Multi-field Open Inflation & Instanton

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Contents

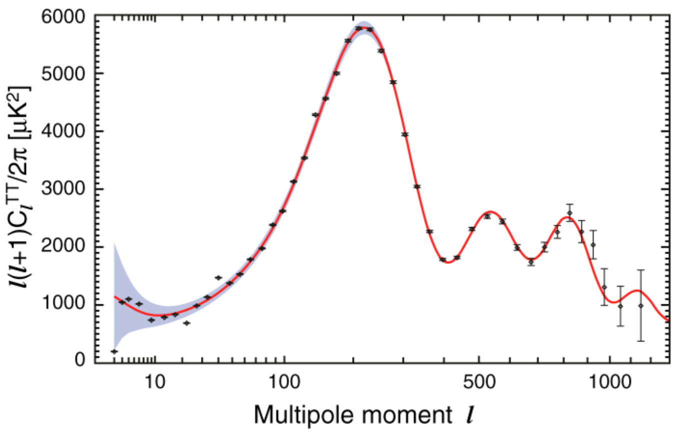
Introductions

Inflation and beyond

- Inflation solves
  - Horizon problem
  - Flatness problem
  - Monopole problem

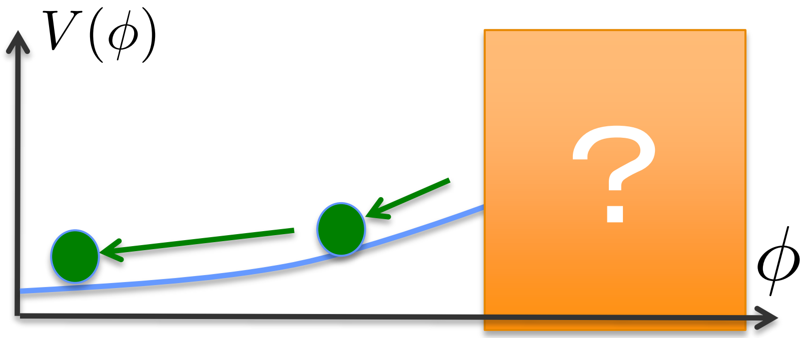
also predicts power spectrum

http://lambda.gsfc.nasa.gov



→ very good agreement!!

- But
  - How is it implemented in particle physics?
  - How does it start?



String landscape

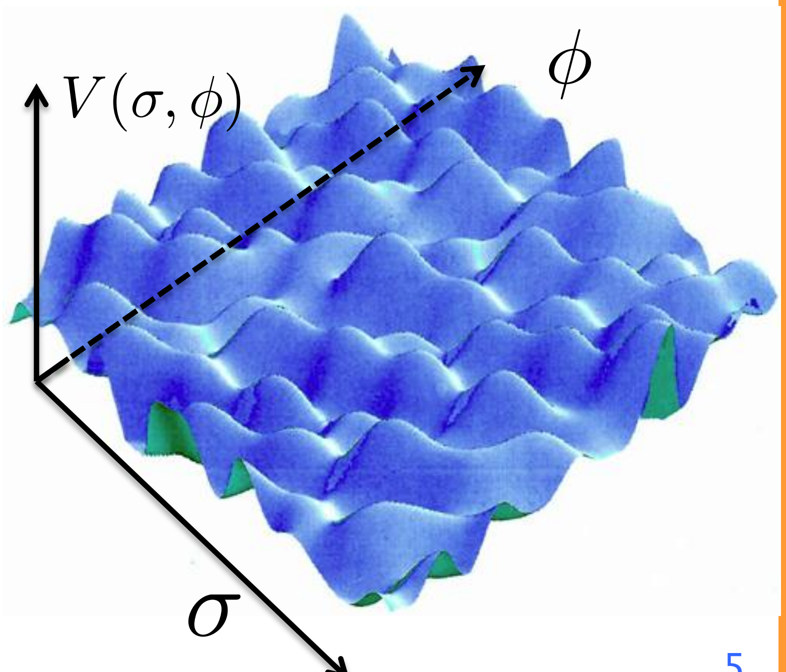
(Susskind, 2003)

- In String theory
  - High dimensionality
  - Integration out of high energy physics

many physical degrees of freedom

Non-trivial structure of vacuum

- implementation of inflation seems possible
  - scalar field
  - flat potential



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String landscape

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- In String theory
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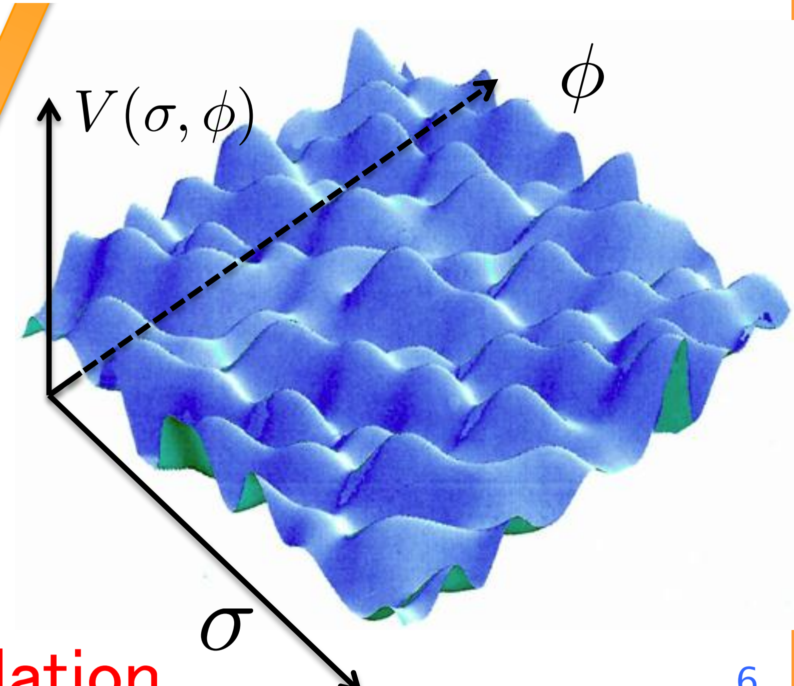
Non-trivial structure of vacuum

- implementation of inflation seems possible
  - scalar field
  - flat potential
- String theory also implies
  - multi-field
  - quantum tunneling

➡ Multi-field open inflation



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Multi-field open inflation

- Quantum tunneling before slow-roll (in multi-field system)

→ (Multi-field) Open inflation

  - $\Omega_k \sim -0.01$ is most favorable(?) (Freivogel, et al., 2006)

  → possibility of curvature detection

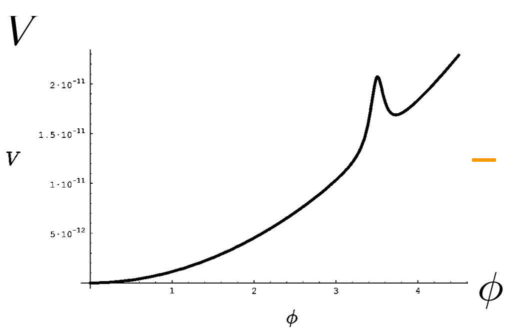
good point of multi-field system

- Open inflation in multi-field system

  may solve a problem in single-field case

  ↕

  - Only an artificial potential model is known (Linde 1998)



We will study multi-field open inflation!!

