V' = 0$, $V'' > 0$

$\frac{\phi}{f'} = \frac{3\pi}{2} \bmod 2\pi$

$V_{QCD} \sim \Lambda_c^4 \cos\frac{\phi}{f'}$

Local min $\downarrow$ $V'_{QCD} = 0$, $V''_{QCD} > 0$

$\frac{\phi}{f'} = \pi \bmod 2\pi$

shift of $O(f')$

GKR's relaxion models

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

During inflation + inflaton σ

$\sigma \approx$ const at least for the most of inflation

$V(\phi) \sim \kappa\sigma^2\phi^2 + \epsilon\phi\Lambda^2 + \cdots$, w/ $\frac{\kappa\sigma^2\Lambda^2}{\epsilon} \gg \Lambda^2\epsilon$

$\tilde{g} \equiv \kappa\sigma^2$

$\theta \equiv \frac{\Lambda^2\epsilon}{\kappa\sigma^2\Lambda^2/\epsilon} = \frac{\epsilon^2}{\tilde{g}}$

@ $\phi \sim \Lambda^2/\epsilon$ ($M_h^2 \sim m_h^2 \sim 0$)

slope of the 1st term $\gg$ slope of the 2nd term

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

After inflation, σ drops to 0.

$V(\phi) \sim \epsilon\phi\Lambda^2 + \cdots$

The slope of ϕ potential drops by a factor of

$\frac{\epsilon\Lambda^2}{\tilde{g}\Lambda^2/\epsilon} = \frac{\epsilon^2}{\tilde{g}} = \theta$

stopping condi. (evaluated @ ϕ not far from Λ^2/ϵ)

$$\frac{\tilde{g}\Lambda^2}{\epsilon} \sim \frac{\Lambda_c^4}{f'} \Rightarrow \frac{\epsilon\Lambda^2}{\theta} \sim \frac{\Lambda_c^4}{f'}$$

GKR’s relaxion models

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

-

GKR's relaxion models

Other problems

- Large amounts of inflation

Tiny coupling ~ 10^-31 GeV

-> severe fine-tuning

Additionally, argument from 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 ~ M_P/f

-

non-negligible NP effects if f >= M_P

Whether this applies to interacting scalars: open question

HMT relaxion models

- Finite T: <h> = 0, time scale asso. w/ tachyon longer due to thermal plasma effects

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

Process of losing energy: dominated by IR

the time it takes for $\dot{\phi}$ to fall below $\dot{\phi}_c$

$$t \sim \frac{T^2 f^3}{\dot{\phi}_c^3}$$

- 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

- **Finite-T** case
- T > v
- System in a plasma state => Charged particles screen electric fields and slow the tachyon growth
- Tachyon modes always in high T modes

$$|\Omega| \ll |k| \ll T.$$

$$\omega = i\Omega, \qquad \Omega \sim \frac{\left(\frac{|\dot{\phi}|}{f}\right)^3}{m_D^2}, \qquad k \sim \dot{\phi}/f$$

- 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 <= 10^5 GeV**

HMT relaxion models

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

- Initial: phi_0 s.t. Higgs has a very large negative mass-squared

$$\dot{\phi}_0 \gtrsim \Lambda_c^2$$

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

- 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

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

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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.

$\dot{\phi} \gtrsim f m_A$

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

No or suppressed relaxion-photon coupling

$m_A \sim < h >$

- The produced gauge bosons quickly reach thermal eq.

really satisfied once the cutoff >> v

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 contri. to its mass-squared due to thermal and finite density effects
- => As <h> decreases, tachyonic condi. is satisfied to a better and better degree
- Eventually, energy density in the gauge field ~ v^4, Higgs mass-squared turns positive -> 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

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

- Relaxion energy is not greater than the vac energy $HM_P \gtrsim \Lambda^4.$
- Relaxion can pass through many minima $\epsilon f'\Lambda^2 \lesssim \Lambda_c^4$
- The scan of Higgs mass has enough precision $\epsilon f' < v^2$
- The energy loss due to exponential production is faster than the energy gain from the linear slope $\Lambda_c^8 > \frac{\epsilon\Lambda^2}{v^3}\dot{\phi}_s^4 \sim \epsilon\Lambda^2 f^4 v.$
- Relaxion does not overshoot the correct Higgs mass $\frac{\epsilon f^3 m_D^2}{v\Lambda_c^4} \lesssim v \Rightarrow \epsilon f^4 \sim v\Lambda_c^4$ $\quad m_D \sim g'T \sim \sqrt{\dot{\phi}} \sim \sqrt{fv}.$
- Relaxion abundance from thermal and non-thermal production will not over close the universe

$$\frac{\partial_\mu\phi}{f_L}J^{5\mu}$$

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 $B\tilde{B}$ $W\tilde{W}$.

