Evolution of Scalar Fields in the Early Universe

Louis Yang

Department of Physics and Astronomy
University of California, Los Angeles

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Advisor: Alexander Kusenko

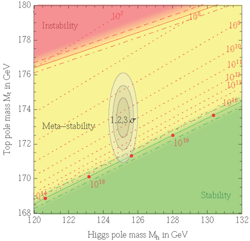
Collaborator: Lauren Pearce

The Motivation

- The recent discovery of the Higgs boson with mass

$$M_h = 125.7 \pm 0.4\,\text{GeV}$$

[Particle Data Group 2014]



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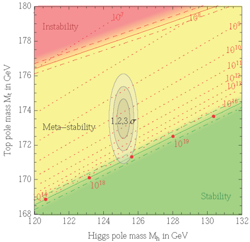

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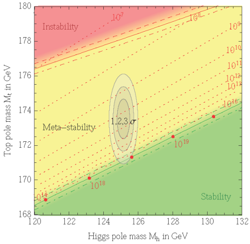

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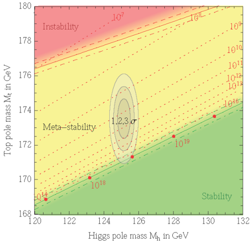

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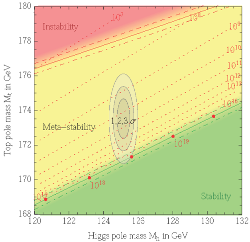

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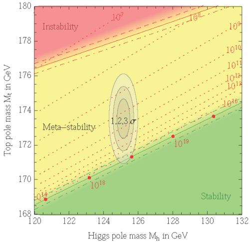

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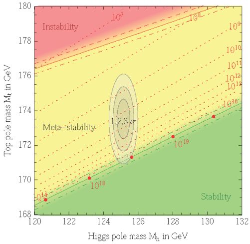

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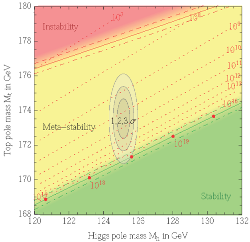
$\Rightarrow$possibility for **Leptogenesis**



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Outline

Quantum Fluctuations in the Inflationary Universe

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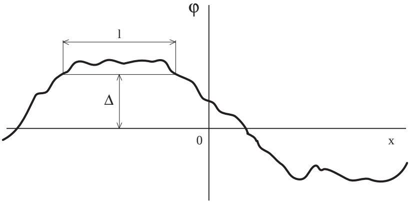

[Figure from A. Linde - arXiv: 0503203]

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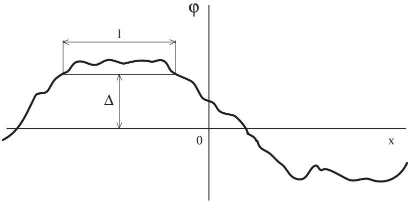

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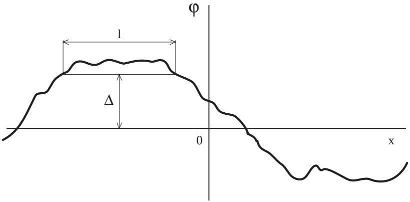

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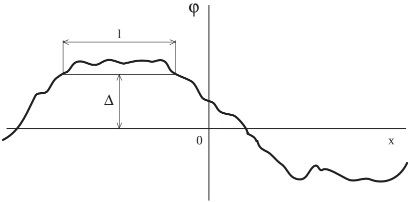

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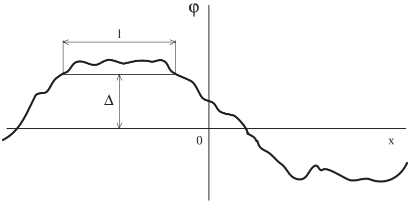

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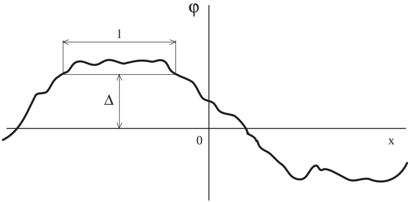
  => behave like (quasi) classical field.