Multi-field open inflation

Multi−field model with a simple potential

$$m_{pl}^2 = \frac{1}{8\pi G}$$

$\alpha = 0.1$ $\beta = 0.01$
$\sigma_0 = 2m_{pl}$ $m_\phi = 10^{-6}m_{pl}$
$M_V = 0.2m_{pl}$ $\phi_0 = 15m_{pl}$

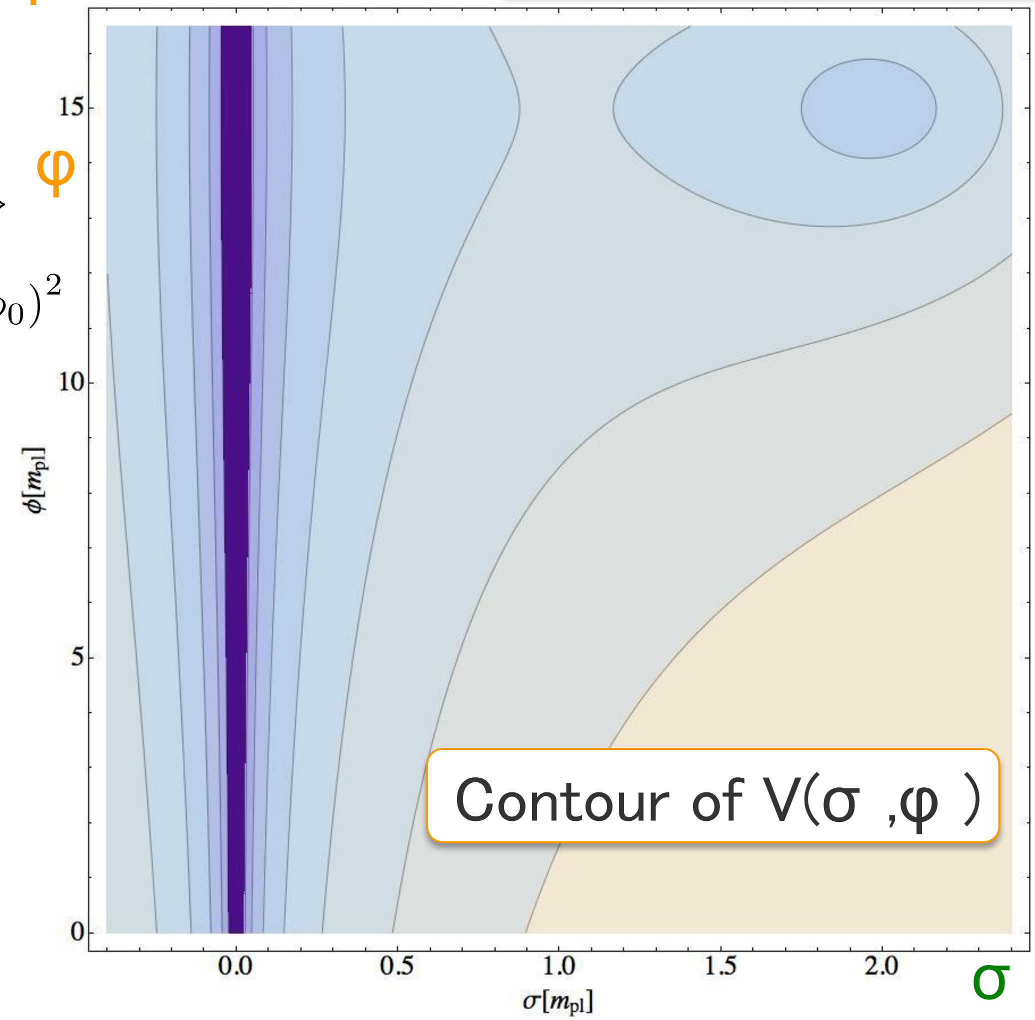
tunneling field σ

inflaton φ

$$V(\sigma,\phi) = V_{\rm tun}(\sigma) + V_{\rm infl}(\sigma,\phi)$$

$$V_{\rm tun}(\sigma) = \alpha\sigma^2\left\{(\sigma-\sigma_0)^2 + M_V^2\right\}$$

$$V_{\rm infl}(\sigma,\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\beta}{2}\sigma^2(\phi-\phi_0)^2$$



