Post-Inflationary Higgs Relaxation and Leptogenesis

Lauren Pearce

University of Minnesota & Valparaiso University, Indiana

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Based on:
A. Kusenko, LP, L. Yang, Phys.Rev.Lett. 114 (2015) 6, 061302
LP, L. Yang, A. Kusenko, M. Peloso, Phys.Rev. D92 (2015) 2, 023509
L. Yang, LP, A. Kusenko, Phys.Rev. D92 (2015) 043506

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- I'd like to talk about why this epoch of inflation may be cosmologically interesting.

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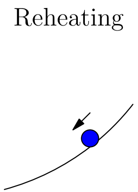
- As Louis told us, Higgs relaxation begins when $H(t) \sim$ effective mass of Higgs field
- This occurs during preheating/reheating, so if we produce an asymmetry is does not get inflated away

Basic Idea

Basic Ingredients

During reheating, Higgs VEV rolls down.



Basic Idea

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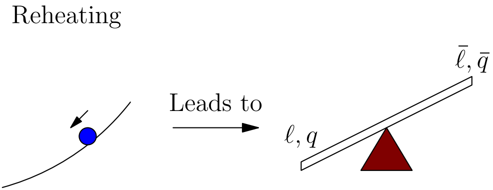
Higher dimensional operators that depend on $\partial_t \phi^2$ can raise the energy of particles as compared to the energy of particles.



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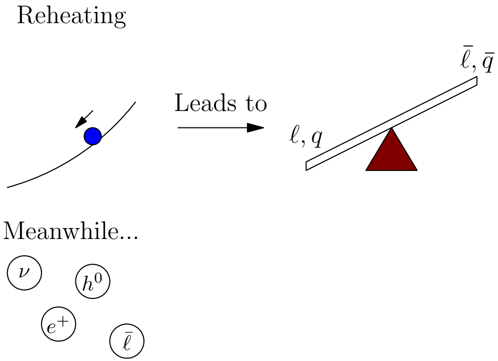
Meanwhile, reheating produces a plasma of particles & antiparticles.



Basic Idea

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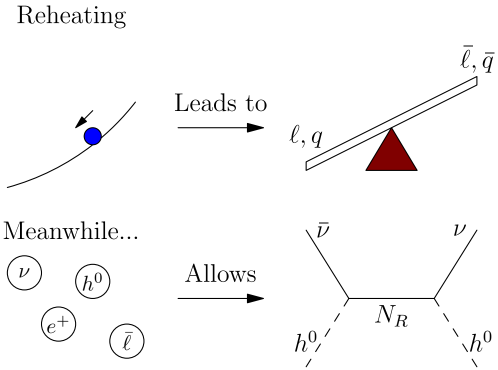
Lepton-number violating interactions (such as those mediated by a RH neutrino) allow antiparticles to become particles.



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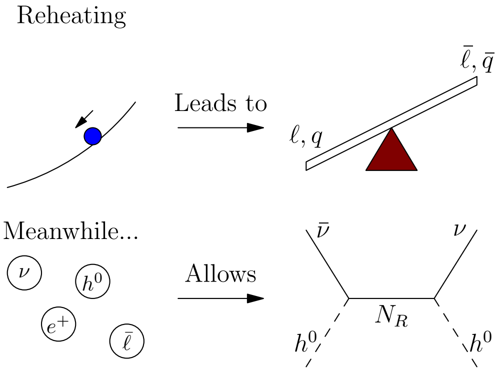
This allows a net excess of particles to develop.



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- A time-dependent Higgs field (Louis' talk)
- An effective operator like $-(\partial_t \phi^2) j_{B+L}$:
  - Produces an effective chemical potential that raises the energy of antiparticles and lowers the energy of particles
- A process which allows particles to become antiparticles and vice versa

Effective Chemical Potential

Effective Operator

- Consider the effective operator:

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 A\tilde{A} - g'^2 B\tilde{B}\right),$$

where A and B are the $\mathrm{SU_L}(2)$ and $\mathrm{U_Y}(1)$ gauge fields
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- Can generate with loops of heavy fermions (with soft masses) or thermal loops
- Scale Λ_n: Mass M or temperature T

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- Using the electroweak anomaly & integration by parts:

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- This operator actually breaks CPT & is similar to one used in spontaneous baryogenesis scenarios.

