Post-Inflationary Higgs Relaxation Leptogenesis

Lauren Pearce

University of Minnesota

Particle Physics in 2017: From the LHC to Dark Matter and Beyond, Aspen, Winter 2017

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
H. Gertov, LP, F. Sannino, L. Yang, Phys.Rev. D93 (2016) 115042
A. Kusenko, LP, L. Yang, Phys.Rev. D93 (2016) 115005
M. Kawasaki, A. Kusenko, LP, L. Yang, arXiv:1701.02175

Outline

1. A New Epoch: Higgs Relaxation
2. What Good Is It? (Leptogenesis)
3. Does This Work?

Higgs Relaxation

The Higgs Potential

- The LHC has found a Higgs boson with mass ~ 125 GeV, which implies $\lambda \sim 0.13$.

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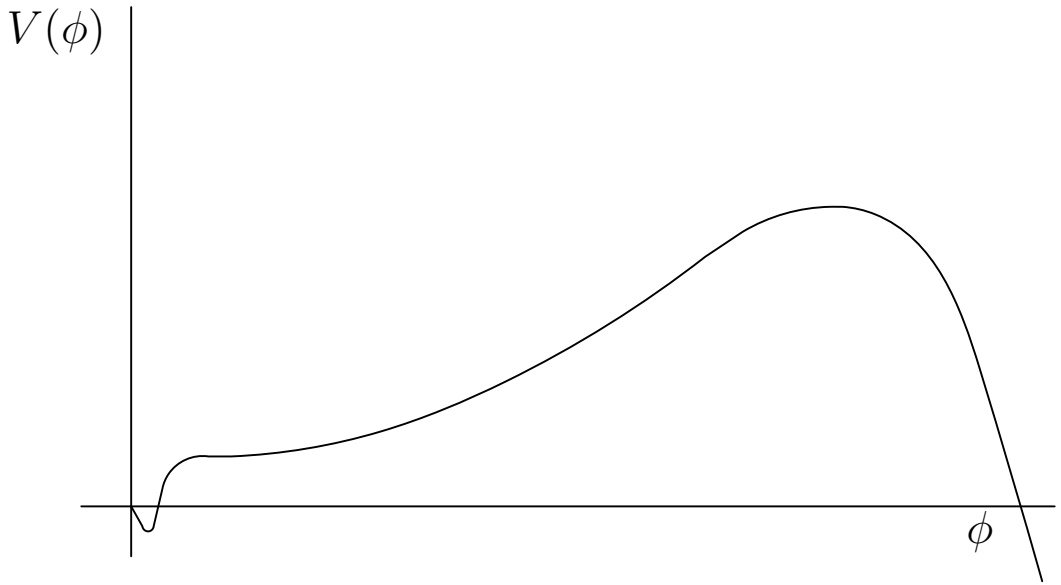
- If we evolve the Standard Model RGE equation out to high scales, the Higgs potential becomes shallow, and even appears to have a second minimum.



Higgs Relaxation

Bunch & Davies (1978), Linde (1982)
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Inflation and the Higgs Potential

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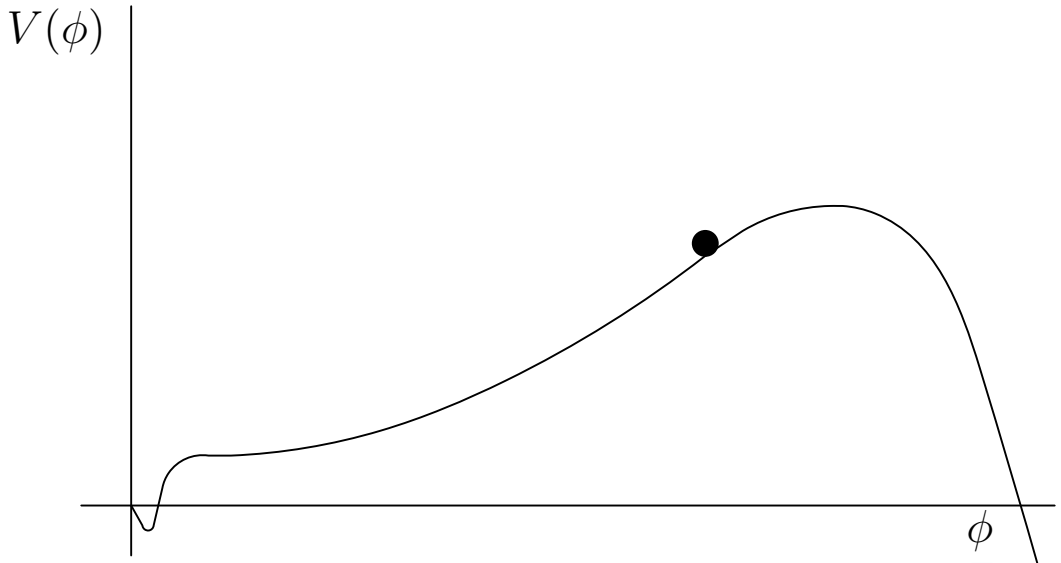

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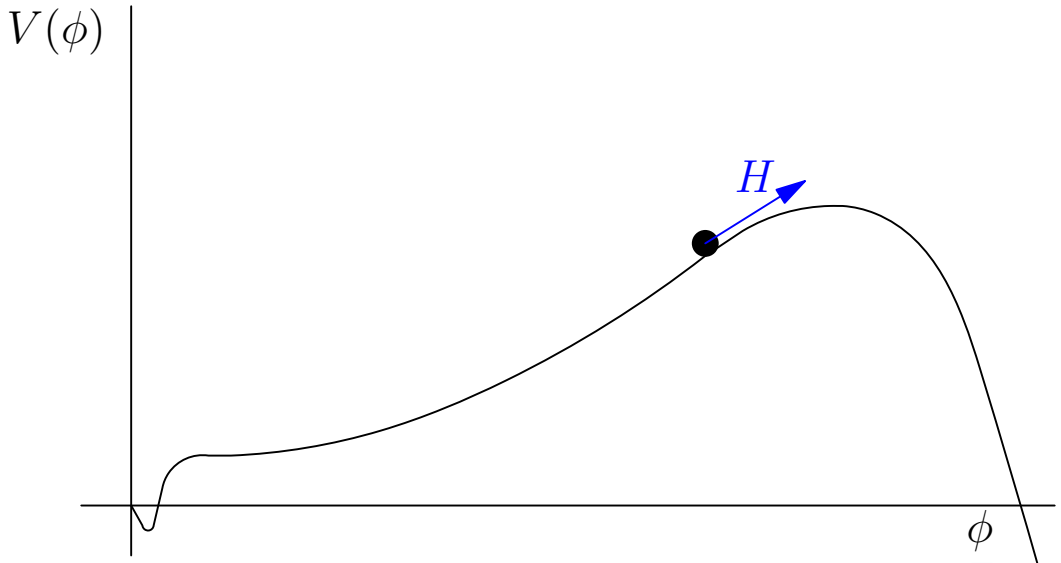
- VEV fluctuates to a large values (due to quantum fluctuations).
- Hubble friction from the expansion of universe prevents from rolling back down.

$$\ddot{\phi} + 3H\dot{\phi} + V'_\phi = 0$$



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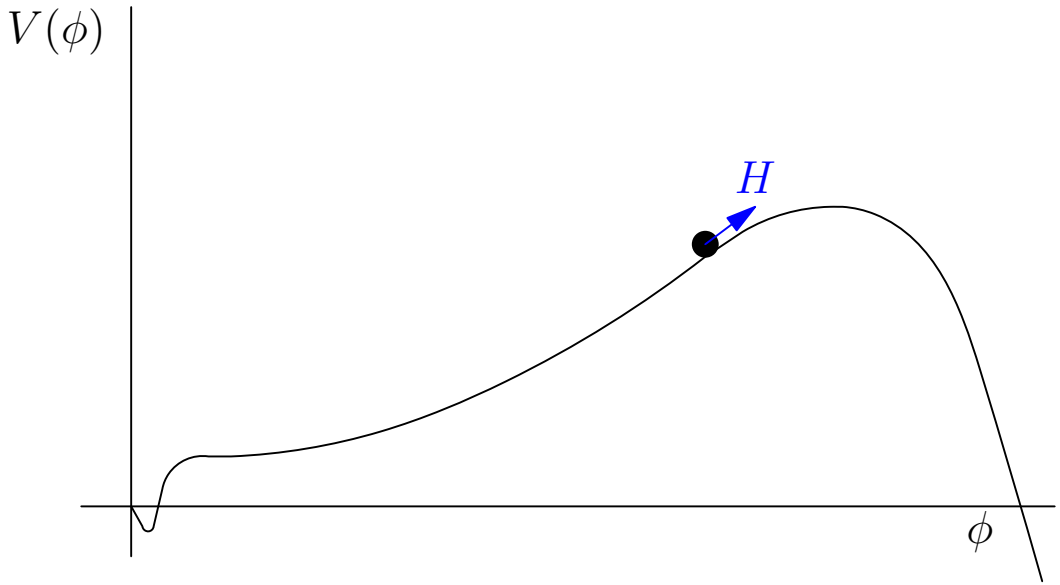
- During reheating, the Hubble parameter decreases.



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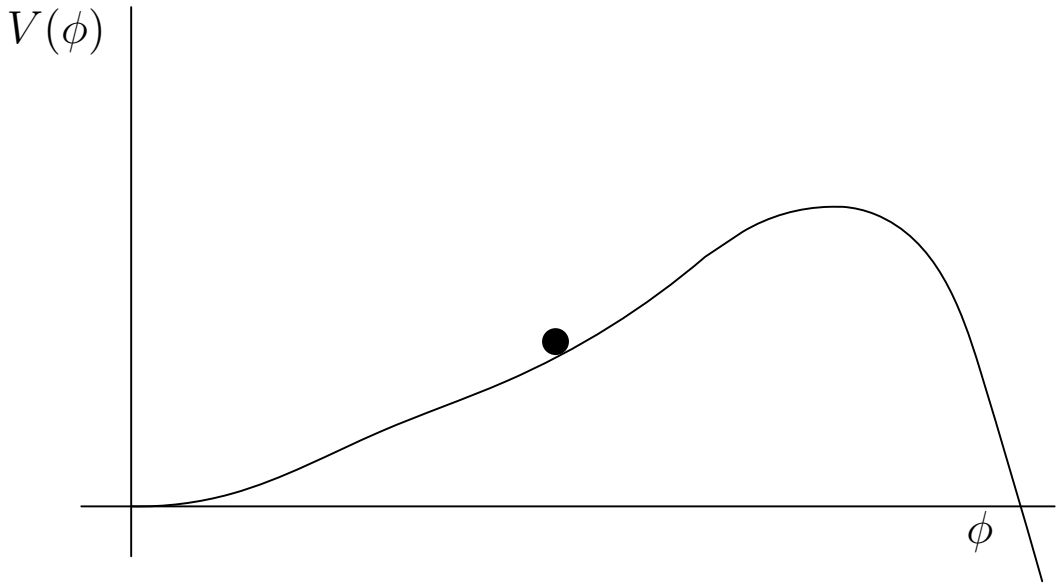

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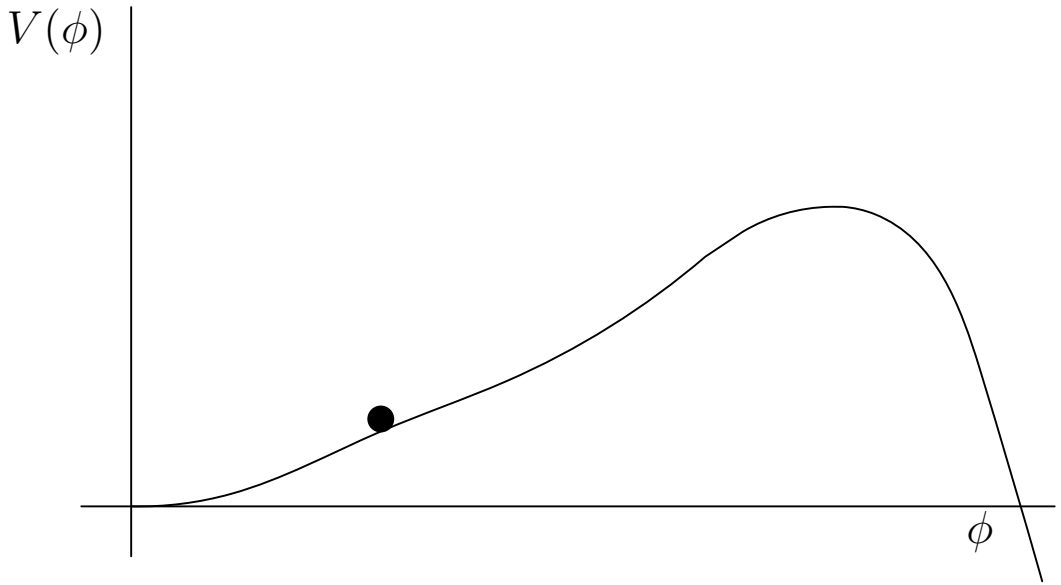