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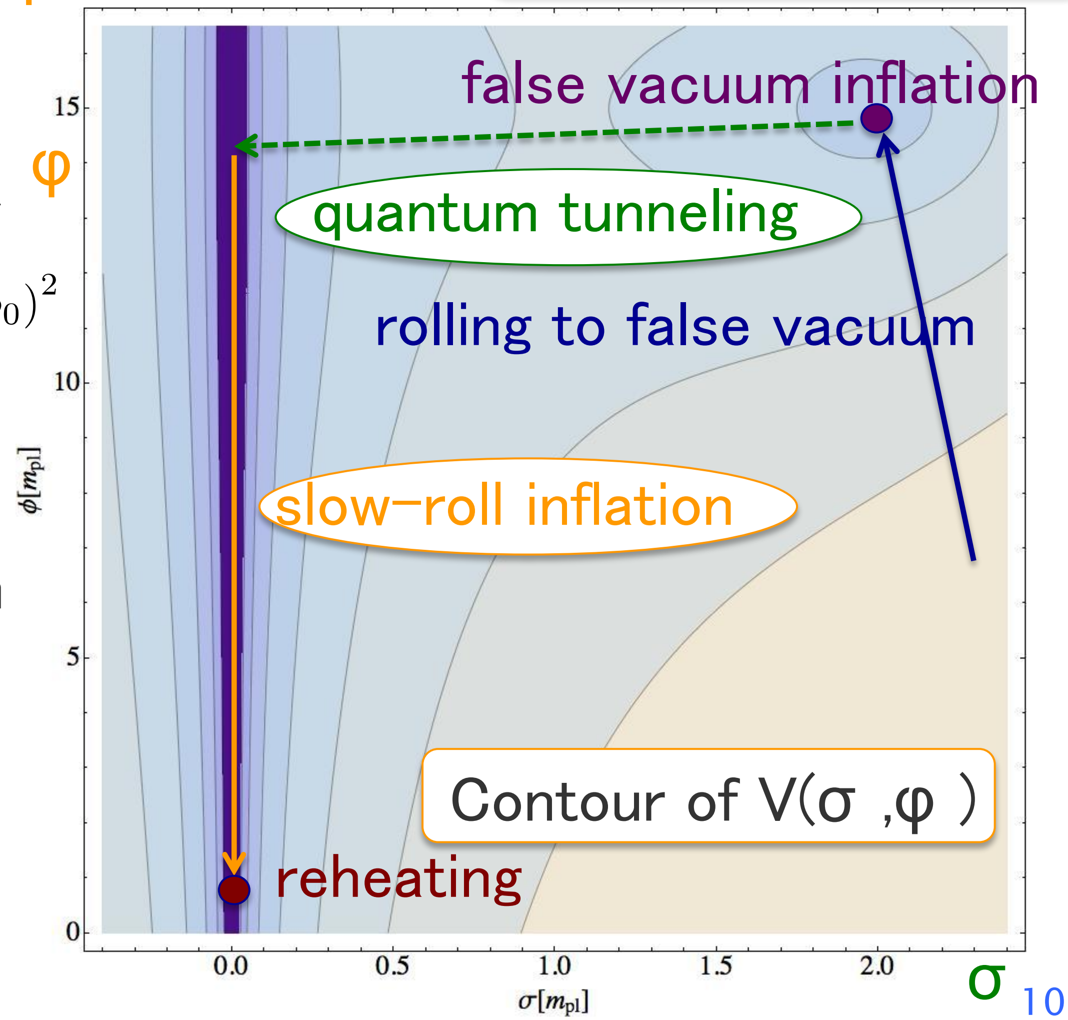
Scenario

1. rolling to false vacuum
2. false vacuum inflation
3. quantum tunneling
4. slow–roll inflation
5. reheating



Formulation of multi-field tunneling with gravity

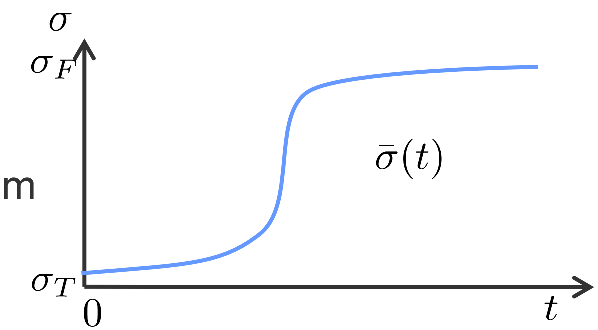
- Multi-field extension of Coleman-De Luccia instanton

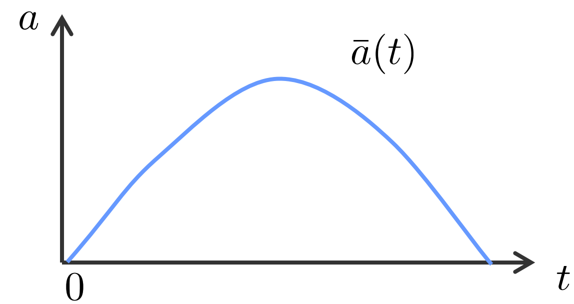
  (Coleman and De Luccia, 1980)

  - instanton $\bar{\sigma}(t), \bar{\phi}(t), \bar{a}(t)$ ⇐ O(4)-symmetric non-trivial Euclidean classical path

Euclidean metric $ds_E^2 = dt^2 + \bar{a}^2(t)dx^2$

image of instanton for single-field system





  - inside of nucleated bubble is open Friedmann universe

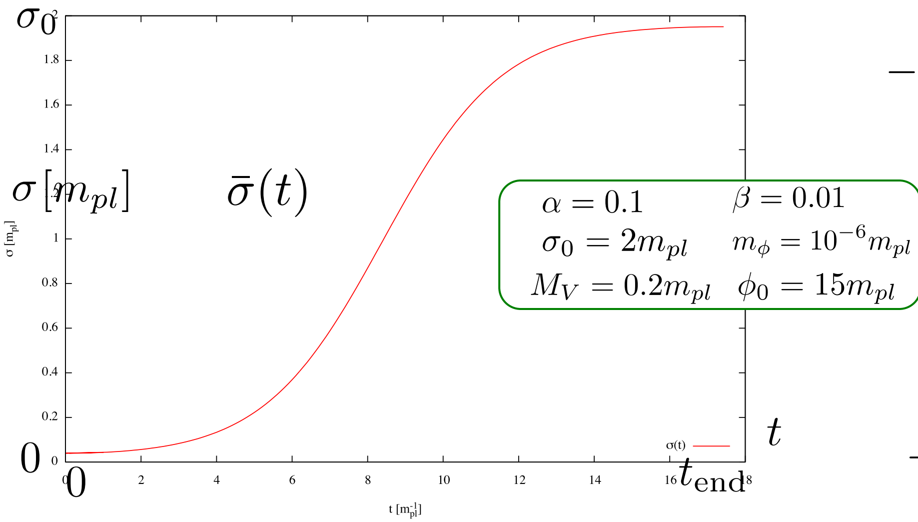
⇐ initial state is given by instanton value at t=0

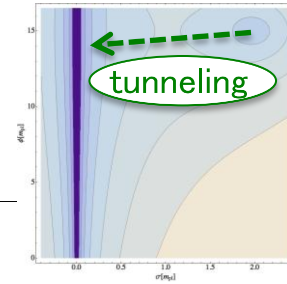
$$\sigma(0) = \bar{\sigma}(0) \qquad \phi(0) = \bar{\phi}(0) \qquad a(0) = 0$$