HMT relaxion models

Constrains

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

- The particle production from a changing <h> is negligible, and thermal effects on the Higgs mass are small. Thermalization of the particles produced by the relaxion is fast. $\Lambda \gg v.$
- 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: $\Lambda \gg \Lambda_c, \quad \dot{\phi}_s \sim fv \lesssim \Lambda^2.$

HMT relaxion models

Constrains

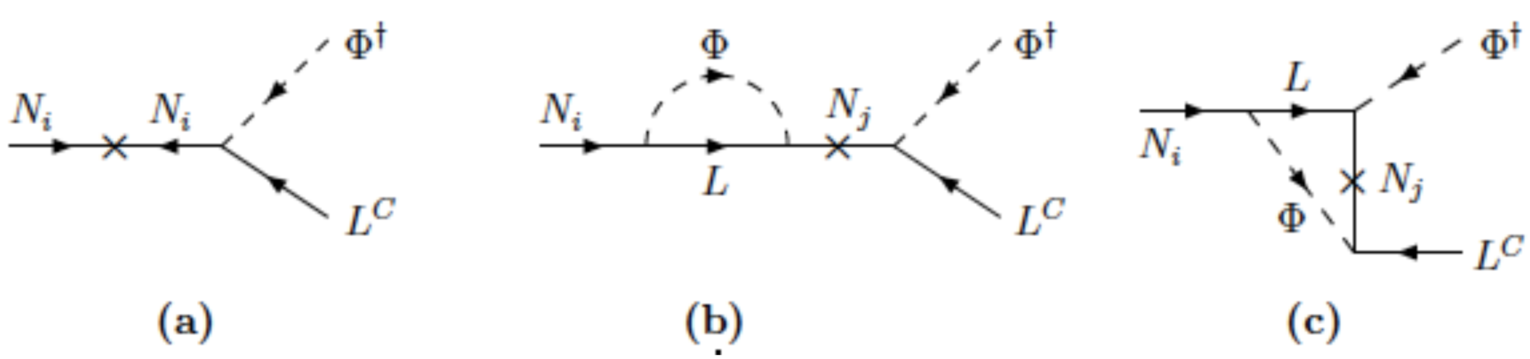
- The above constraints + sub-Planckian field excursion -> Upper bound on the cutoff

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

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 —> 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

del Aguila, Aparici, Bhattacharya, Santamaria, Wudka, 1204.5986

$$\mathcal{O}^{(7)} = \bar{L}\gamma^{\mu} e^{c} h (h^{\dagger} D_{\mu} \tilde{h})$$

Neutrinoless double beta decay $\Lambda_7 \gtrsim 10^5 \text{ GeV for } c^{(7)} \sim \mathcal{O}(1)$

1-loop induced light neutrino mass $\Lambda_7 \gtrsim 10^7 \text{ GeV}$

Larger phase space suppression in LNV rate

Need to raise T_reh (cutoff) to 10^6 GeV (slightly super-Planckian)

Leptogenesis

- **Sources of OOE leptons**

- **Lepton pair production from the classically rolling relaxion**

Classical production $\frac{\partial_\mu \phi}{f_L} J^{5\mu}$

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 ~ $\dot{\phi}_v / f_F \gtrsim v.$

P. Adshead and E. I. Sfakianakis, JCAP **1511** (2015) 021 doi:10.1088/1475-7516/2015/11/021 [arXiv:1508.00891 [hep-ph]]. P. Adshead, L. Pearce, M. Peloso, M. A. Roberts and L. Sorbo, arXiv:1803.04501 [astro-ph.CO].