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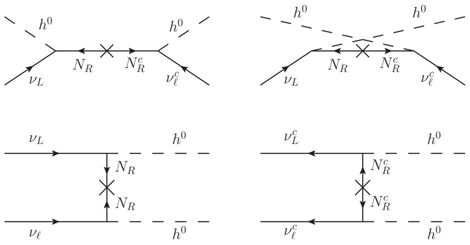
- Use right-handed neutrinos to generate lepton-number-violation...
- ...but ensure $T \ll M_R$ to suppress standard leptogenesis!
- (M_R fixed by LH neutrino masses with couplings of order 0.1.)



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- (However, since the Higgs VEV evolves quickly, $\partial_t \phi^2$, and hence the chemical potential, is large).
- The system won't reach the equilibrium asymmetry, but approaches it:

$$\frac{d}{dt} n_L + 3Hn_L \cong -\frac{2}{\pi^2} T^3 \sigma_R \left(n_L - \frac{2}{\pi^2} \mu_{\text{eff}} T^2 \right).$$

(Boltzmann equation)

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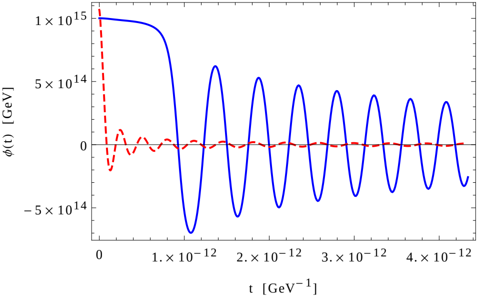
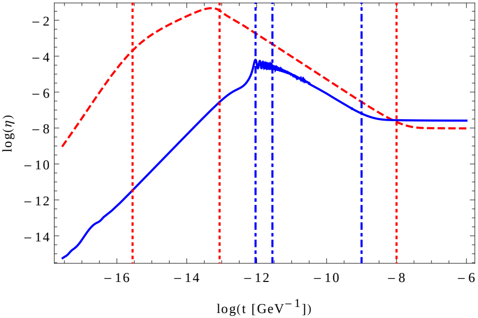
To suppress washout due to oscillations:

- Choose parameters such that the asymmetry generation freezes out during the first swing (if it is even in equilibrium)
- Or choose parameters such that the Higgs oscillation is significantly damped; then the chemical potential is smaller during subsequent oscillations



Sample plots of Higgs evolution; see Louis Yang's talk for details.

Plasma Scatterings: Sample Plots of Asymmetry Evolution



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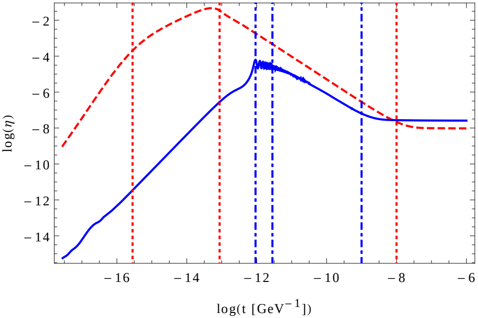

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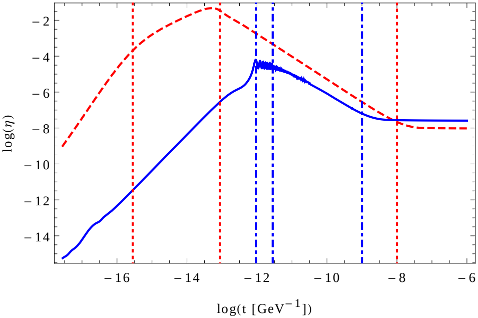

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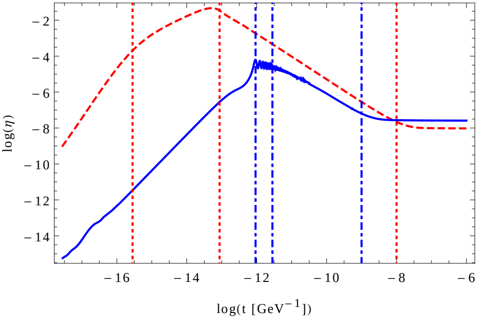