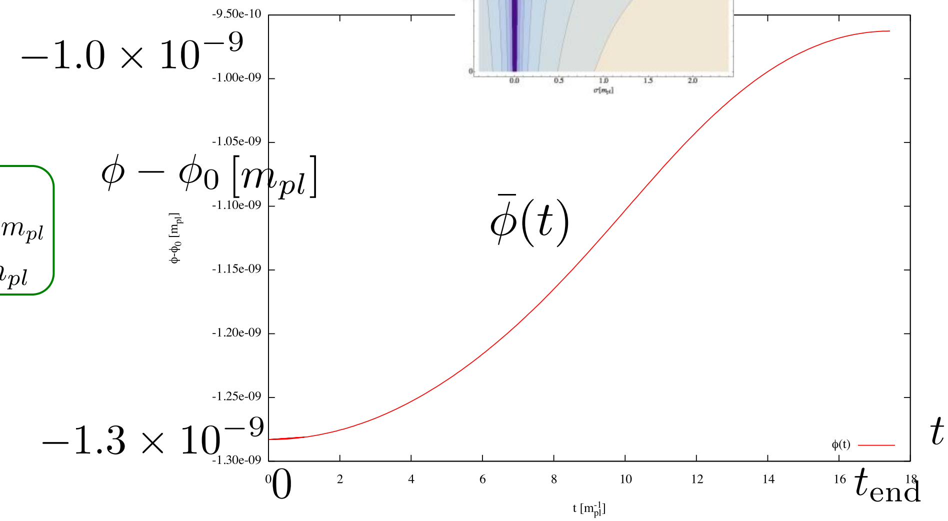
We will

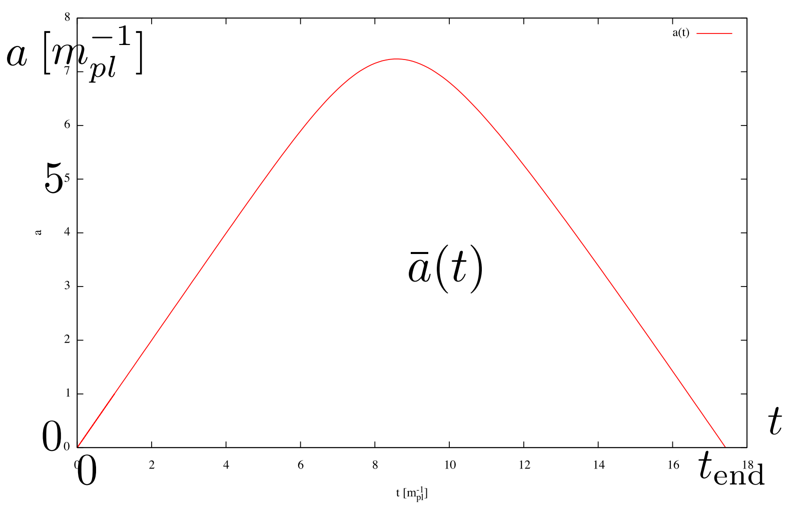
1. construct a multi-field instanton
2. evolve the universe inside bubble

Multi-field instanton





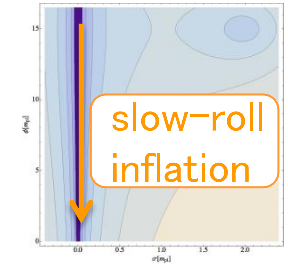


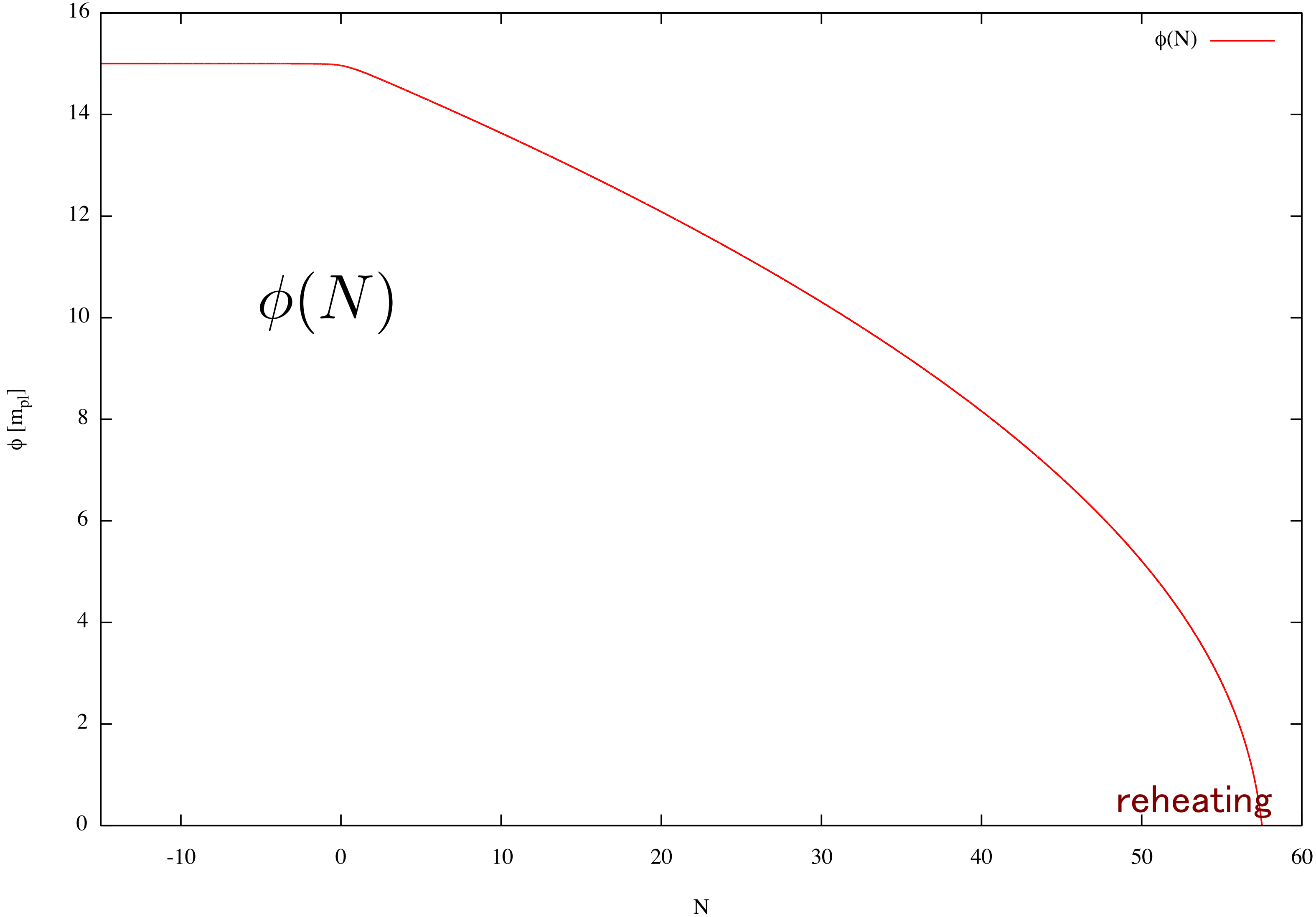


- multi-field instanton with gravity is explicitly constructed for the first time
- inflaton φ moves during tunneling but a little for this parameter choice
- instanton value at t=0 gives the initial state of bubble