- Effective number density for OOE leptons n'_ϕ should include both contributions. For simplicity and to get a preliminary result, allow the effective number density to range in

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

Baryogenesis in relaxion models

- **Electroweak baryogengesis (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 baryogengesis (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

$$\mathcal{L}_\varphi \ni -\frac{1}{f_0}\partial_\mu\varphi\, j^\mu_B, \qquad \mathcal{L}_\varphi \ni -\mu n_B, \qquad n_B = j^0_B, \text{ and } \mu =< \dot{\varphi} > / f_0$$

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
- -> SBG can’t be realized in a minimal relaxion model

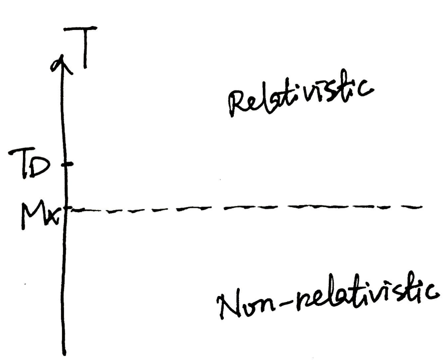
Baryogenesis in relaxion models

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

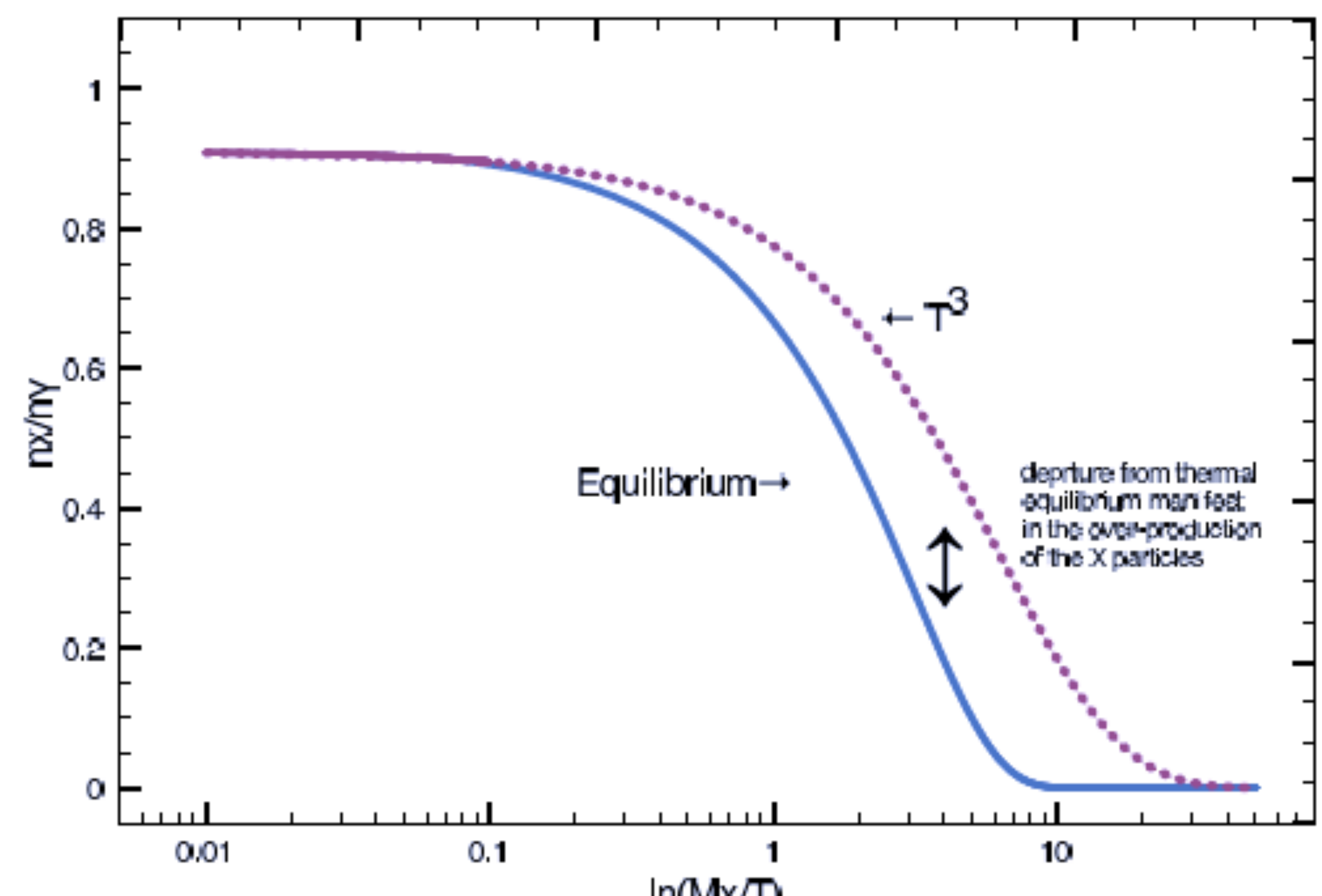
- If at some high temperature (> M_X), X's are so weakly coupled that they can't catch up the expansion of the universe, X's remain in their initial abundance and decouple from the thermal bath.