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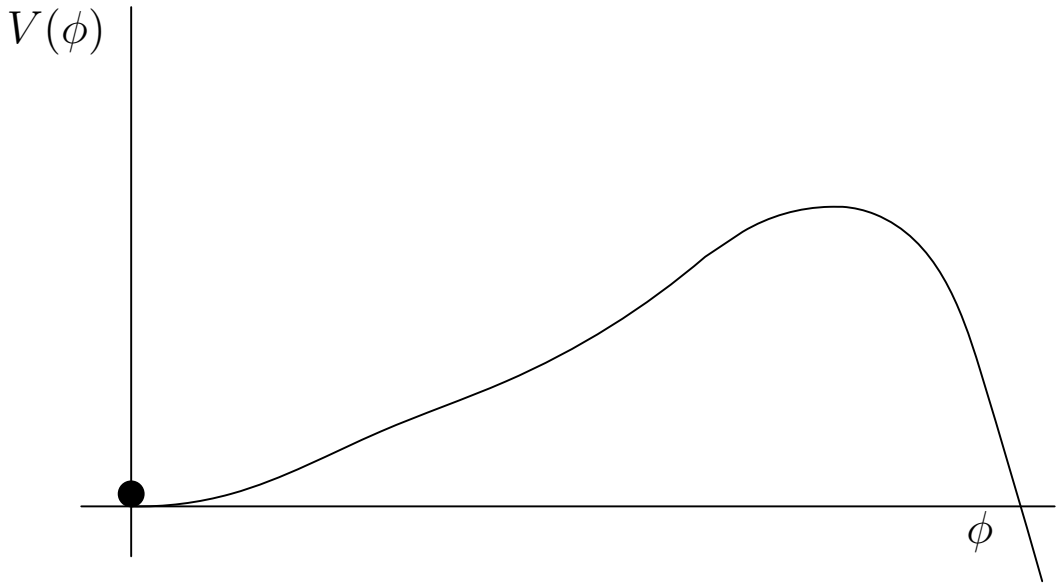

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This Higgs relaxation epoch is a **new epoch** in the early history of the universe!

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How can we use this time-dependent Higgs VEV in baryogenesis or leptogenesis?

M. E. Shaposhnikov (1987)
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Effective Operator

- Consider the effective operator:

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

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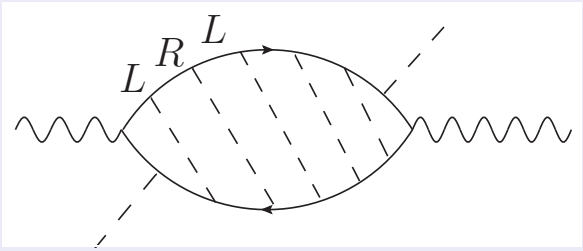

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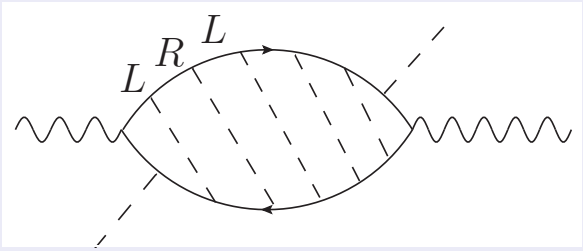

- Suppressed by small Yukawas and small CP-violating phase.

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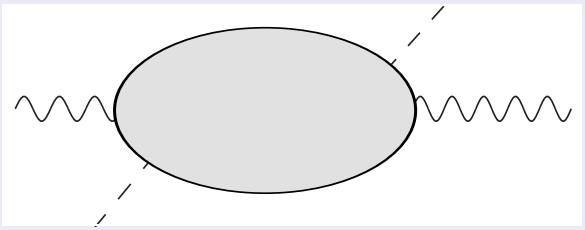

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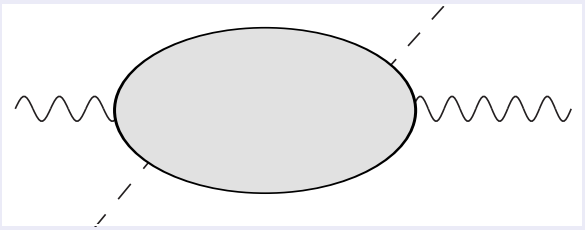

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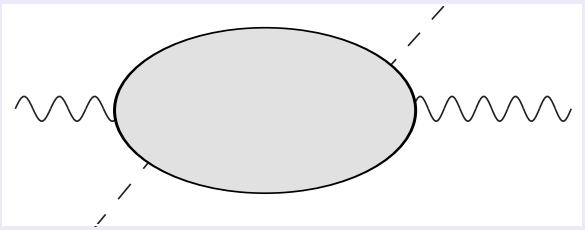

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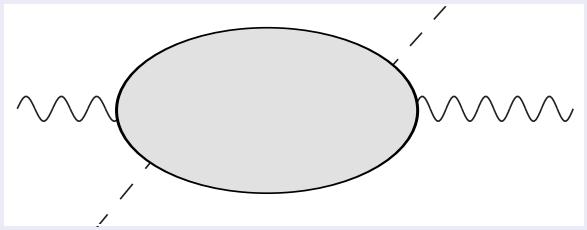

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Dine et. al. (1991)
Cohen, Kaplan, Nelson (1991)

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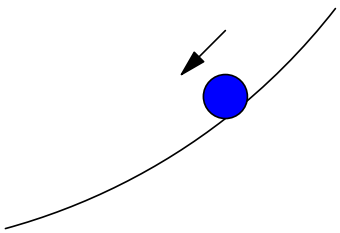

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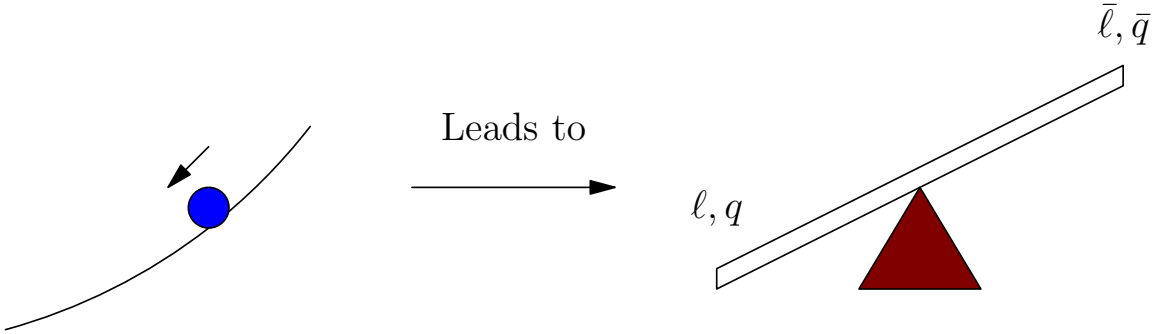

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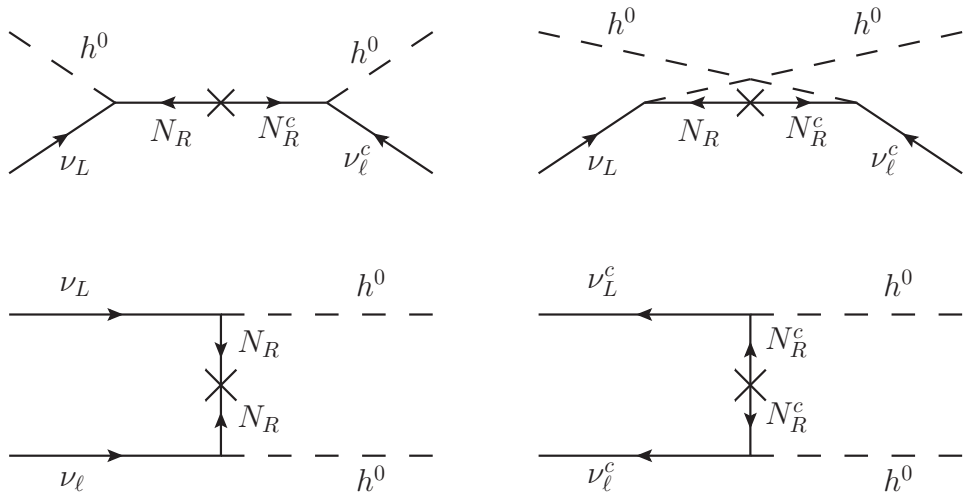

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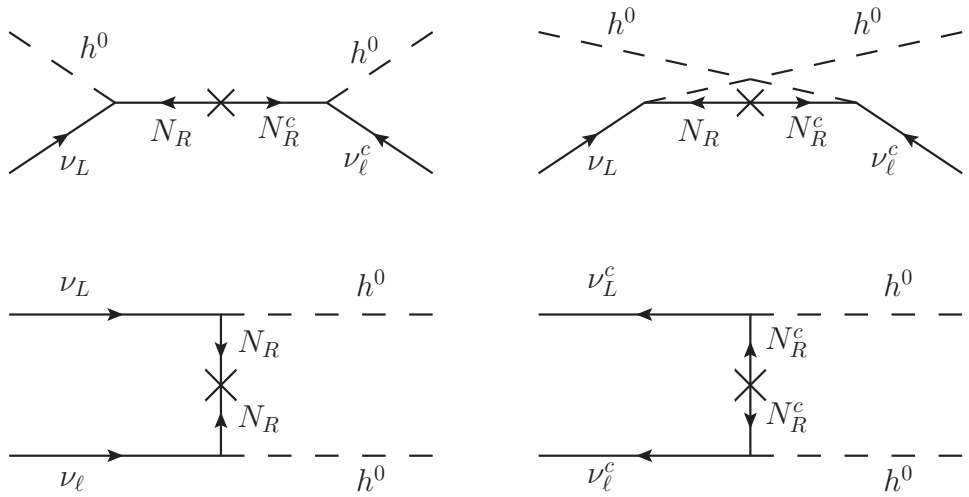

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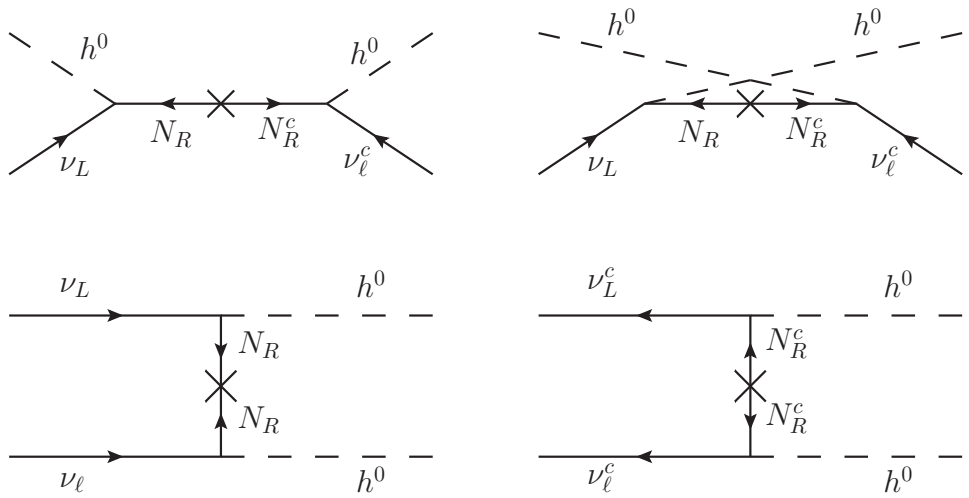
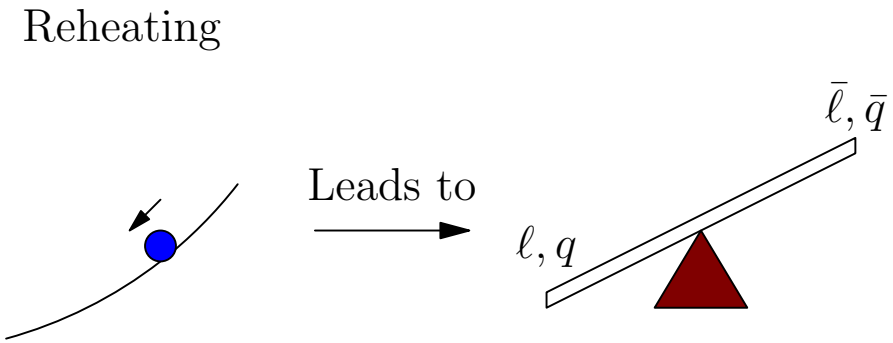
- ...but ensure $T \ll M_R$ to suppress thermal leptogenesis.