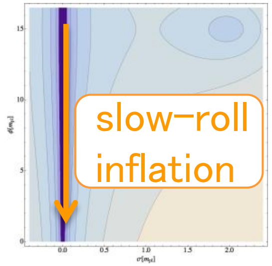
→ evolution after tunneling

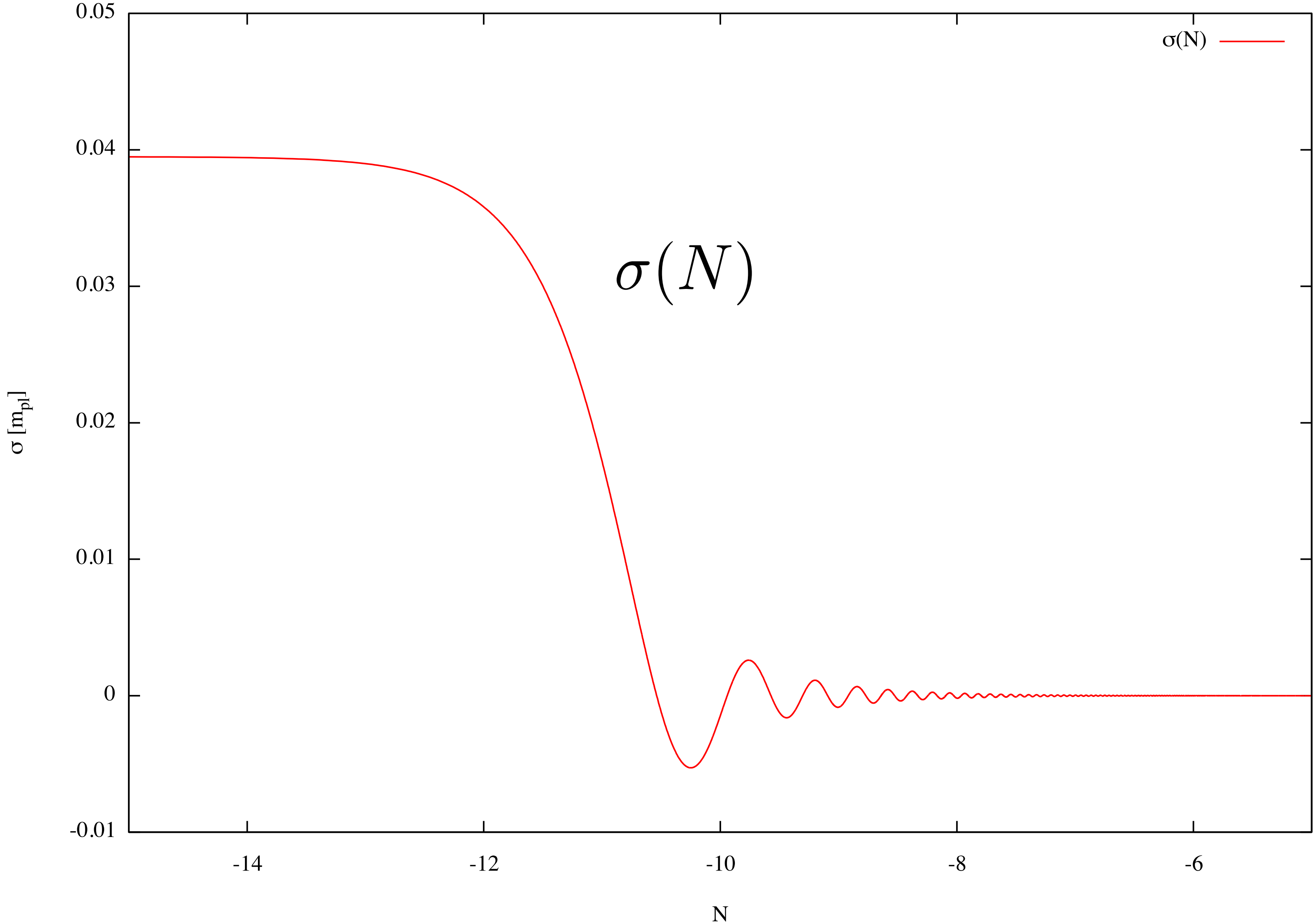
Evolution of inflaton ϕ after tunneling





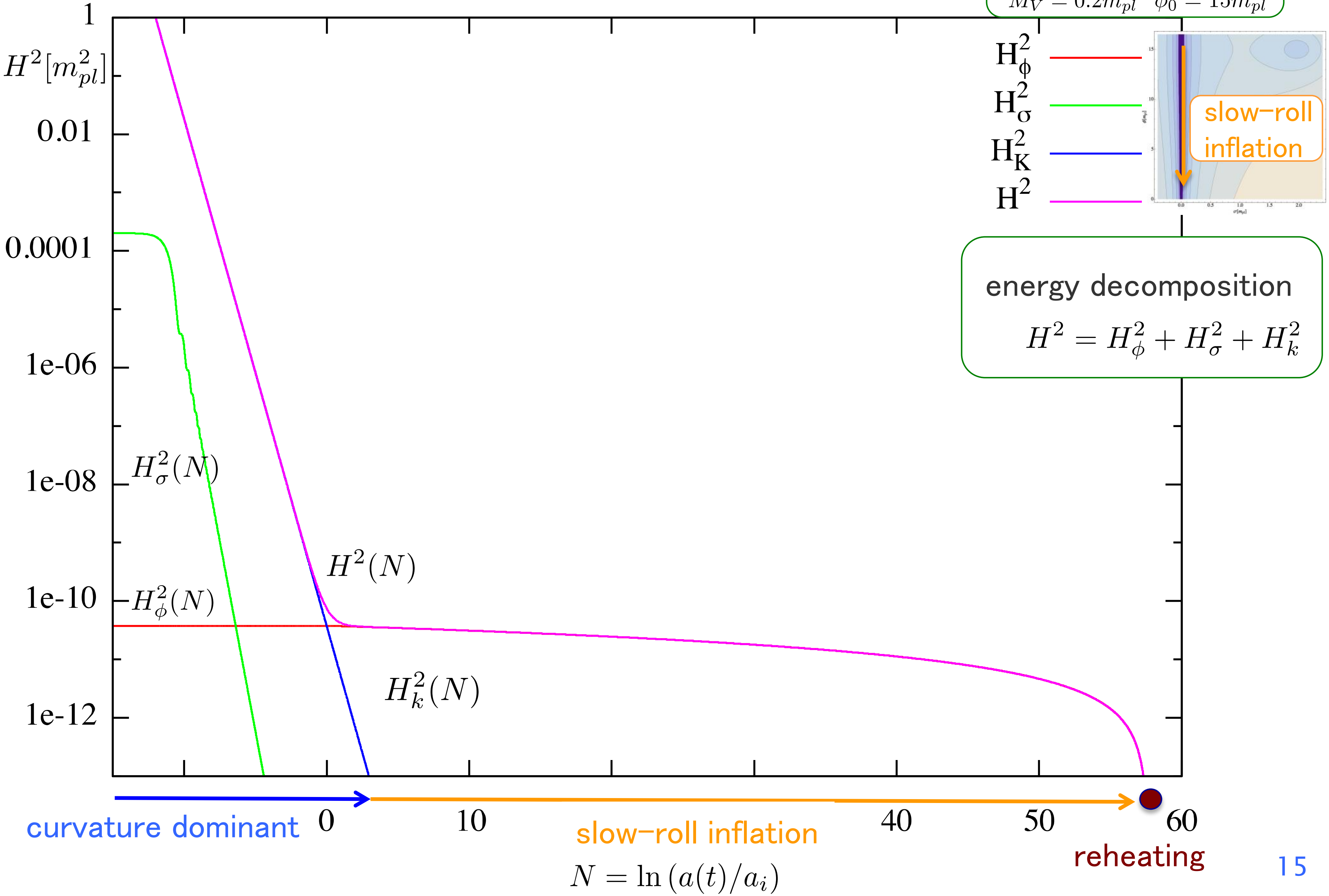
Evolution of tunneling field σ after tunneling





Evolution after tunneling

$\alpha = 0.1$ $\beta = 0.01$
$\sigma_0 = 2m_{pl}$ $m_\phi = 10^{-6} m_{pl}$