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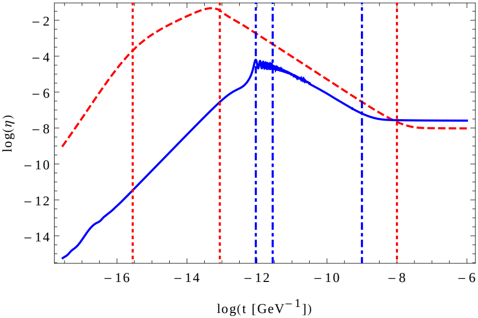

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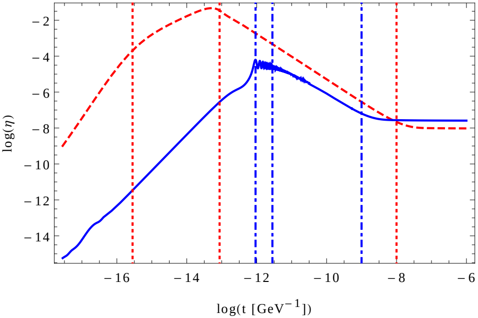

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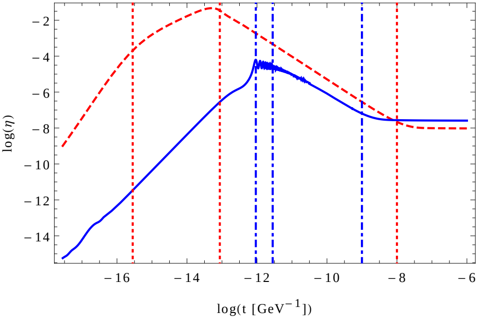

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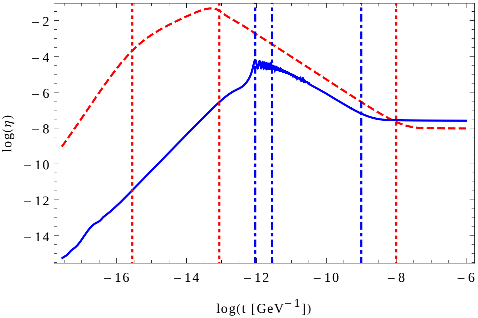

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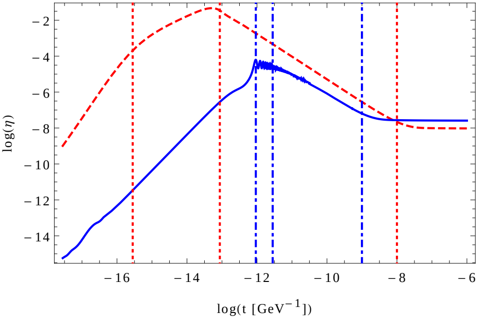

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Kusenko, LP, Yang
Phys.Rev.Lett. 114 (2015)

Analytic Approximation

Approximate analytical formula for asymmetry:

$$\eta \approx \frac{45}{2\pi^2}\frac{\sqrt{\lambda}\phi_0^3\Lambda_I}{M_n^2 T_R^2}\; t_{\rm rlx}^2\Gamma_I^2 \times \min\left\{1,\, T_{\rm rlx}^3 t_{\rm rlx}\sigma_R\right\}$$

$$\times \exp\left[-\left(\frac{24+3\sqrt{15}}{\sqrt{3g_*\pi^7}}\right)\sigma_R M_P T_R\right]$$

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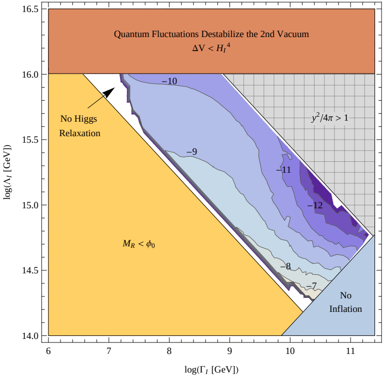
Accurate to within an order of magnitude.

Sample Parameter Space Plots

Yang, LP, Kusenko
Phys.Rev. D92 (2015)



False minimum scenario with scale of $\mathcal{O}_6$ operator set by T. Restricts inflationary parameters.