Putting It Together



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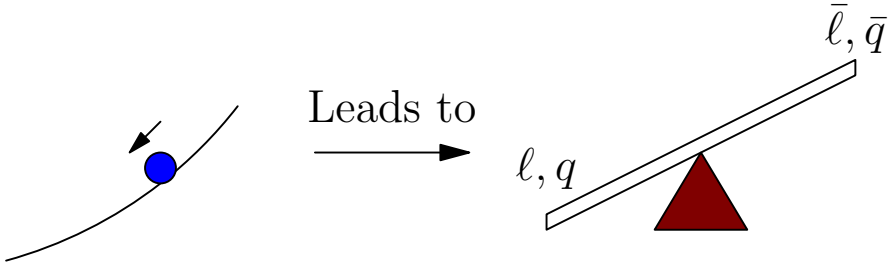

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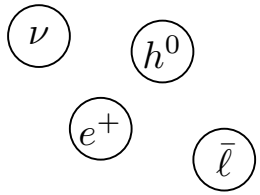

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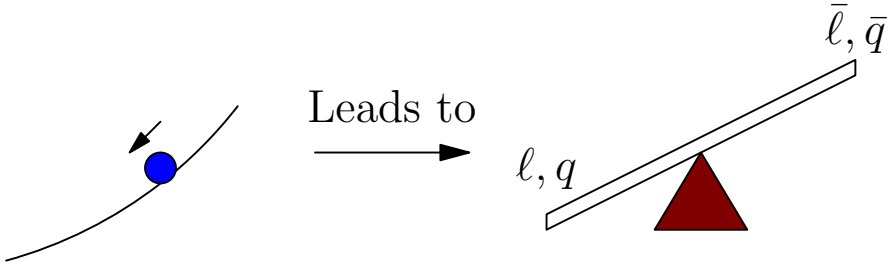

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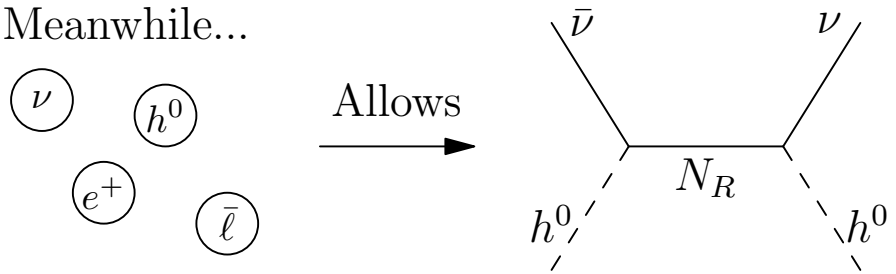

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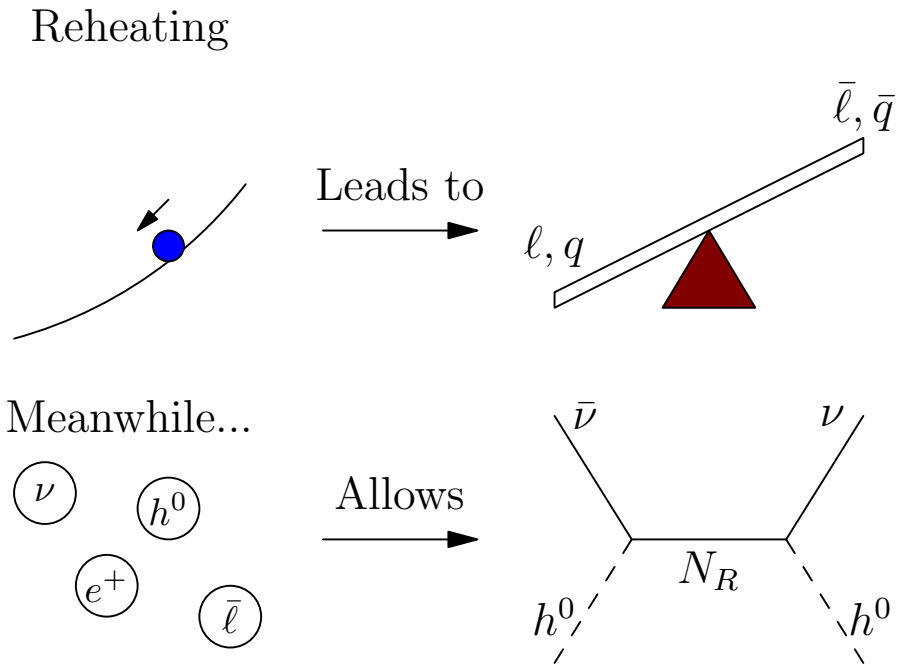

We now have all three ingredients for leptogenesis!
(Electroweak sphalerons redistribute lepton asymmetry to baryons.)

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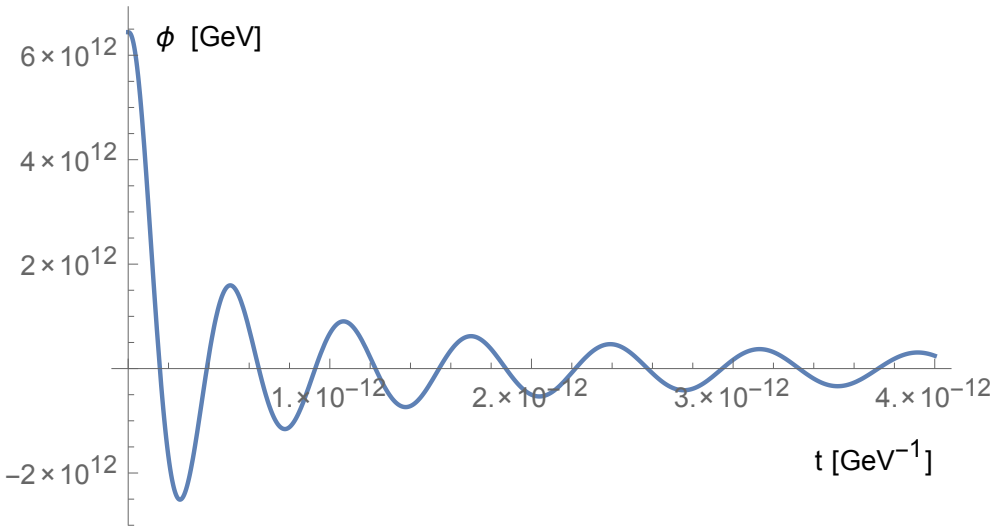

Sample evolution of Higgs VEV
$\Lambda_I = 5 \times 10^{15}\,\mathrm{GeV}$, $\Gamma_I = 10^7\,\mathrm{GeV}$.

(Recall H_I determines initial value.)

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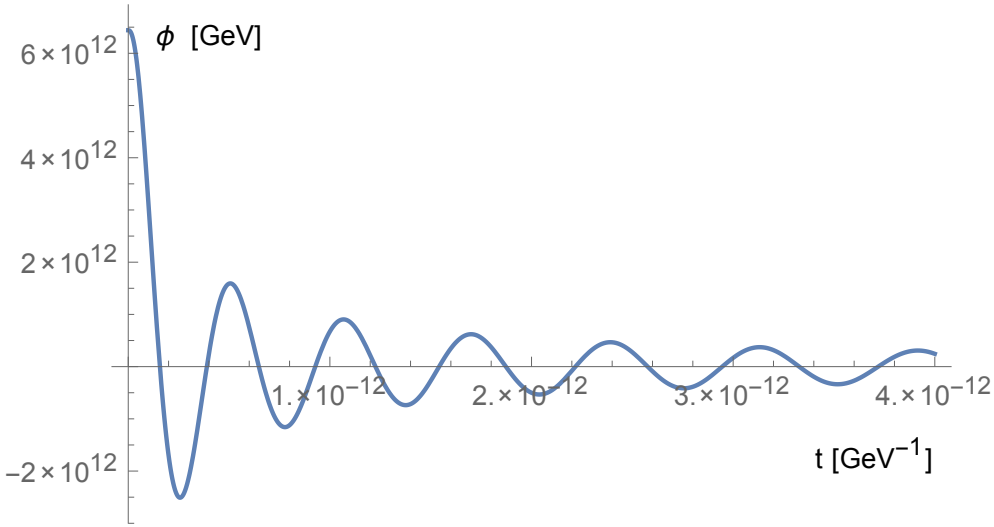

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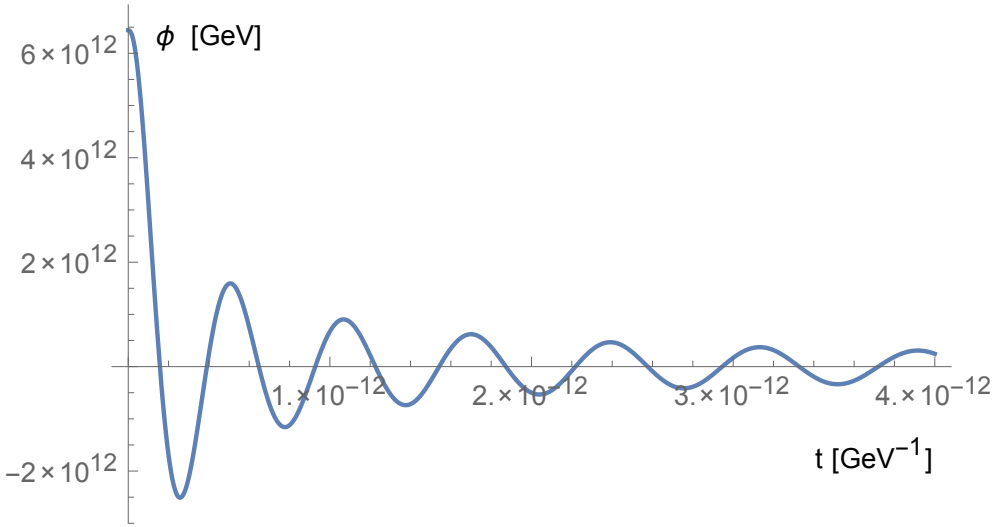

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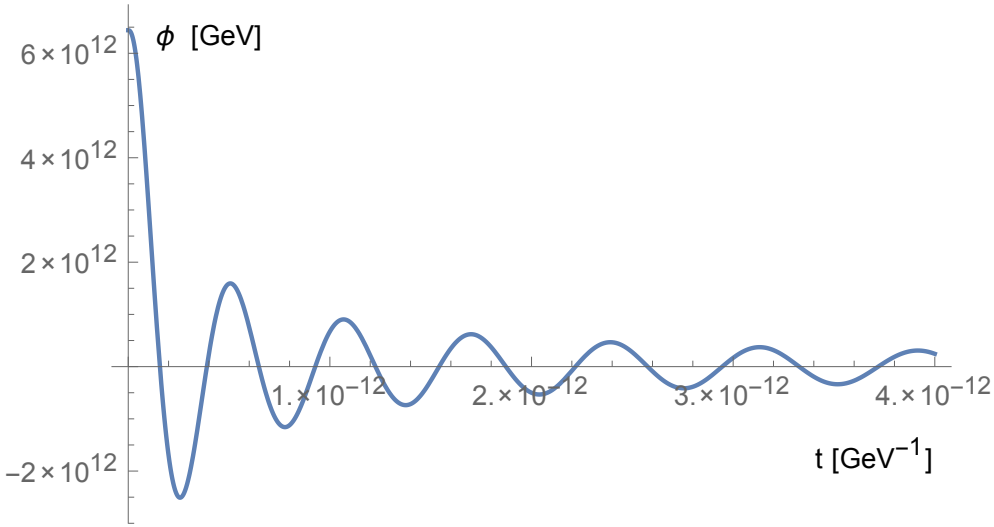