$M_V = 0.2m_{pl}$ $\phi_0 = 15m_{pl}$



energy decomposition

$$H^2 = H^2_\phi + H^2_\sigma + H^2_k$$

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- tunneling field σ is massive

  ➡ damped oscillation $H_\sigma^2 \propto a^{-3}$

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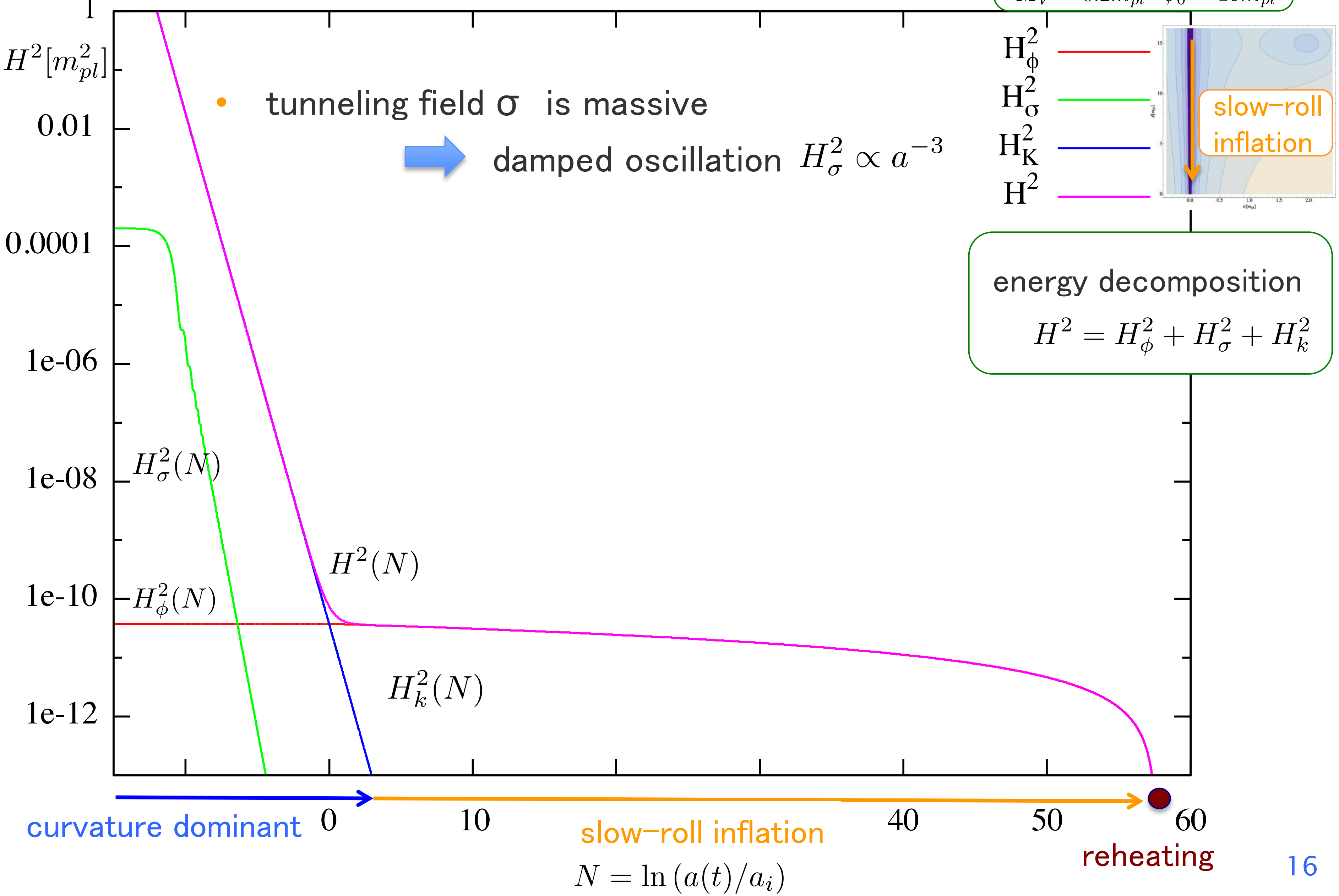