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Yang, LP, Kusenko
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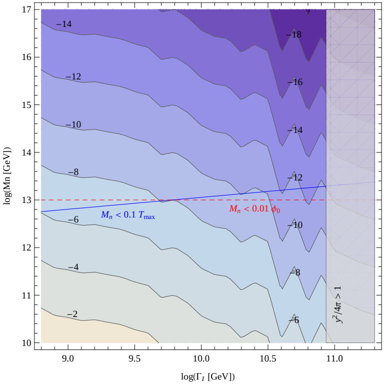

Taking the scale of the $\mathcal{O}_6$ operator to be an independent parameter gives additional freedom.

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- For comparable parameters, a larger asymmetry is produced in the scenario in which the Higgs relaxes from a false vacuum:
- The delay in tunneling out of the false vacuum means there is more plasma when relaxation occurs

Particle Production From Background Field Evolution

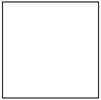
Consider the vacuum state at time $t = 0$ (that is, $\left\langle \mathrm{VAC}, 0 | \hat{N}_k(0) | \mathrm{VAC}, 0 \right\rangle = 0$ for all modes)

$$\left\langle \psi | a^\dagger(t=0) a(t=0) | \psi \right\rangle = 0$$

Particle Production From Background Field Evolution

As the VEV for a classical background field evolves, the creation and annihilation operators evolve into a superposition of the $t = 0$ creation and annihilation operators.

α, β: Bogoliubov coefficients



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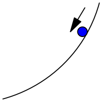

$$a(t) \sim \alpha a(0) + \beta a^\dagger(0)$$

Particle Production From Background Field Evolution

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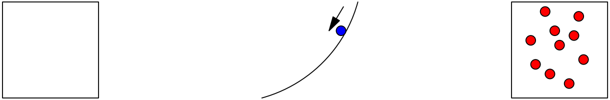
At a later time, the "vacuum" state is no longer empty! (That is, $\left\langle \mathrm{VAC}, 0 | \hat{N}_k(t) | \mathrm{VAC}, 0 \right\rangle \neq 0$)



$\left\langle \psi | a^\dagger(t=0) a(t=0) | \psi \right\rangle = 0$ $\quad a(t) \sim \alpha a(0) + \beta a^\dagger(0)$ $\quad \left\langle \psi | a^\dagger(t) a(t) | \psi \right\rangle \propto |\beta|^2$

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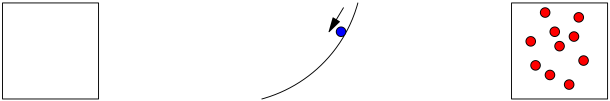
Thus the relaxation of the Higgs field also results in particle production: can we create a large enough asymmetry from this production mechanism?



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  - $E = \sqrt{|\boldsymbol{p}|^2 + h\mu_{\text{eff}})^2 + M_L^2}$, so the $\mathcal{O}_6$ operator is necessary to bias the energy of particles ($h = -1$) vs. antiparticles ($h = +1$)

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  - $E = \sqrt{|\boldsymbol{p}|^2 + h\mu_{\rm eff})^2 + M_L^2}$, so the $\mathcal{O}_6$ operator is necessary to bias the energy of particles ($h = -1$) vs. antiparticles ($h = +1$)
- With these two ingredients, $|\beta_\nu|^2 \neq |\beta_{\bar{\nu}}|^2$

Analysis

- Resulting asymmetry:

$$\eta \approx -\frac{\pi}{2\zeta(3)T(t)^3}\frac{a(t_S)^3}{a(t)^3}\frac{\mu_{\max}^3}{(2\pi)^3}\sum_h h|\bar{\beta}_{\mu_{\max},h}(t_E)|^2.$$

where t_S is the state of Higgs relaxation, t_E is the effective end of particle production, and $\bar{\beta}$ is the Bogoliubov coefficient (with some approximations)

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- Numerical analysis shows regions of parameter space where a sufficiently large asymmetry is generated:

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- Resulting asymmetry:

$$\eta \approx -\frac{\pi}{2\zeta(3)T(t)^3}\frac{a(t_S)^3}{a(t)^3}\frac{\mu_{\max}^3}{(2\pi)^3}\sum_h h|\bar{\beta}_{\mu_{\max},h}(t_E)|^2.$$

  where t_S is the state of Higgs relaxation, t_E is the effective end of particle production, and $\bar{\beta}$ is the Bogoliubov coefficient (with some approximations)
- Numerical analysis shows regions of parameter space where a sufficiently large asymmetry is generated:
- New scales generally $10^{11} \sim 10^{12}$ GeV

Production From Background Field Evolution

Discussion

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- Electroweak sphalerons later redistribute asymmetry between leptons and baryons
- Entropy dilution from SM degrees of freedom going out of equilibrium; decreases final asymmetry about an order of magnitude

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Thank you! Questions?