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- In a pure **de Sitter spacetime**, a scalar field with mass m can obtain a large VEV

$$\langle \phi^2 \rangle = \frac{3H^4}{8\pi^2 m^2} \quad \text{for } m^2 \ll H^2.$$

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- In the **inflationary universe**, the exponential expansion period exists for a **finite time** t

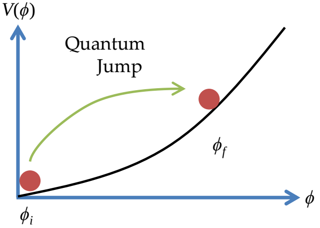
$$\langle\phi^2\rangle \approx \frac{H^2}{2\left(2\pi\right)^3}\int_{He^{-Ht}}^{H}\frac{d^3k}{k} = \frac{H^3}{4\pi^2}t \simeq \frac{H^2}{4\pi^2}N$$

for $m^2 = 0$ or $m^2 \ll H^2$ with $t \lesssim 3H/m^2$. $N \simeq Ht$ is the number of e-folds. [A. Linde, Phys. Lett. B116, 335 (1982)]

Hawking-Moss tunneling

Hawking & Moss (1982)

- One can also understand the fluctuation as both the **scalar field** $\phi(x)$ and the **metric** $g_{\mu\nu}(x)$ experience quantum jumps.



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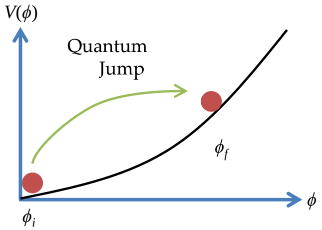
- **The Hawking-Moss instanton**

$$\frac{\Gamma\left(\phi_i \to \phi_f\right)}{\mathcal{V}} = Ae^{S_E(\phi_i) - S_E(\phi_f)}, \qquad \text{where} \quad S_E(\phi) = -\frac{3m_{pl}^4}{8V\left(\phi\right)}$$

is the Euclidean action and A is some $\mathcal{O}(m^4)$ prefactor.



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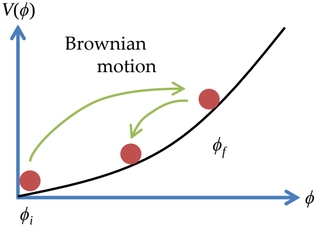
- The entire process can then be viewed as the fields are underdoing **Brownian motion** and can be described by **diffusion equation**.



Stochastic approach & Hawking-Moss tunneling

- $P_c(\phi, t)$: the probability distribution of finding ϕ at time t
- Diffusion equation

$$\frac{\partial P_c}{\partial t} = -\frac{\partial j_c}{\partial \phi} \quad \text{where} \quad -j_c = \frac{\partial}{\partial \phi}\left(\frac{H^3 P_c}{8\pi^2}\right) + \frac{P_c}{3H}\frac{dV}{d\phi}$$

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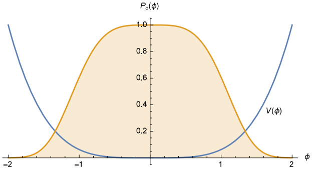

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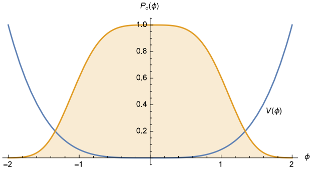
- In equilibrium $\partial P_c / \partial t = 0$, $j_c = 0$. One obtain the distribution

$$P_c(\phi) = e^{S_E(\phi_{\min}) - S_E(\phi)}$$

$$\approx \exp\left[\frac{-3m_{pl}^4}{8}\frac{\Delta V(\phi)}{V(\phi_{\min})^2}\right]$$

for $\Delta V = V(\phi) - V(\phi_{\min}) \ll V(\phi_{\min})$.