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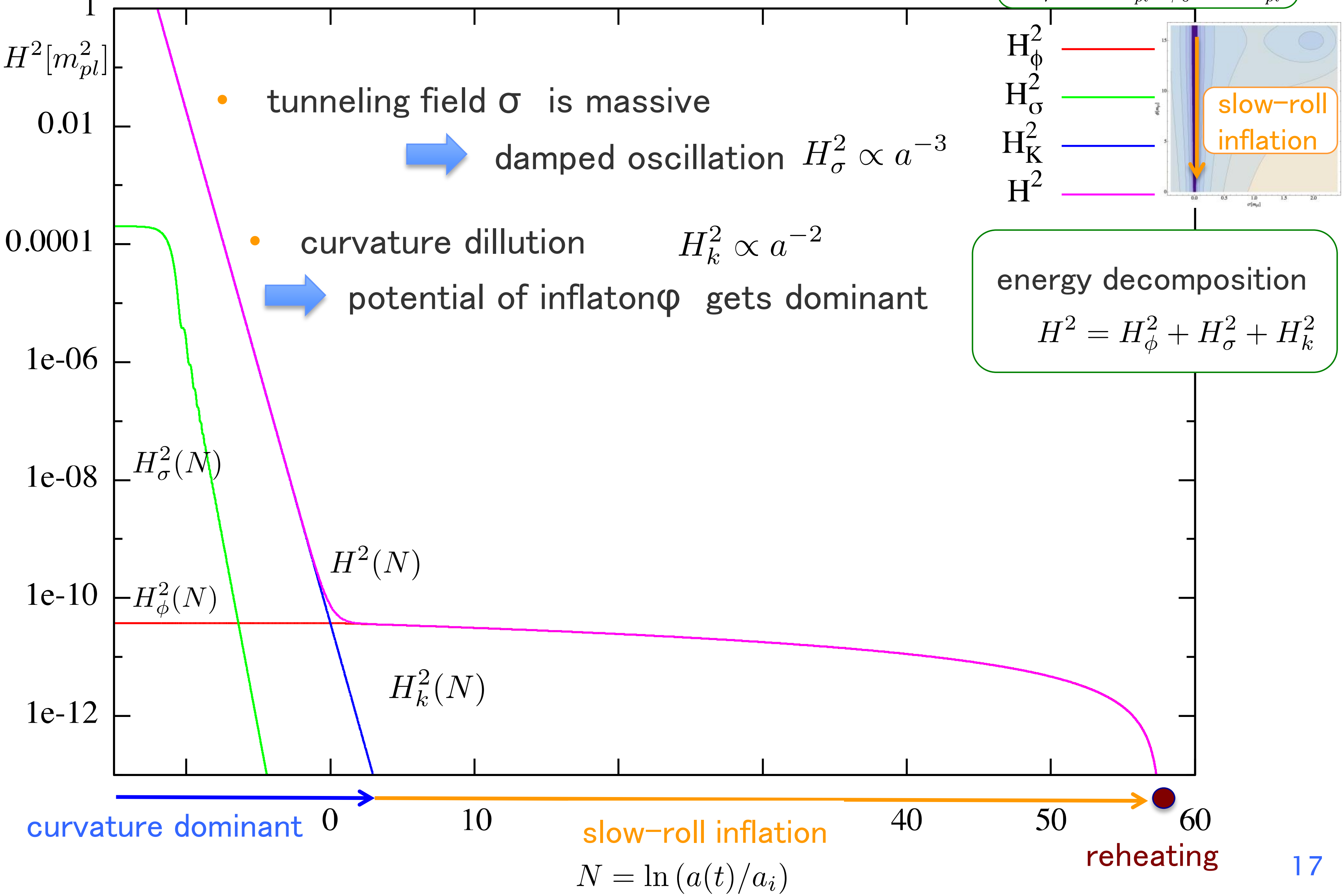

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- curvature dillution $H_k^2 \propto a^{-2}$
  ➡ potential of inflaton φ gets dominant
- inflation lasts for 60 e−foldings $H_\phi^2 \sim \text{const}$

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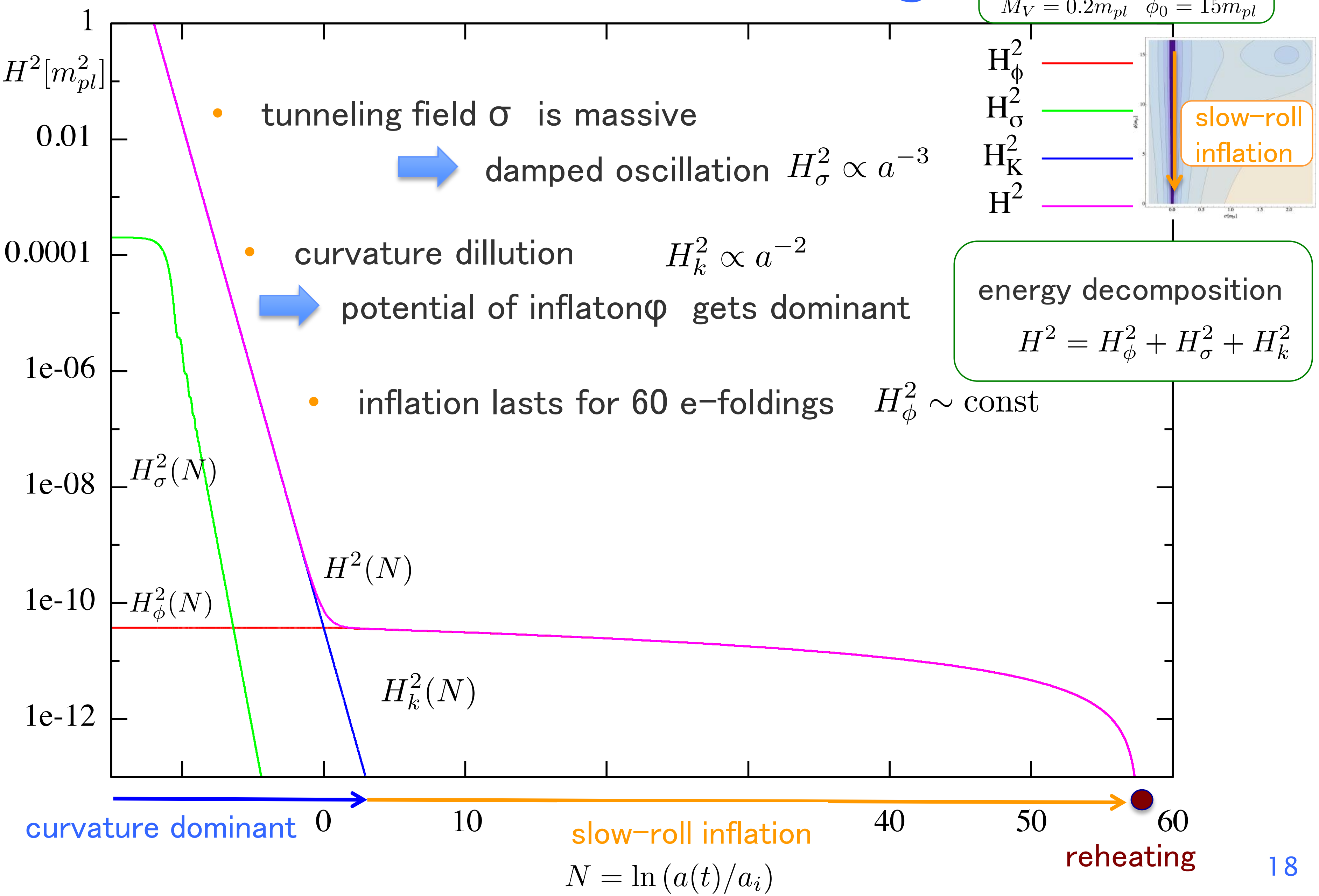