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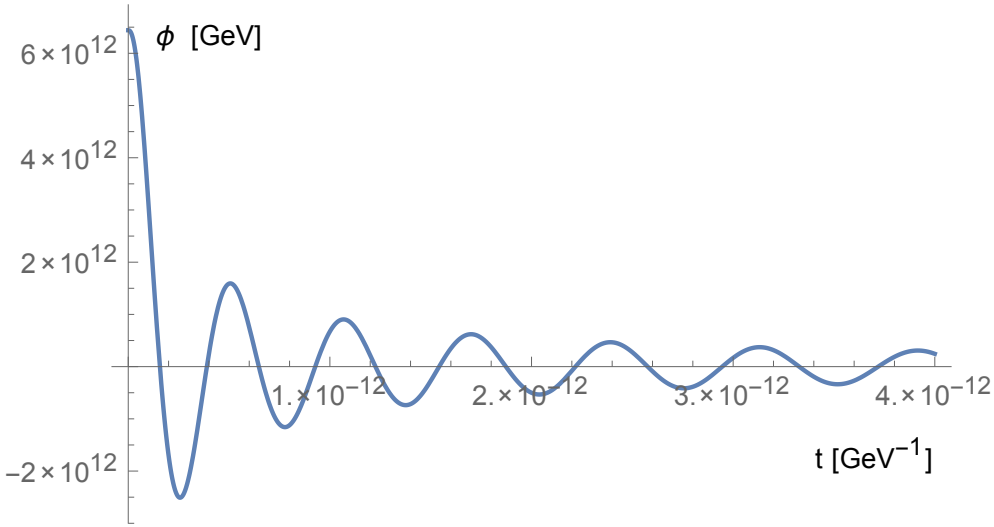

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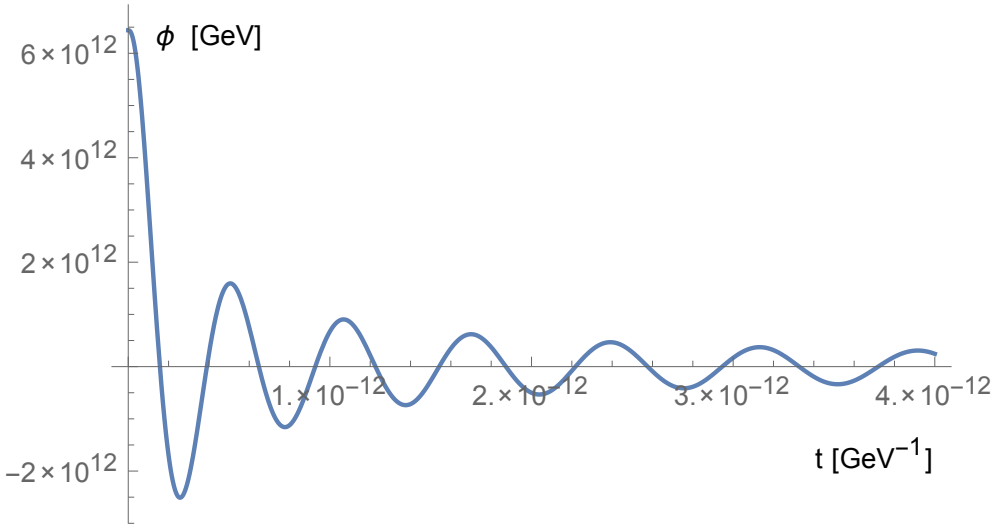
  - Early freeze-out of lepton-number-violating interactions



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- The system won't reach the equilibrium asymmetry, but approaches it.

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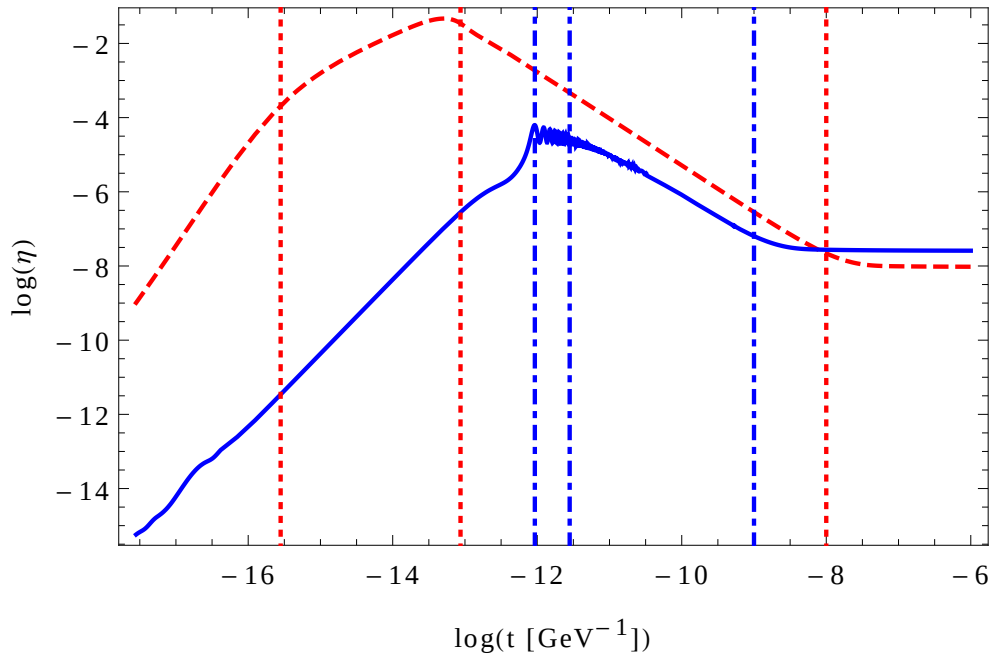
- If we take $T \ll M_R$ (to suppress thermal leptogenesis), lepton-number-violating interactions are suppressed.
- Interactions may not ever be in equilibrium, become ineffective early.
- Asymmetry can still be sizeable if μ_{eff} is large.
- The system won't reach the equilibrium asymmetry, but approaches it.
- Production of asymmetry described by Boltzmann equation:

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

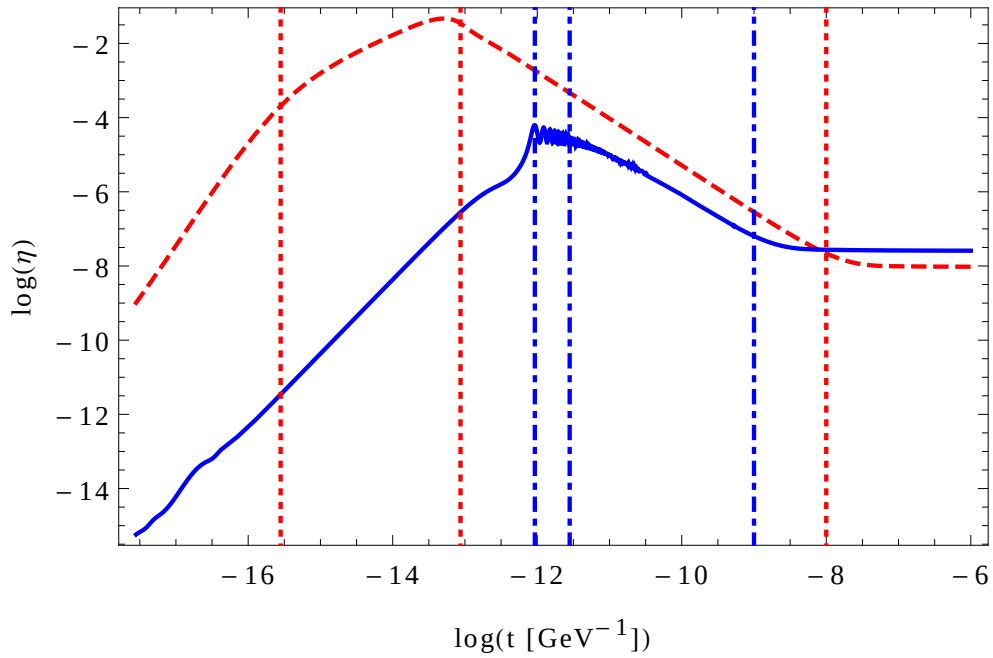
Calculating the Lepton Asymmetry



Blue: Vertical lines: 1) First Higgs VEV crossing, 2) $T = T_{\max}$, 3) Start of radiation domination.

- $\Lambda_I = 10^{15}$ GeV, $\Gamma_I = 10^9$ GeV, $M_R = 9 \cdot 10^{15}\,\mathrm{GeV}$ (near perturbativity bound) and $T_{\max} = 6 \times 10^{13}$ GeV.
- Chose $\Lambda_n = T$ in μ_{eff}.
- (Initial Condition Type 1.)

Calculating the Lepton Asymmetry

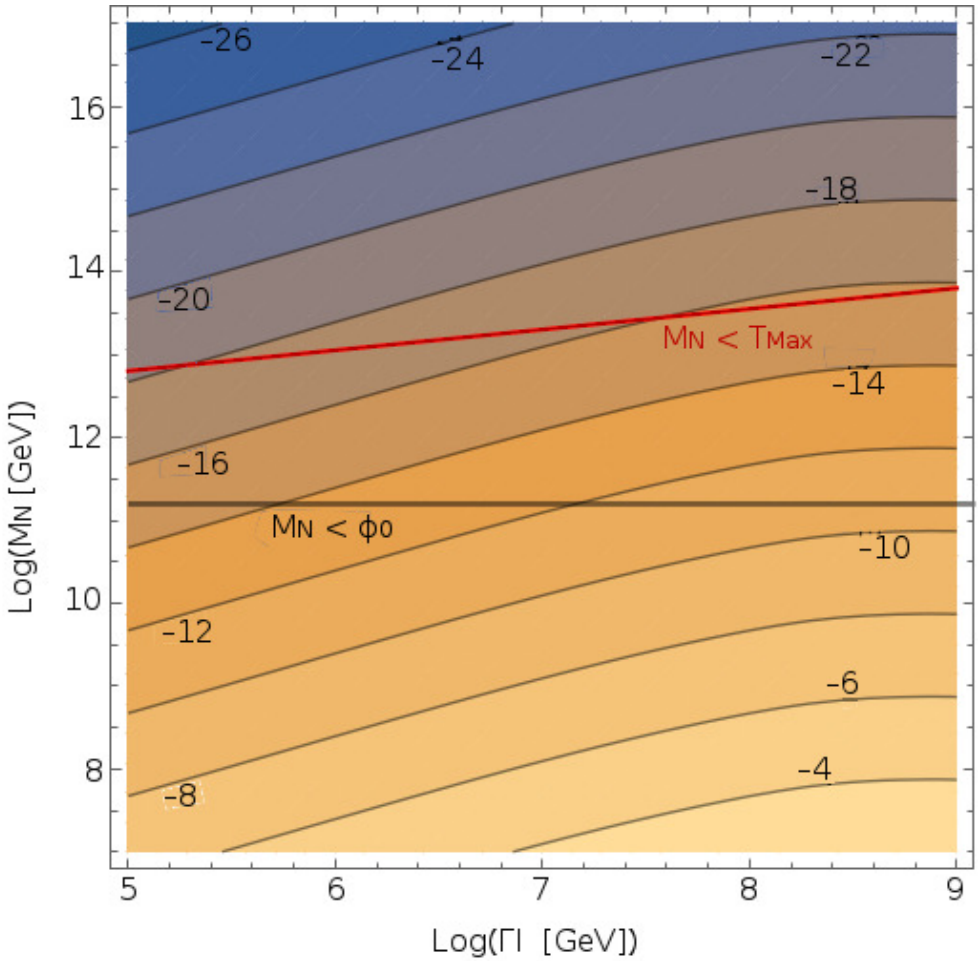


Red: Vertical lines: 1) $T = T_{\max}$, 2) First Higgs VEV crossing, 3) Start of radation domination.

- $\Lambda_I = 10^{17}$ GeV, $\Gamma_I = 10^8$ GeV, $M_R = 9 \cdot 10^{15}\,\mathrm{GeV}$ (near perturbativity bound) and $T_{\max} = 3 \times 10^{14}$ GeV.
- Chose $\Lambda_n = 5 \times 10^{12}$ GeV in μ_{eff}.
- (Initial Condition Type 2.)