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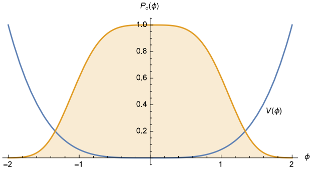

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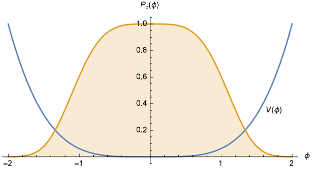

- The variance of the fluctuation is

$$\langle \phi^2 \rangle = \frac{\int \phi^2 P_c(\phi) d\phi}{\int P_c(\phi) d\phi}$$

Quantum fluctuation of the Higgs field

- Example: the Higgs field ϕ on the inflationary background (inflaton I).

$$V\left(\phi, I\right) = V_H\left(\phi\right) + V_I\left(I\right) + \ldots \approx \frac{1}{4}\lambda_{\text{eff}}\phi^4 + \Lambda_I^4 + \ldots$$

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$$\frac{1}{4}\lambda_{\rm eff}\phi^4 < \frac{8}{3}\left(\frac{\Lambda_I^2}{m_{pl}}\right)^4 \sim H_I^4 \qquad \Rightarrow \qquad |\phi| < 0.62\lambda_{\rm eff}^{-1/4} H_I$$

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- Generally, during inflation, we expect the scalar field to obtain a large VEV ϕ_0 such that

$$V_H(\phi_0) \sim H_I^4$$

Classical Motion of Scalar Fields

Slow rolling during inflation

- Scalar field in an expanding universe

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$$9H^2 \gg \frac{\partial^2 V(\phi, I)}{\partial \phi^2} = m_{\text{eff}}^2(\phi) \quad \text{and} \quad \sqrt{48\pi}\frac{V(\phi, I)}{m_{pl}} \gg \left|\frac{\partial V(\phi, I)}{\partial \phi}\right|.$$

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- **As long as $m_{\text{eff}}(\phi) \ll H$, there is insufficient time for the scalar field to roll down.**

Slow rolling of the Higgs field

- For $\frac{1}{4}\lambda\phi^4$ or the Higgs potential, the slow-roll conditions are

$$|\phi| \ll 3\lambda_{\text{eff}}^{-1/2} H_I \qquad \text{and} \qquad |\phi| \ll \left(\frac{27}{4\pi}\right)^{1/6} \lambda_{\text{eff}}^{-1/3} \left(m_{pl} H_I^2\right)^{1/3}.$$

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- The conditions for all the quantum fluctuations to be unable to roll are:

$$\lambda_{\text{eff}} \ll 4800 \qquad \text{and} \qquad \lambda_{\text{eff}} \ll 3 \times 10^5 \left(\frac{m_{pl}}{\Lambda_I}\right)^2,$$

which are easily satisfied when $\Lambda_I < m_{pl}$.

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$$\lambda_{\text{eff}} \ll 4800 \qquad \text{and} \qquad \lambda_{\text{eff}} \ll 3\times 10^5 \left(\frac{m_{pl}}{\Lambda_I}\right)^2,$$

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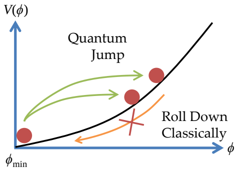
- In other words, during inflation, the Higgs field **can jump quantum mechanically** but **cannot roll down classically**.



Slow rolling of the Higgs field

- For $\frac{1}{4}\lambda\phi^4$ or the Higgs potential, the slow-roll conditions are

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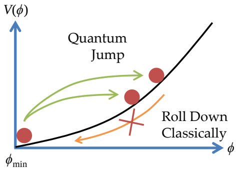
  $\Rightarrow$ a **large Higgs VEV** is developed.