In eq.

$$n_X = n_{\overline{X}} \simeq n_\gamma \quad \text{for} \quad T \gtrsim M_X \,,$$
$$n_X = n_{\overline{X}} \simeq (M_X T)^{3/2} e^{-M_X/T} \ll n_\gamma \quad \text{for} \quad T \lesssim M_X$$



Decoupling : $T_X \lesssim H$



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 $\frac{\Gamma}{H} \propto \frac{1}{M_X}$

- 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 $\Lambda \lesssim (M_p v^5)^{1/6} \sim 5 \times 10^4\ \mathrm{GeV}$

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.

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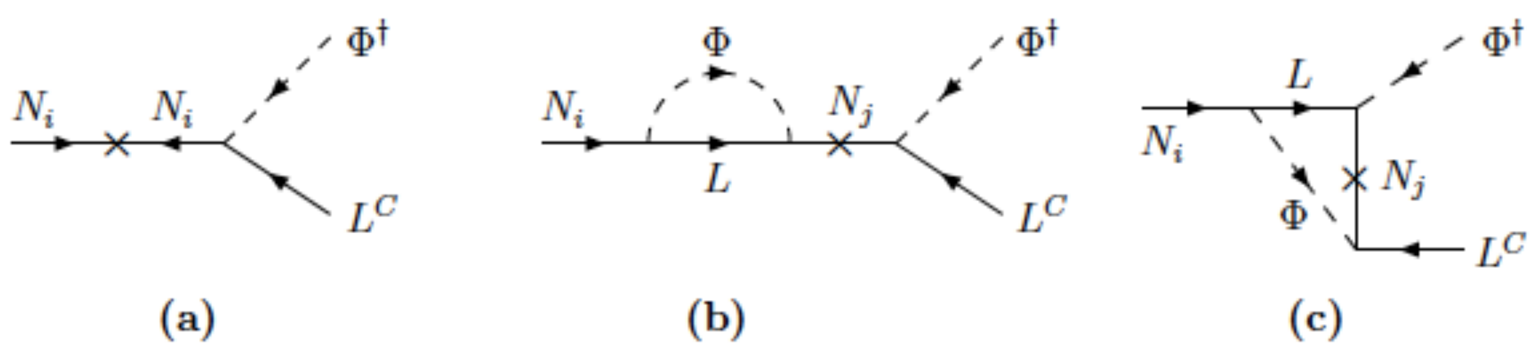
Baryogenesis in relaxion models

- 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)



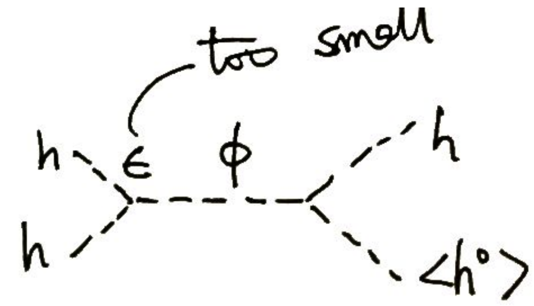
Enhancement condi

$$m_{N_i} - m_{N_j} \sim \frac{\Gamma_{N_{i,j}}}{2}, \qquad \frac{|\mathrm{Im}\,(h^{\nu\dagger}h^{\nu})^2_{ij}|}{(h^{\nu\dagger}h^{\nu})_{ii}\,(h^{\nu\dagger}h^{\nu})_{jj}} \sim 1,$$