Sample Parameter Space Plots

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

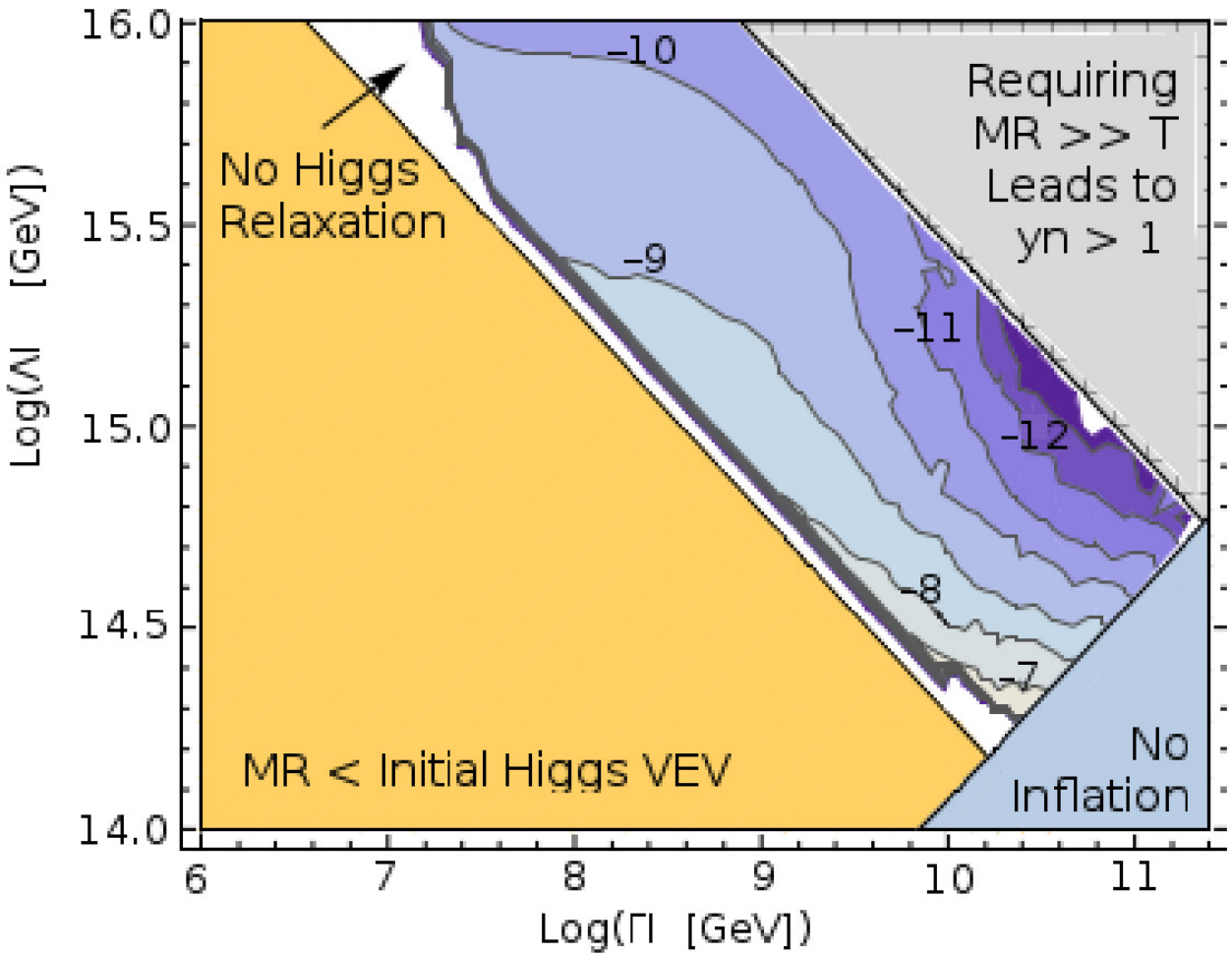


Contours of $\log(Y)$ shown. Need $\mathcal{O}(10^{-10})$ or larger.

$\Lambda_I = 10^{15}\,\mathrm{GeV}$. Parameter space only where use of effective operator is questionable.

Sample Parameter Space Plots

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



Contours of $\log(Y)$ shown. Need $\mathcal{O}(10^{-10})$ or larger.

If 2nd Higgs minimum is quasistable, have parameter space even with scale of $\mathcal{O}_6$ operator set by T.

Further Extensions

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- Analyzed using Bogoliubov transformations to describe particle production from Higgs condensate.

  LP, L. Yang, A. Kusenko, M. Peloso, Phys.Rev.D92 2, 023509

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- Small variations in initial VEV between Hubble patches can source isocurvature pertubations and affect the cosmic infrared background radiation.

  M. Kawasaki, A. Kusenko, LP, L. Yang, arXiv:1701.02175

Conclusions

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- **The measured Higgs mass suggests the existence of a Higgs relaxation epoch!**

The Higgs,
relaxing at Aspen

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- Via an $\mathcal{O}_6$ operator, the evolving Higgs VEV can act as a chemical potential for baryon and lepton number.

The Higgs, relaxing at Aspen

Conclusions

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- **The measured Higgs mass suggests the existence of a Higgs relaxation epoch!**
- Via an $\mathcal{O}_6$ operator, the evolving Higgs VEV can act as a chemical potential for baryon and lepton number.
- Then we can have successful leptogenesis in this new epoch.

The Higgs, relaxing at Aspen

Back-Up Slides

Back-Up Slides: Reheating

Reheating

- Used a very simple model for reheating:
- Temperature of plasma from radiation density:

$$\rho_R = \frac{g_* \pi^2}{30} T^4$$

- Preheating (increasing the amount of plasma) would generally be helpful for our model

Back-Up Slides: Generating the $\mathcal{O}_6$ Operator

Requirements

To generate the $\mathcal{O}_6$ operator, need the following:

1. Heavy states which do NOT get masses via the Higgs mechanism
2. Which couple to $\mathrm{SU_L}(2)$, $\mathrm{U}(1)$ gauge bosons

Options:

1. Scalars: $\mathrm{SU}(2)$ triplet which also couples to Higgs
   - If neutral member, no or small VEV (electroweak precision)
2. Fermions: Requires two doublets, L and R, each of which couples to $\mathrm{SU}(2)$ (see below)

Back-Up Slides: Generating the $\mathcal{O}_6$ Operator

Example Explicit Fermionic Model

- Fields:
  - Set of Dirac spinors ψ_{Di} (*both left and right*): $\mathrm{SU}(2)$ doublet, hypercharge $-1/2$
  - Dirac spinor ψ_S (*both left and right*): $\mathrm{SU}(2)$ singlet, hypercharge -1
  - Higgs field Φ: $\mathrm{SU}(2)$ doublet, hypercharge $1/2$

where $Y_W = Q - T_3$.

Back-Up Slides: Generating the $\mathcal{O}_6$ Operator

Lagrangian

- With these fields, we can write the Lagrangian:

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

- Last line is allowed because both $\bar{\psi}_{DL}$ and $\bar{\psi}_{DR}$ are $\mathrm{SU}(2)$ doublets
- 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.

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:

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

  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 to the heavy fermions that generate the $\mathcal{O}_6$ operator

Back-Up Slides: Interpretting μ

Interpretting μ

- If ϕ propagating d.o.f., then drops out of Hamiltonian.
- Require separation of scales:
  - Typical scatterings in plasma at temp T (High)
  - Time scales of VEV evolution (Low)
- Introduce Wilsonian cutoff, integrate out scales
- Effective theory: ϕ, $\partial_t \phi$ not propagating degrees of freedom
- Construct Hamiltonian for plasma in usual manner, has chemical potential

Back-Up Slides: Spontaneous Barygonesis

Dine et. al. (1991)

Cohen, Kaplan, Nelson (1991)

Effective Chemical Potential

$$\mathcal{O}_6 \propto -\frac{1}{\Lambda_n^2}(\partial_\mu \phi^2) j^\mu_{\mathrm{B+L}},$$

- This $\mathcal{O}_6$ is similar to the one used in spontaneous baryogenesis.
- However, we have $\mu_{\mathrm{eff}} \sim (\partial_t \phi^2)$, not $\partial_t \phi$.
- Therefore, asymmetry with same sign generated in all Hubble patches.

Back-Up Slides: Sphaleron Redistribution

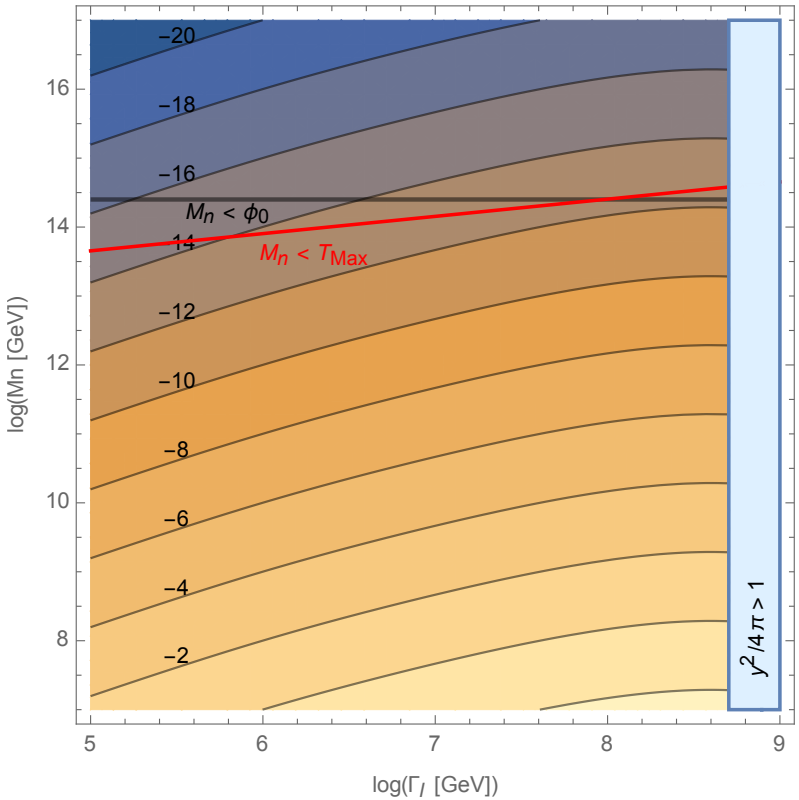
Leptons to Baryons

- Only lepton number violation, so produce a lepton asymmetry
- Electroweak sphalerons redistribute asymmetry between leptons and baryons
- (Actually, since EW sphalerons conserve $B - L$, want to make an excess of antileptons $\rightarrow$ sign change in $\mathcal{O}_6$)

Back-Up Slides: Parameter Space with M_n

Yang, LP, Kusenko

Phys.Rev. D92 (2015)



$\Lambda_I = 5 \cdot 10^{16}\,\mathrm{GeV}$ fixed. Taking the scale of the $\mathcal{O}_6$ operator to be an independent parameter gives additional freedom. However, the use of effective field theory may not be valid in regions with large enough asymmetry.

Back-Up Slides: Plasma Scatterings Summary

General Remarks

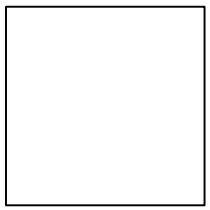
To create a sufficiently large asymmetry, there should be sufficiently many interactions in the plasma during Higgs relaxation:

- Requires a fast reheating (preheating?)
- Therefore favors a high reheat temperature

Back-Up Slides: Particle Production From Background Field Evolution

Particle Production From Background Field Evolution

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



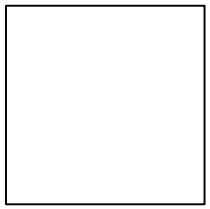
$$\left\langle \psi|a^\dagger(t=0)a(t=0)|\psi \right\rangle = 0$$

Back-Up Slides: Particle Production From Background Field Evolution

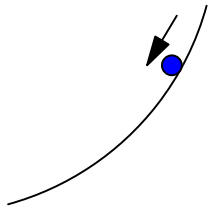
Particle Production From Background Field Evolution

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



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

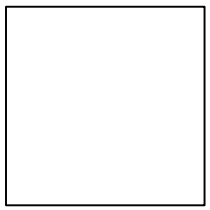


$$a(t) \sim \alpha a(0) + \beta a^\dagger(0)$$

Back-Up Slides: Particle Production From Background Field Evolution

Particle Production From Background Field Evolution

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



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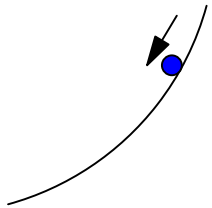
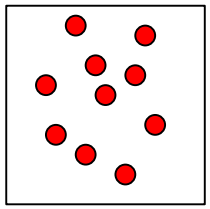


$a(t) \sim \alpha a(0) + \beta a^\dagger(0)$

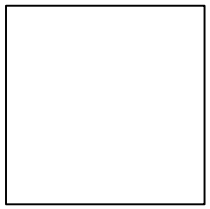


$\left\langle \psi|a^\dagger(t)a(t)|\psi \right\rangle \propto |\beta|^2$

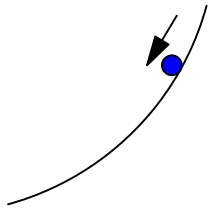
Back-Up Slides: Particle Production From Background Field Evolution

Particle Production From Background Field Evolution

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



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



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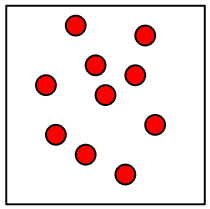


$$\left\langle \psi | a^\dagger(t) a(t) | \psi \right\rangle \propto |\beta|^2$$

Back-Up Slides: Production From Background Field Evolution

Analysis

- Advantage: No longer requires a fast reheating.
- Still requires both $\mathcal{O}_6$ operator AND RH neutrino mass:
  - Without M_R, there is no mixing between positive and negative frequency solutions
  - $E = \sqrt{(|\mathbf{p}|^2 + h\mu_{\rm eff})^2 + M_L^2}$, so the $\mathcal{O}_6$ operator is necessary to bias the energy of particles ($h = -1$) vs. antiparticles ($h = +1$)
- With these two ingredients, $|\beta_\nu|^2 \neq |\beta_{\bar{\nu}}|^2$