Brief summary

Quantum fluctuation

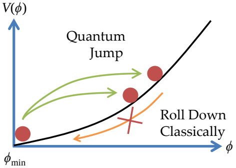
Brings the field to a VEV ϕ_0 such that

$$V_\phi\left(\phi_0\right) \sim H^4$$

Slow rolling

The field won't roll down if

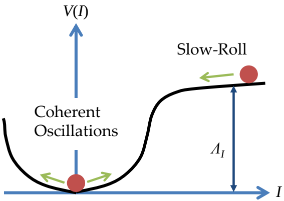
$$m_{\text{eff}}^2 \ll H^2$$

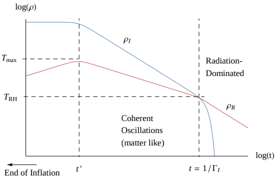


Relaxation of the Higgs field after inflation

- As inflation ends, the inflaton enters the coherent oscillations regime, $H < m_{\text{eff}}(\phi_0)$. The Higgs field is no longer in slow-roll.

Inflaton





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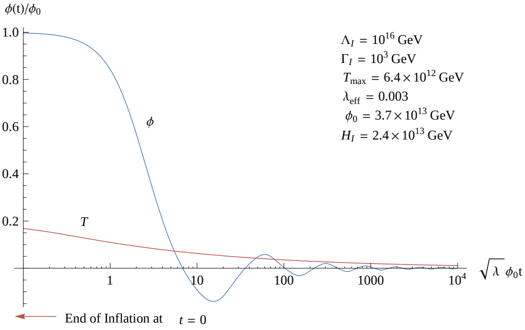
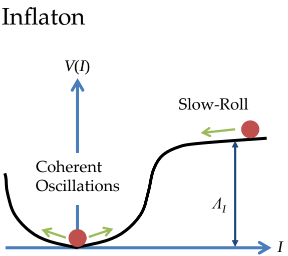
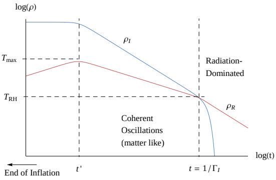
- The Higgs then rolls down and oscillates around $\phi = 0$ with decreasing amplitude within $\tau_{\text{roll}} \sim H^{-1}$.

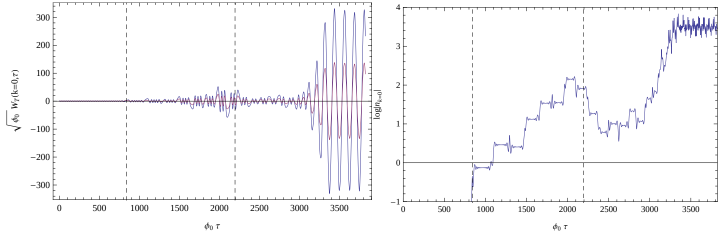






Relaxation of the Higgs field after inflation

- During the oscillation of the Higgs field, the Higgs condensate can decay into several product particles:
  - **Non-perturbative** decay: W and Z bonsons.



$$\Lambda_I = 10^{15} \text{ GeV and } \Gamma_I = 10^9 \text{ GeV for IC-1}$$

  - **Perturbative** decay (thermalization): top quark.
- Those decay channels do affect the oscillation of the Higgs field but they becomes important only after several oscillations.

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Issue with Isocurvature Perturbations

Isocurvature perturbations

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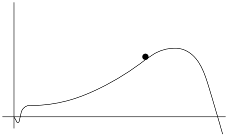

[Figure from Lauren Pearce]

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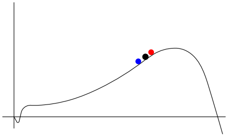

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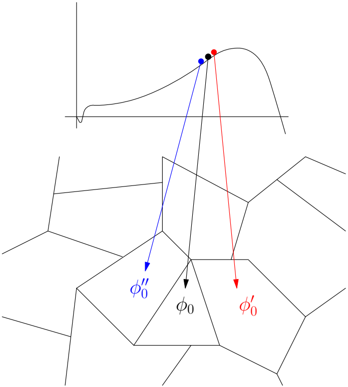

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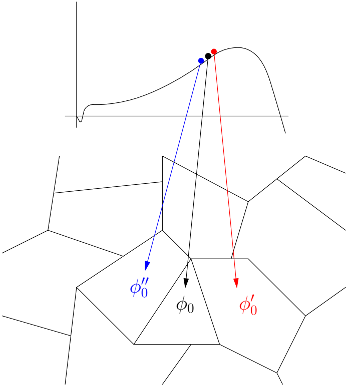