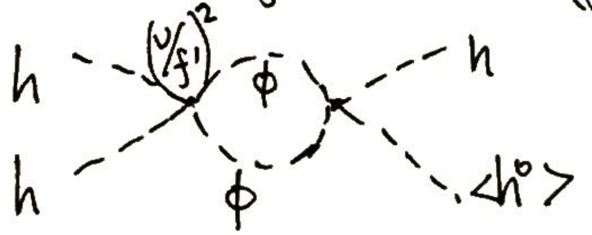
Cubic terms from periodic potential

Hook's: Λ_c^4 indep of h

GKR's: $\Lambda_c^4 \sim h^n v^{4-n}$ $\quad 0 \le n \le 3$

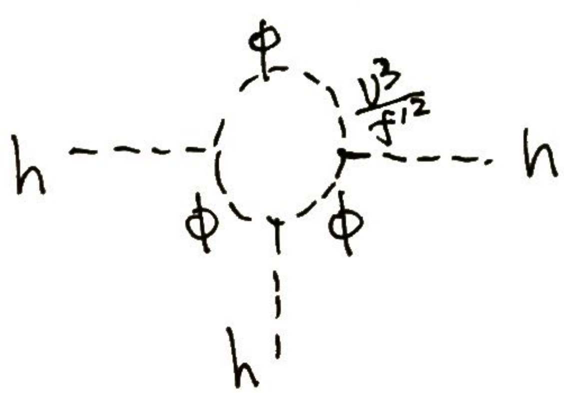


e.g. $h^2 v^2 \cos\frac{\phi}{f'} \Rightarrow h^2 v^2 \left(\frac{\phi}{f'}\right)^2$



$\Rightarrow \frac{1}{16\pi^2}\left(\frac{v}{f'}\right)^4 v \ln\frac{\Lambda}{m_\phi} \ll v$ $\left(\begin{array}{l} \Lambda \lesssim O(10^4)\,\text{GeV} \\ f' > 10^9\,\text{GeV} \\ m_\phi \sim \Lambda_c^2/f' \sim v^2/f' \end{array}\right)$

e.g. $h v^3 \cos\frac{\phi}{f'} \Rightarrow h v^3 \left(\frac{\phi}{f'}\right)^2$



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

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.

$$\begin{aligned}
\mathcal{O}^{(7\text{-I})} &= (\overline{D_\mu \ell_L} \tilde{\phi})(\phi^\dagger D^\mu \tilde{\ell}_L) \\
\mathcal{O}^{(7\text{-II})} &= (\overline{\ell_L} D_\mu \tilde{\ell}_L)(\phi^\dagger D^\mu \tilde{\phi}) \\
\mathcal{O}^{(7\text{-III})} &= (\overline{\ell_L} \tilde{\phi}) \partial_\mu (\phi^\dagger D^\mu \tilde{\ell}_L)
\end{aligned}$$