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  - Higgs field Φ: $\mathrm{SU}(2)$ doublet, hypercharge $1/2$

where $Y_W = Q - T_3$.

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Lagrangian

- With these fields, we can write the Lagrangian:

$$\mathcal{L} = \text{kinetic terms} + y_i e^{i\delta_i}\Phi(\bar{\psi}_{DLi}\psi_{SR} + \bar{\psi}_{DRi}\psi_{SL}) + m\bar{\psi}_S\psi_S$$
$$+ M_{ij}(\bar{\psi}_{DLi}\psi_{DRj} + \bar{\psi}_{DRj}\psi_{DLi}) + h.c..$$

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- Two component notation (Wess & Bagger style):

$$\mathcal{L} = \text{kinetic terms} + y_i e^{i\delta_i}\Phi_a\left(\bar{\psi}^a_{Li\dot{\alpha}}\bar{\xi}^{\dot{\alpha}} + \epsilon^{ab}\psi^{\alpha}_{Rib}\chi_\alpha\right) + M_{ij}(\epsilon_{ab}\bar{\psi}^a_{Li\dot{\alpha}}\bar{\psi}^{\dot{\alpha}b}_{Rj} + \epsilon^{ab}\psi^{\alpha}_{Rja}\psi_{Li\alpha b}) + m(\xi^\alpha\chi_\alpha + \bar{\chi}_{\dot{\alpha}}\bar{\xi}^{\dot{\alpha}})$$

where i, j are flavor indices, a, b are $\mathrm{SU}(2)$ indices, and α is a spinor index. ξ and χ are the two-component spinors of ψ_S.

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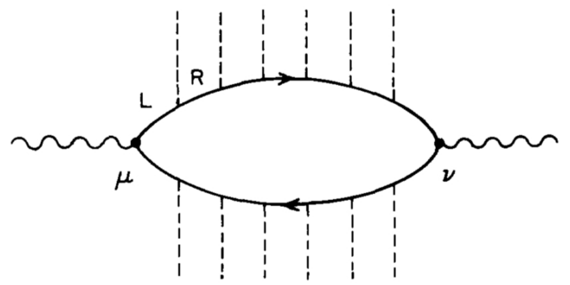
Connect all but two Higgs lines in:



Integrating out the heavy fermionic loop gives the desired operator.
Number of Higgs vertices set requirement to have nonzero physical phase.

Back-Up Slides: What if EW Sphalerons Aren't In Equilibrium?

What if Electroweak Sphalerons Aren't in Equilibrium?

- If EW sphalerons aren't in thermal equilibrium, the $\mathcal{O}_6$ operator biases nonzero Chern-Simons number density, but not lepton/baryon number.

  See Ibe & Kaneta, arXiv:1504.04125

- However, any gauge boson that couples chirally to the SM degrees of freedom contributes to:

$$\partial_\mu j^\mu_{B+L} = (\text{EW anomaly}) + \frac{\mathcal{C}g^2}{32\pi^2}\epsilon_{\alpha\beta\mu\nu}\mathsf{F}^{\mu\nu}\mathsf{F}^{\alpha\beta},$$

  where F corresponds the new gauge field and $\mathcal{C}$ is a constant determined by the charges of the leptons and baryons under the new gauge group.

Back-Up Slides: What if EW Sphalerons Aren't In Equilibrium?

General Requirements

So then we need a gauge boson such that:

1. Has a mass such that its interactions are in thermal equilibrium during Higgs relaxation (hence perhaps not dominated by SM Higgs mechanism)
2. Couples chirally to SM fields (to contribute to $\partial_\mu j^\mu_{B+L}$)
3. Couples non-chirally to the heavy fermions that generate the $\mathcal{O}_6$ operator