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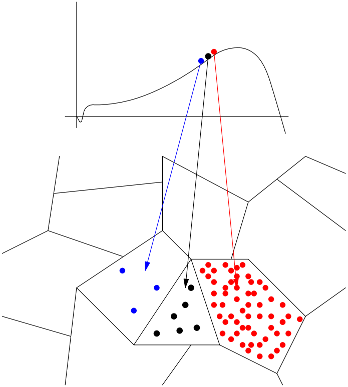

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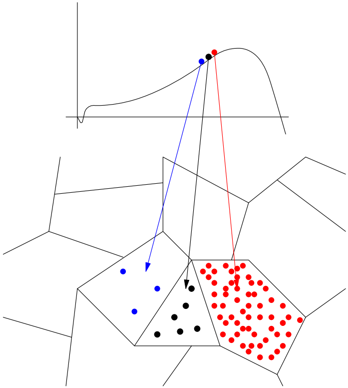
  $\Rightarrow$ Large **isocurvature perturbations**, which are constrainted by current CMB observation.



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Solutions to the isocurvature perturbation issue

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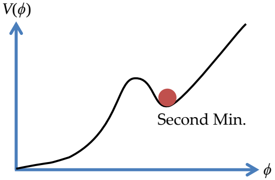

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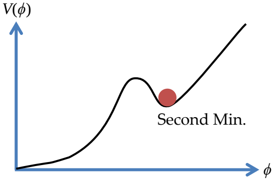

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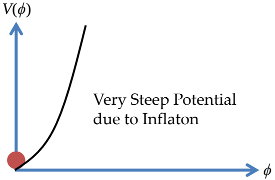

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- The second minimum becomes metastable and higher than the EW vacuum.

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- The scenario:
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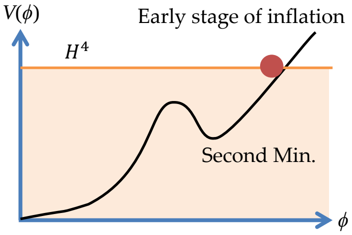

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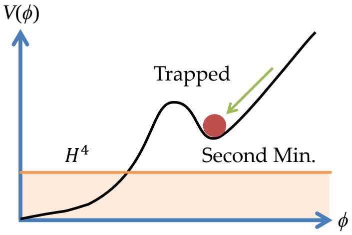

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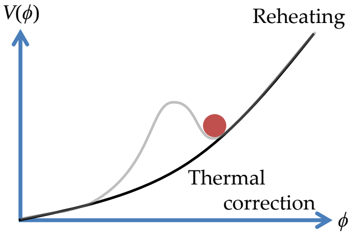

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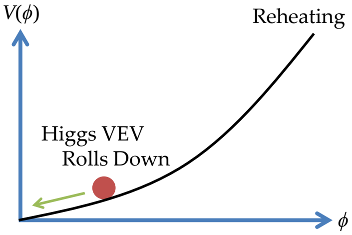

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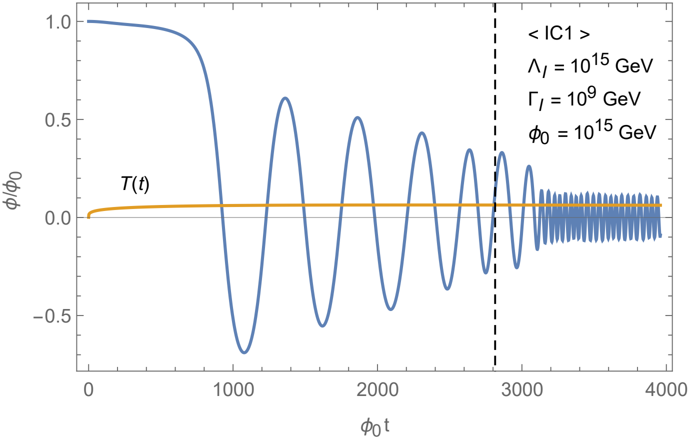