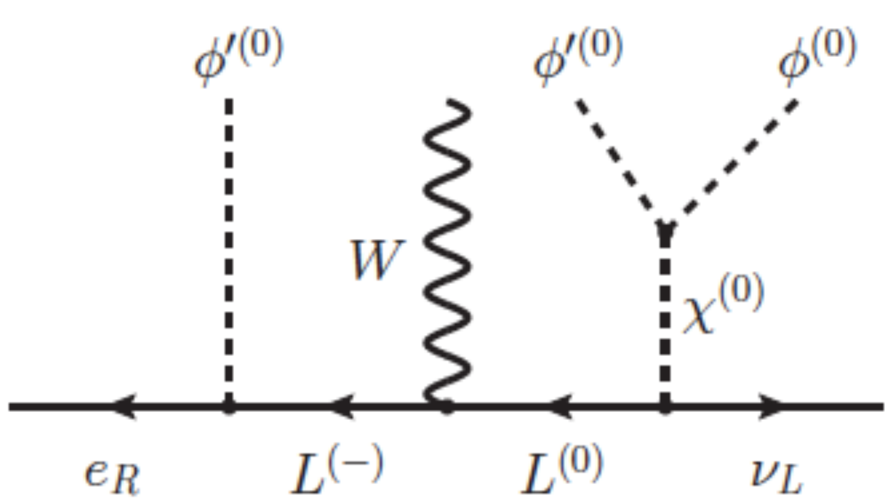
-

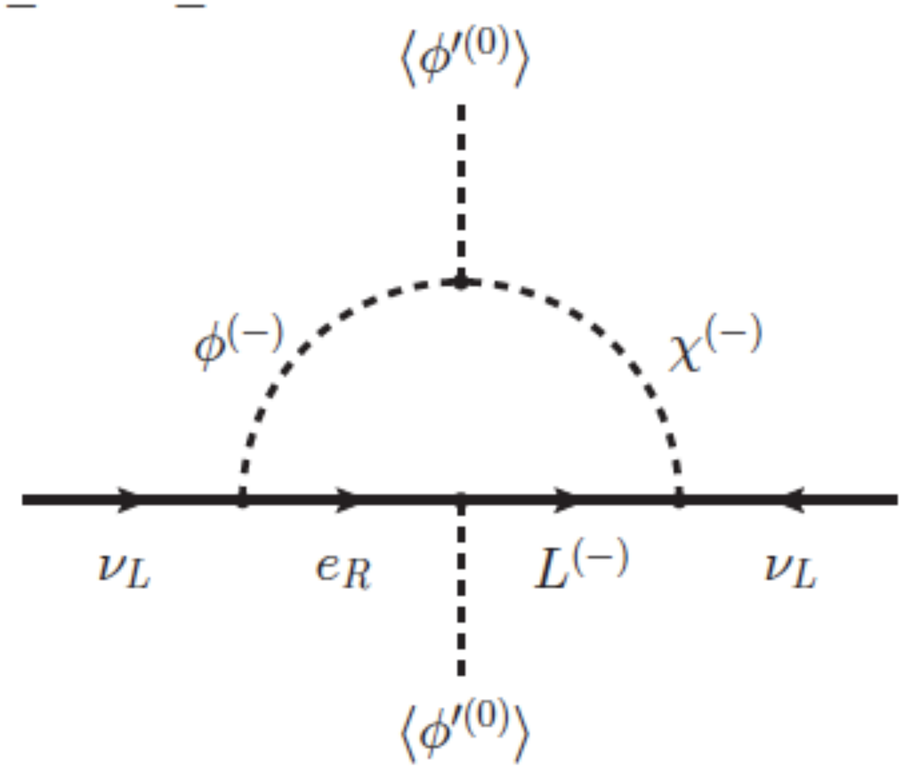
Tree-level dim-7 LNV from renormalizable theory

- 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

	L_{La}	L_{Ra}	χ	ϕ'
$SU(2)_L$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{2}$
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	1	$\frac{1}{2}$
Z_2	–	–	–	–

- 



Baryogenesis in relaxion models

Baryogenesis	Work in the minimal model?	Connection to relaxation
EW	X	N/A
Spontaneous	X	N/A
Decay	TeV-scale resonant leptogenesis ✓	Weak
Reheating-era leptogenesis	✓	Strong

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

$$Z(\mu, T, V) = \mathrm{Tr}[e^{-\beta(H - \sum_i \mu_i Q_i)}] \qquad n_i - \overline{n}_i = -\frac{\partial \Omega(\mu, T)}{\partial \mu_i}$$

$$\Omega(\mu, T) = -\frac{T}{V} \ln Z(\mu, T, V) \qquad n_i - \overline{n}_i = \frac{1}{6} g T^3 \begin{cases} \beta\mu_i + \mathcal{O}((\beta\mu_i)^3), & \text{fermions} \\ 2\beta\mu_i + \mathcal{O}((\beta\mu_i)^3), & \text{bosons} . \end{cases} \quad \beta\mu_i \ll 1$$

- 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 $\mathcal{O}_{B+L}$ 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, $\prod_i (q_{L_i} q_{L_i} u^c_{R_i} d^c_{R_i})$. 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,

$$\mu_{q_i} - \mu_H - \mu_{d_j} = 0 ,$$
$$\mu_{q_i} + \mu_H - \mu_{u_j} = 0 ,$$
$$\mu_{\ell_i} - \mu_H - \mu_{e_j} = 0 .$$

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i})$$
$$L = \sum_i L_i, \quad L_i = 2\mu_{\ell_i} + \mu_{e_i} .$$

Connecting B to L

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

- Together w/ sphaleron, hyper charge constrains

$$\mu_e = \frac{2N_f + 3}{6N_f + 3}\mu_\ell, \quad \mu_d = -\frac{6N_f + 1}{6N_f + 3}\mu_\ell, \quad \mu_u = \frac{2N_f - 1}{6N_f + 3}\mu_\ell$$

$$\mu_q = -\frac{1}{3}\mu_\ell, \quad \mu_H = \frac{4N_f}{6N_f + 3}\mu_\ell .$$

$$B = -\frac{4}{3}N_f\mu_\ell \ ,$$

$$L = \frac{14N_f^2 + 9N_f}{6N_f + 3}\mu_\ell .$$

-