Back-Up Slides: Background Field Evolution

LP, Yang, Kusenko, Peloso

Phys.Rev. D92 (2015)

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)

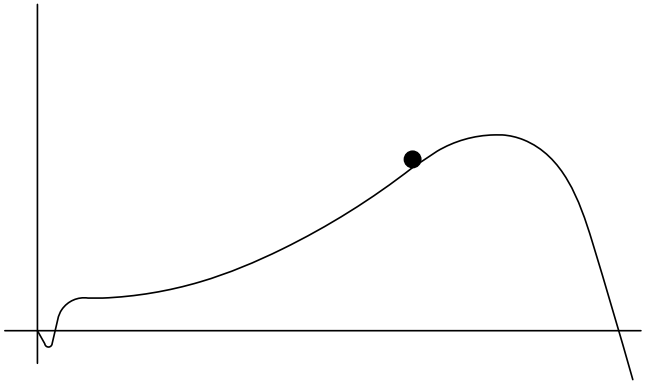
- Numerical analysis shows regions of parameter space where a sufficiently large asymmetry is generated:
- New scales generally $10^{11} \sim 10^{12}$ GeV

Back-Up Slides: Production From Background Field Evolution

Discussion

- Asymmetry proportional to $\eta_L \sim \mu_{\max}^3 T_{\rm RH}/\Lambda_I^4$ where Λ_I is the energy density of inflaton field
- Since $T_{\rm RH} \lesssim \Lambda_I$, this mechanism favors low reheat temperatures
- (Unlike first mechanism)

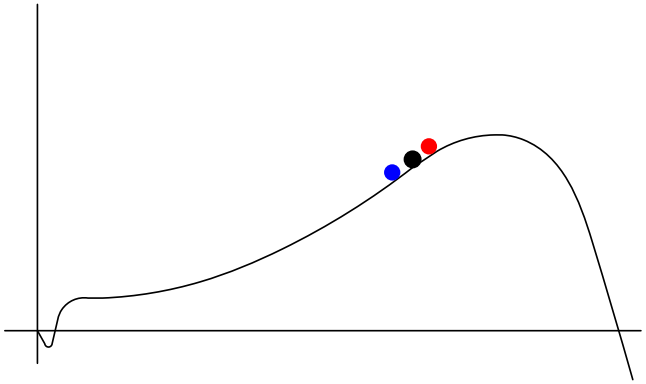
Back-Up Slides: Generating Isocurvature Perturbations



Back-Up Slides: VEV Variation

- The discussion above is about the *average* Higgs VEV, when averaged over many Hubble volumes.

Back-Up Slides: Generating Isocurvature Perturbations



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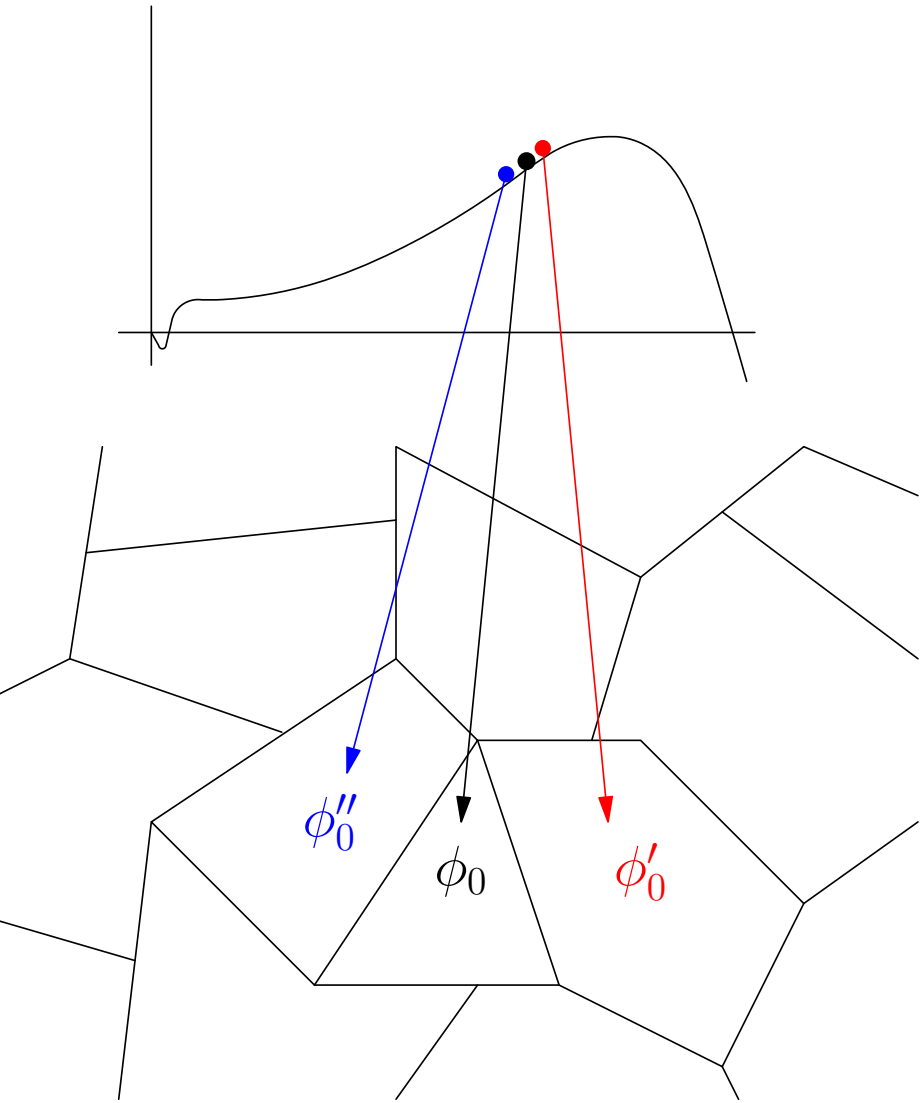

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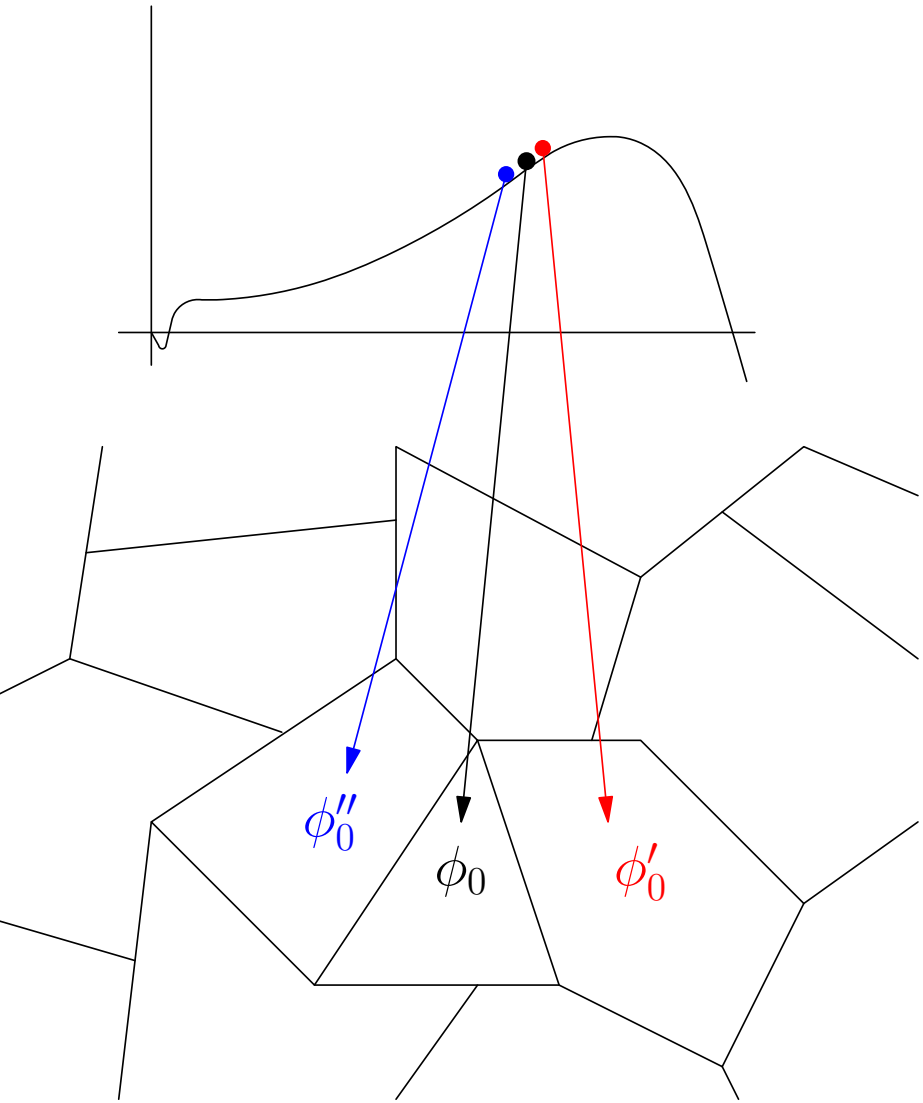

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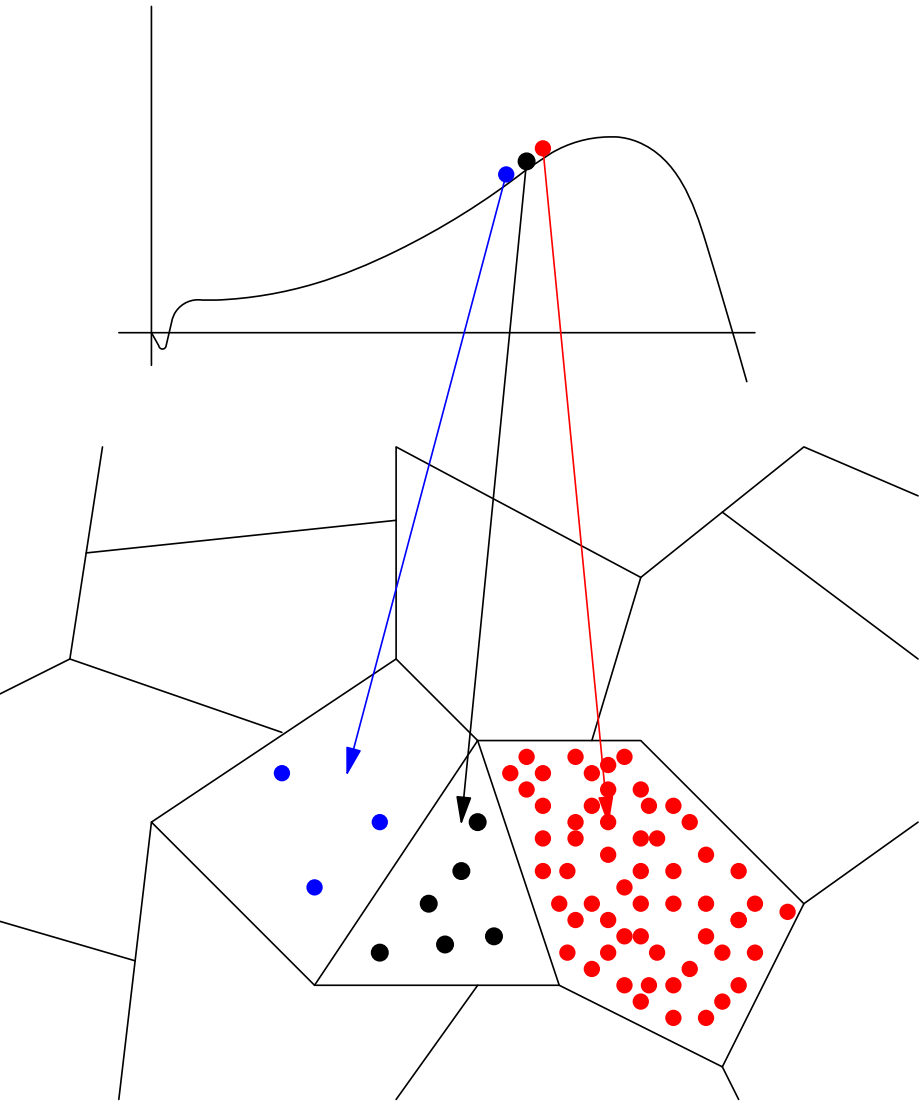