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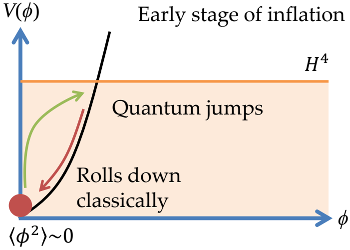

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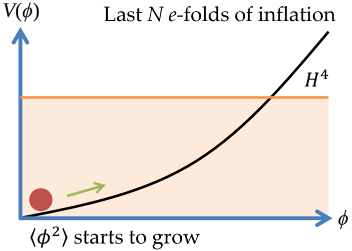

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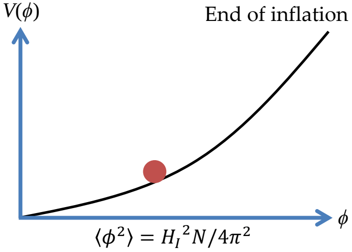

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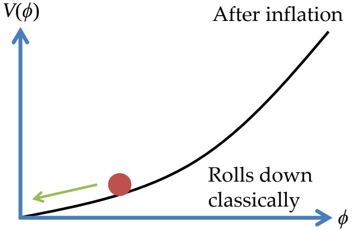
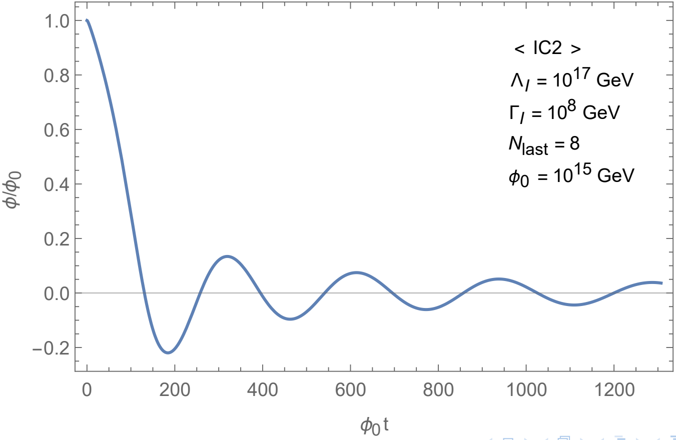


IC-2: Inflaton-Higgs coupling

- For $N_{\text{last}} = 5 - 8$, the isocurvature perturbation only develops on the **small angular scales** which are not yet constrained.



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- As the inflation end, the Higgs field rolls down within around Hubble time scale and oscillates around its minimum.

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Thank you for your listening!

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$$\ddot{I} + 3H\dot{I} + \Gamma_I \dot{I} + \frac{dV_I(I)}{dI} = 0, \quad \text{with} \quad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_{pl}^2}\left(\rho_I + \rho_{other}\right)$$

where we assume a uniform field configuration and a FRW spacetime $ds^2 = dt^2 - a(t)^2 \left(dr^2 + r^2 d\boldsymbol{\Omega}^2\right)$.

The Brief History of the Early Universe

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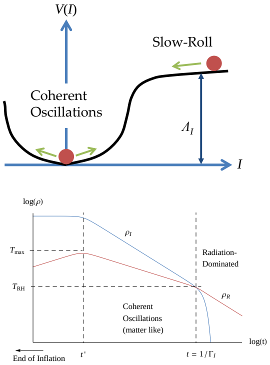

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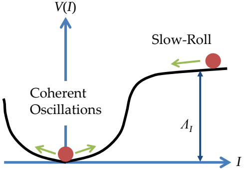

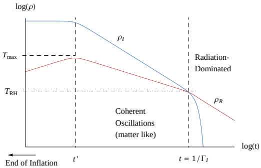

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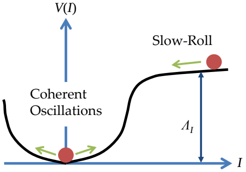

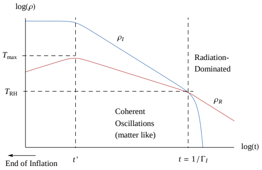

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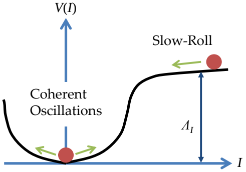