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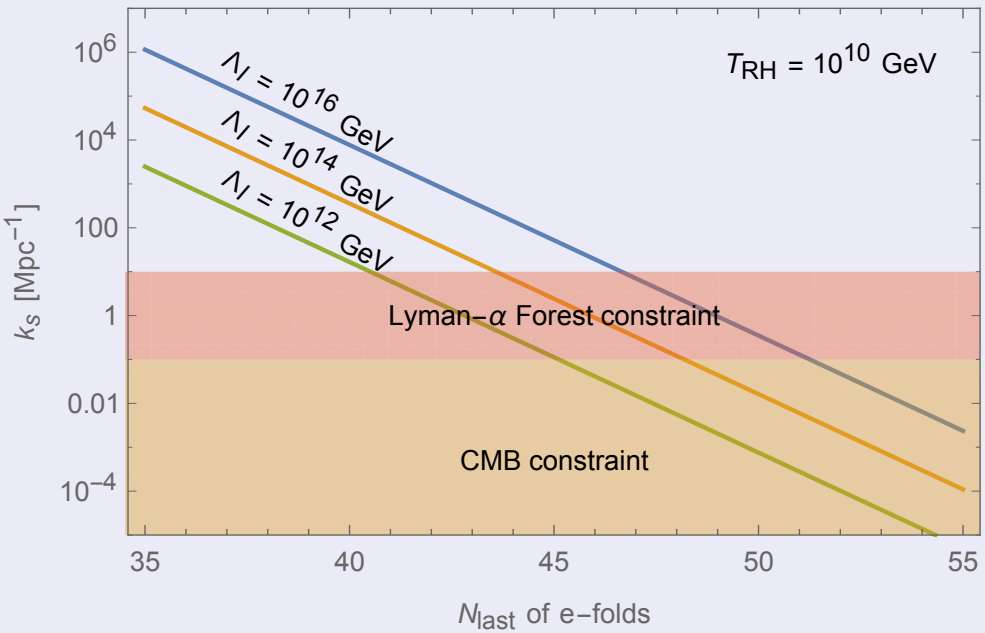
- The VEVs in individual Hubble volumes varies.
- The final particle-antiparticle asymmetry depends on the initial Higgs VEV.
- Different amount of baryons in different Hubble volumes leads to isocurvature perturbations.

Back-Up Slides: Bounds on $N_{\rm last}$

Bound on Growth of Initial VEV

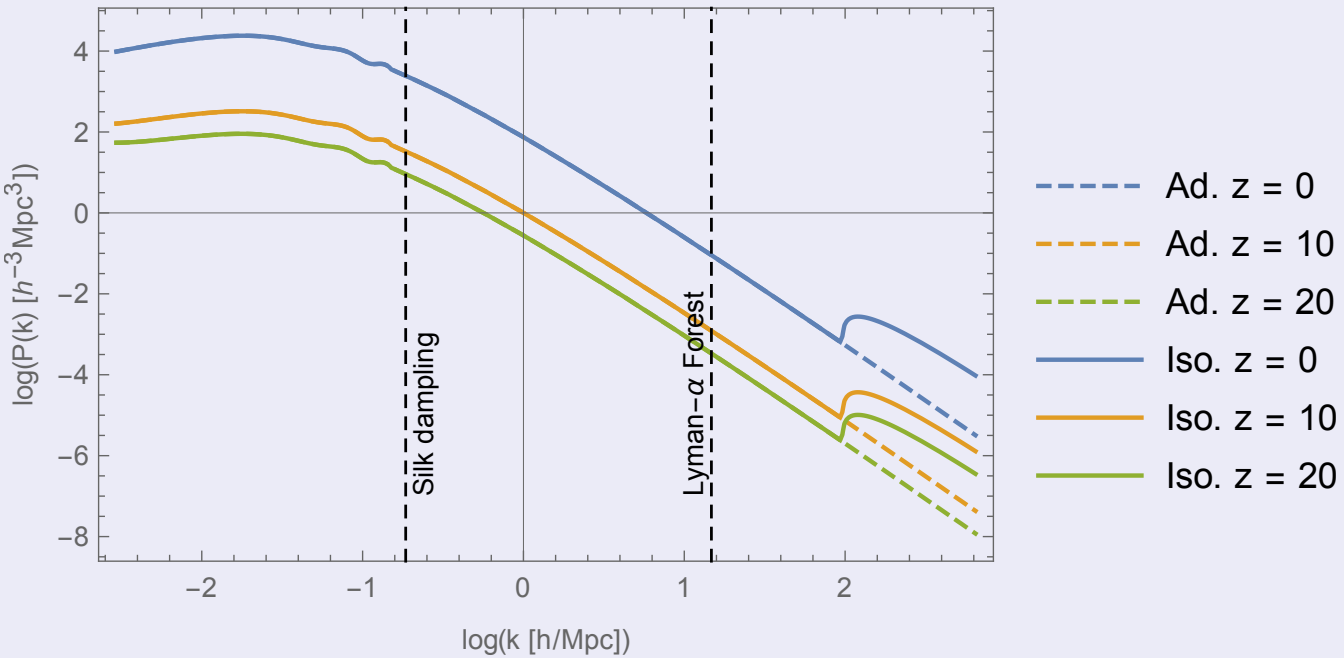
k_s: Comoving wavenumber of mode that exits at $N_{\rm last}$ e-folds before the end of inflation (limit of flat potential)



Back-Up Slides: Cosmic Infrared Background

Isocurvature Modes

- Isocurvature perturbations produced for $k > k_S$ set by scale at which Higgs VEV starts growing (during inflation):



Back-Up Slides: Recently...

Kashlinsky et. al. (2015)

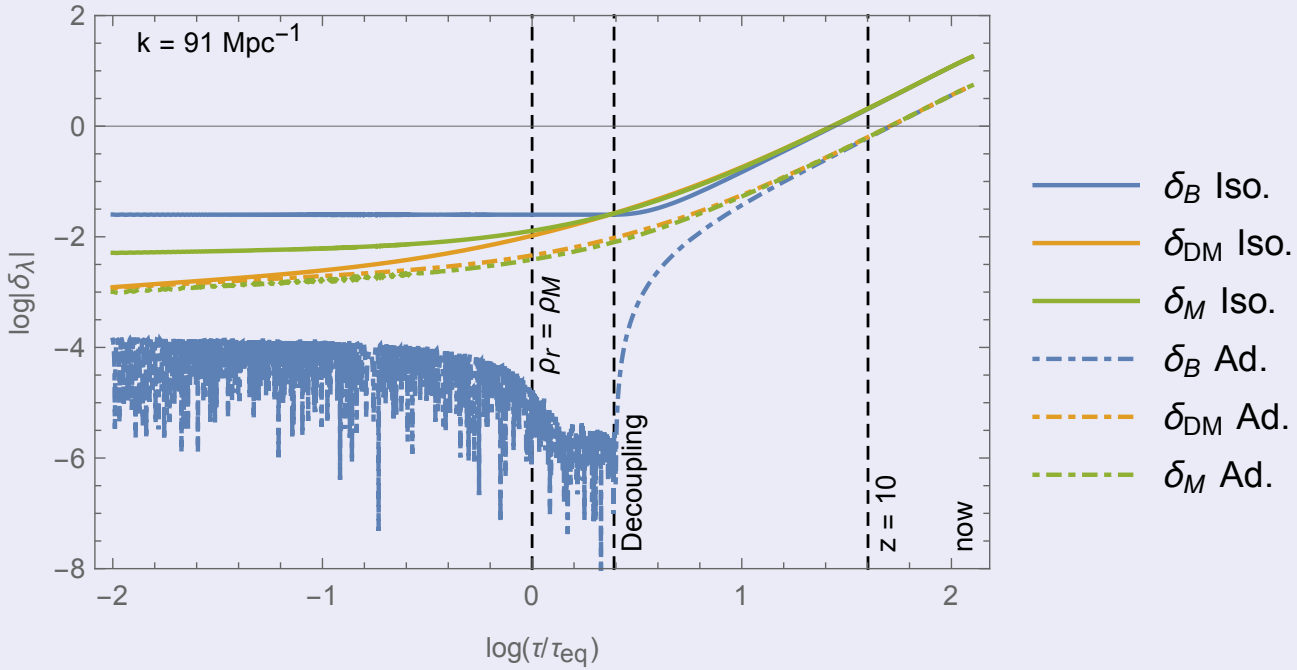
Why?

- Spitzer and Akari space telescopes have observed (source-subtracted) anisotropies in the cosmic infrared background (5 arcminutes, $2 - 5\,\mu\mathrm{m}$, $0.09\,\mathrm{nW\,m^{-2}\,sr^{-1}}$)
- From the anisotropy, infer a large isotropic CIB flux
- Explain with early stars ($z = 10$)?
- Requires mass fraction of baryons in star-forming collapsed halos, f_{halo}, ~ 0.2, which is too large...
- ...but isocurvature perturbations can enhance f_{halo}!

Back-Up Slides: Cosmic Infrared Background

Isocurvature Fluctuations

- Evolve isocurvature perturbations forward in time:



- Find power spectrum

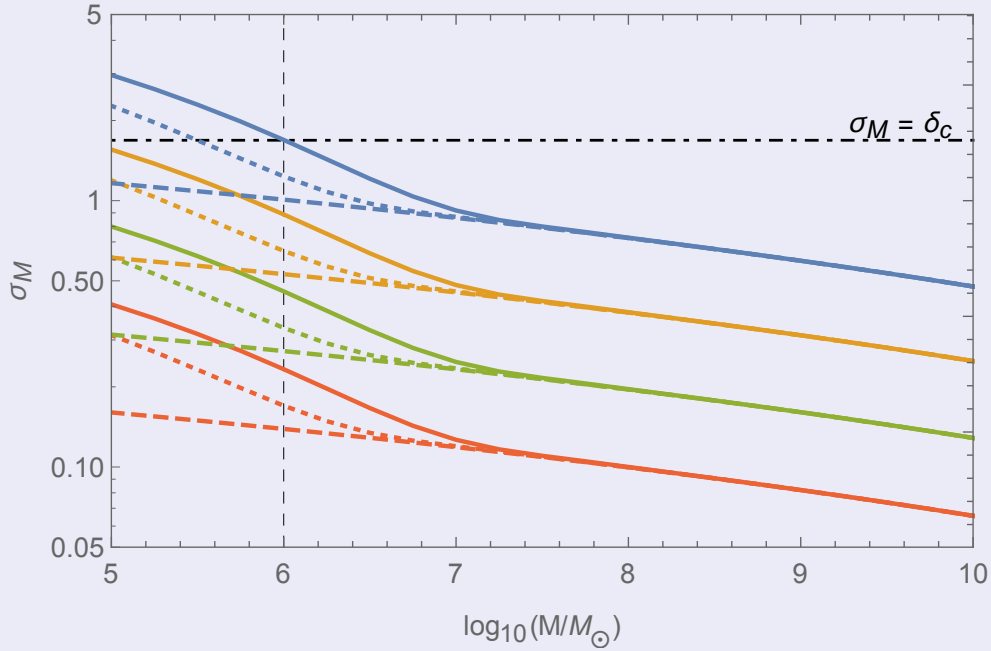
Back-Up Slides: Cosmic Infrared Background

Isocurvature Fluctuations

Back-Up Slides: Cosmic Infrared Background

Isocurvature Fluctuations

- Isocurvature perturbations cause clumps of matter to evolve non-linearly:

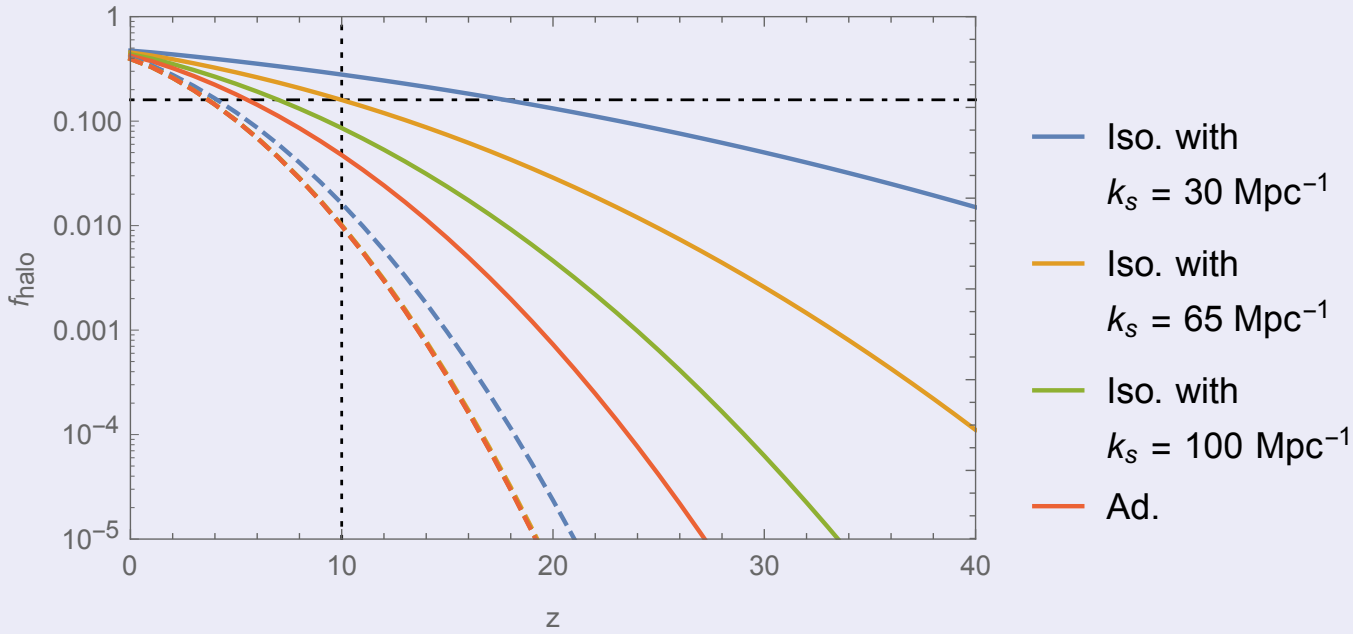


Dashed color lines: No isocurvature perturbations
Solid color lines: Including isocurvature perturbations, $k_s = 65\,\mathrm{Mpc}^{-1}$
Dotted color lines Including isocurvature perturbations, $k_s = 100\,\mathrm{Mpc}^{-1}$
Blue: $z = 10$, Yellow: $z = 20$, Green: $z = 40$, Red: $z = 80$

Back-Up Slides: Cosmic Infrared Background

Isocurvature Fluctuations

- Calculate $f_{\rm halo}$:



Solid: Mass fraction of baryons in collapsed halos of mass $10^6 M_\odot$ (star forming)

Dashed: Mass fraction of baryons in collapsed halos of mass $10^8 M_\odot$ (dwarf galaxy)

Back-Up Slides: How To Suppress Isocurvature Perturbations

Higher Dimensional Operators

- At large VEVs, the Higgs potential may be sensitive to higher dimensional operators, which are suppressed by large mass powers.
- We will consider two specific cases of effective operators that can appropriately modify the potential.

Back-Up Slides: IC-2: Higgs-Inflaton Coupling

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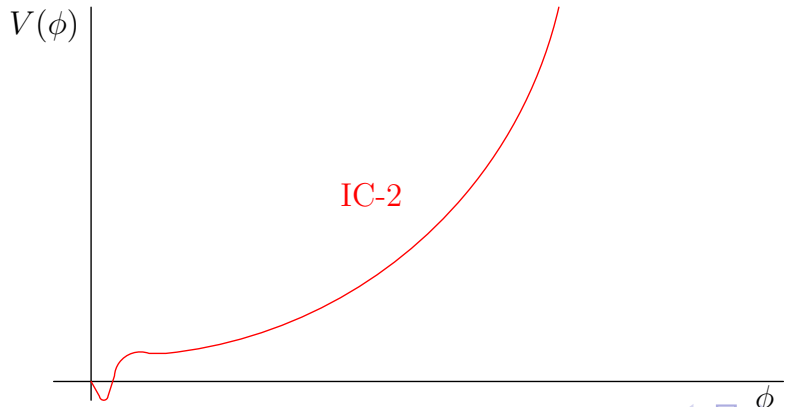

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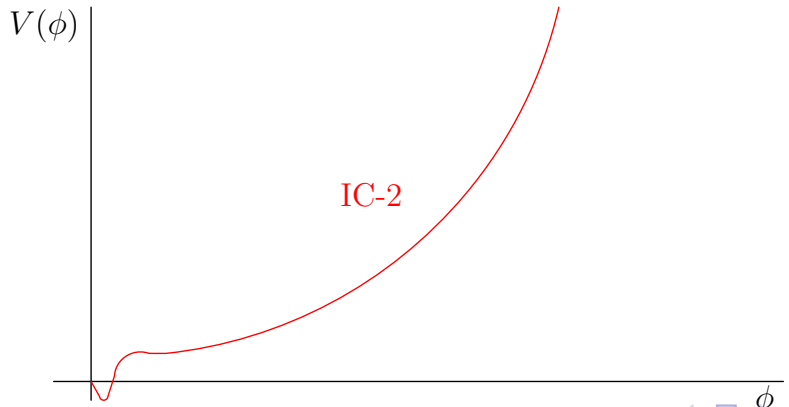

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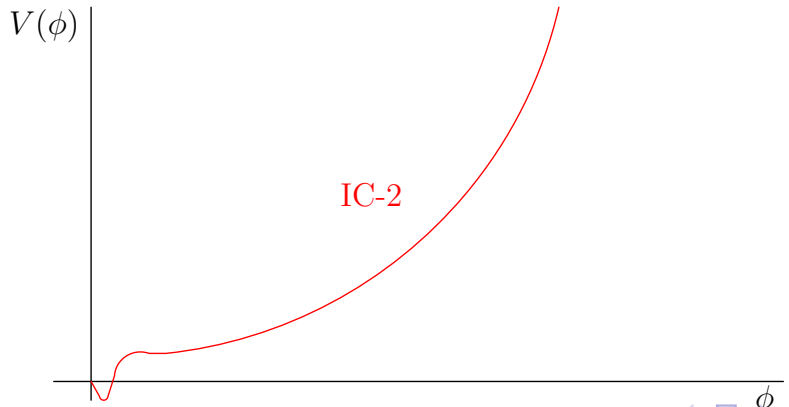

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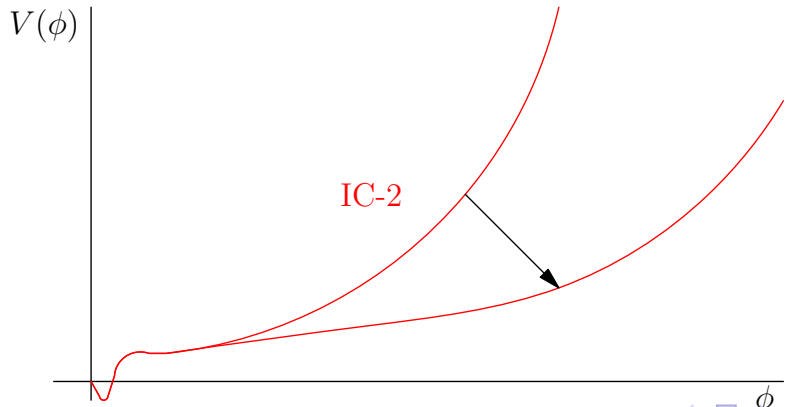

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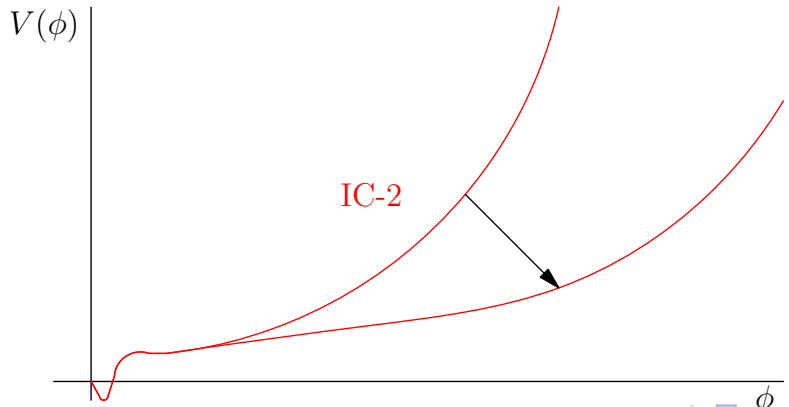

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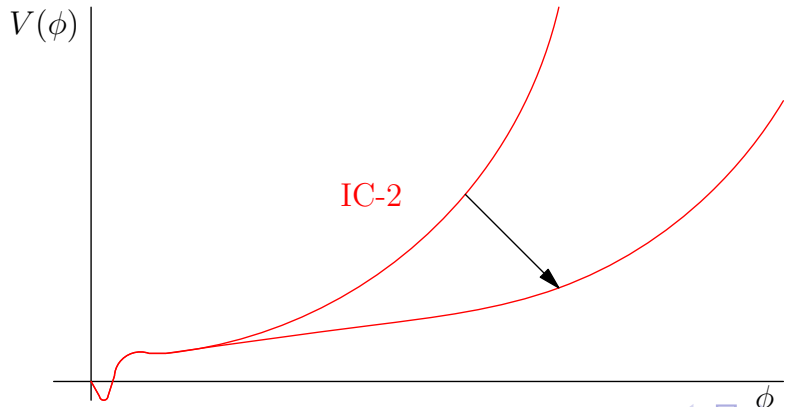

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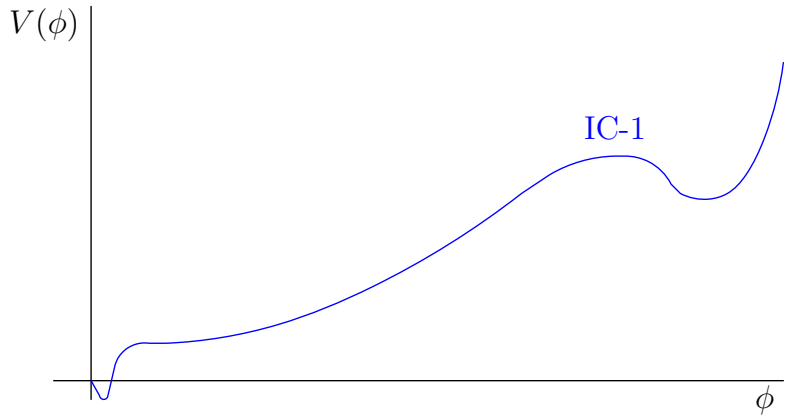

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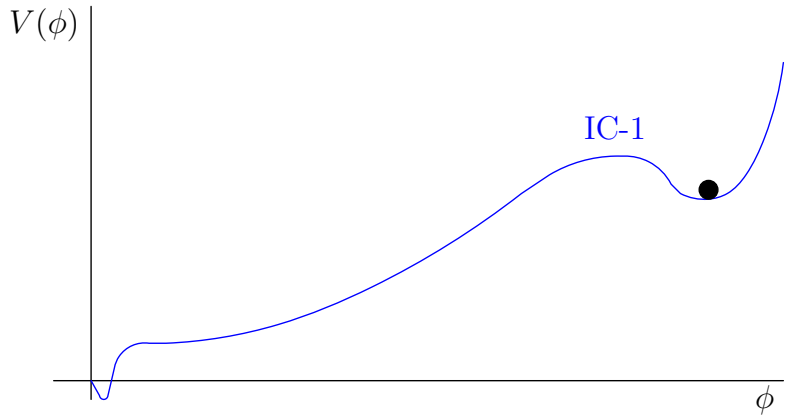
- There is (some) cosmological motivation to lift this vacuum.
- If we lift, but don't eliminate, the second vacuum, the Higgs VEV could remain trapped in it during inflation (assuming it takes a stochastic distribution of values, similar to chaotic inflationary models).



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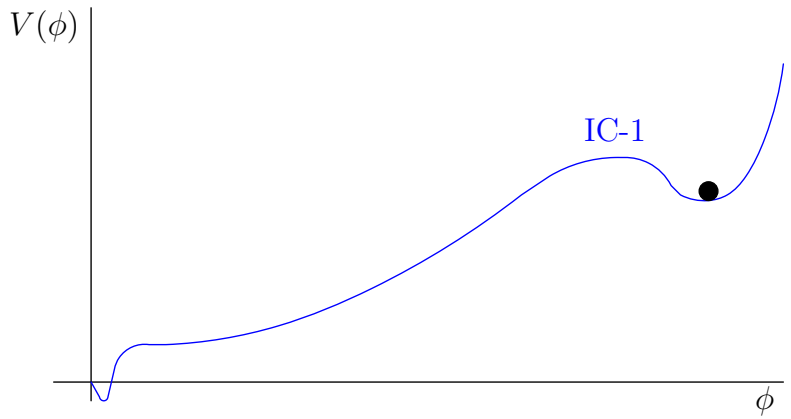
- If reheating is sufficient to destabilize this false vacuum, then the Higgs VEV will roll down to the finite-temperature minimum at $\phi = 0$.
- Use effective operators of the form ϕ^{2n}/M^{2n-4}.