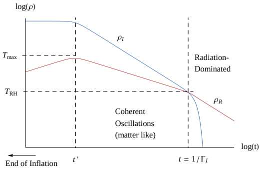

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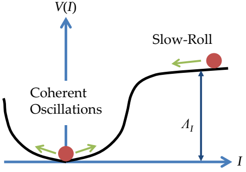

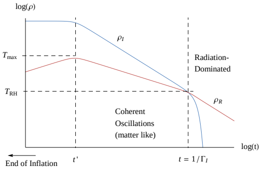

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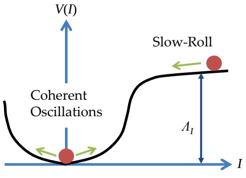

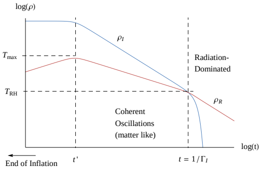

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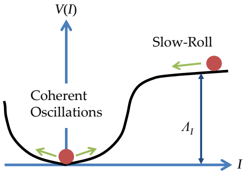

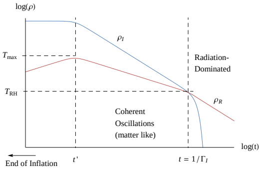

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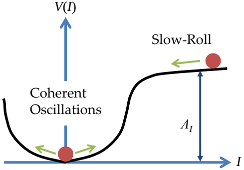

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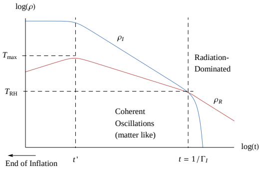

3. **Radiation-dominated** regime: $a(t) \propto (t - t_i)^{1/2}$
   - At $t = 1/\Gamma_I$, most of the inflatons decay into ρ_R, and the reheating is complete.

The Hawking-Moss Tunneling

- If $|V(\phi_f) - V(\phi_i)| \ll V(\phi_i)$, we have

$$S_E(\phi_i) - S_E(\phi_f) = -\frac{3m_{pl}^4}{8}\left[\frac{1}{V(\phi_i)} - \frac{1}{V(\phi_f)}\right] \approx -\frac{3m_{pl}^4}{8}\frac{V(\phi_f) - V(\phi_i)}{V(\phi_i)^2}$$

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- Thus, the transition is not suppressed as long as

$$V(\phi_f) - V(\phi_i) < \frac{8}{3m_{pl}^4}V(\phi_i)^2$$

Reheating

- As inflation ends, the inflatons enter the coherent oscillations regime, the Higgs field is no longer in slow-roll. In this case, we have to consider the full equation of motion

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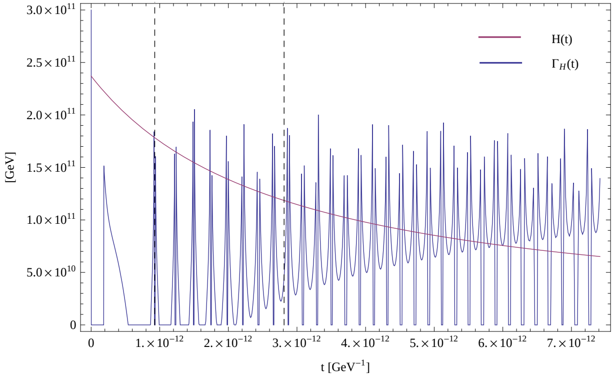
- While the decay of Higgs may produce some non-zero lepton number by itself, most of the plasma are generated by the decay of inflaton.

Perturbative decay (thermalization) to top quark

- Thermalization rate is comparable to the Hubble parameter only after the maximum reheating has been reached.



$H(t)$ vs $\Gamma_H(t)$ through top quark for IC-1, with the parameters $\Lambda_I = 10^{15}$ GeV and $\Gamma_I = 10^9$ GeV. The vertical lines: the first time the Higgs VEV crosses zero, and the time of maximum reheating, from left to right.