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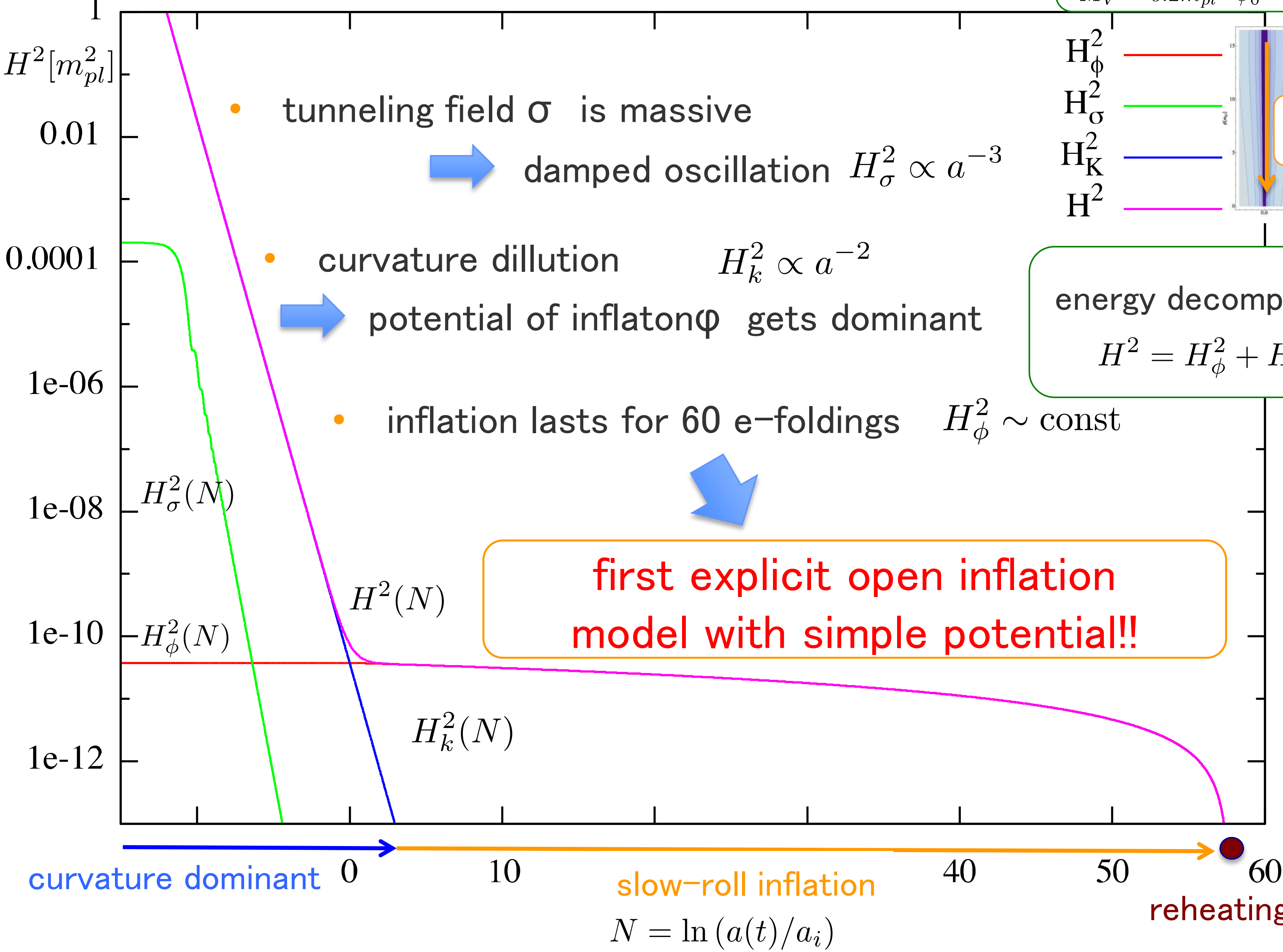
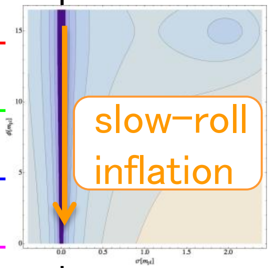
energy decomposition

$$H^2 = H_\phi^2 + H_\sigma^2 + H_k^2$$

first explicit open inflation model with simple potential!!





Conclusions and Discussions

Conclusions

- We studied about Multi-field open inflation, which is motivated by string landscape
- The Coleman De Luccia instanton method was extended to the multi-field case
- Multi-field instanton with gravity and the evolution inside the bubble were explicitly calculated
- Our multi-field open inflation model is the first explicit open inflation model with a simple potential

Discussions and Future works

- Method to calculate a quantum fluctuation in open inflation seems possible to be applied to our model

  (Garriga, Montes, Sasaki, Tanaka (1998))

- Interaction between heavy oscillating tunneling field and inflaton may produce some interesting features in power spectrum

- Quantum tunneling changes the state of the universe from Bunch-Davies vacuum, and this may produce a characteristic non-gaussianity

  (now we are working!)

- If we are very lucky, we may find an evidence of our model, or string landscape, from observations

Appendix

Interaction effect on decay rate

naive question about multi-field dynamics

Q. Do multi-field dynamics make decay rate larger, or smaller?

- decay rate $\propto e^{-B[\bar{\sigma},\bar{\phi},\bar{a}]}$ $\quad B[\bar{\sigma},\bar{\phi},\bar{a}] = S_E[\bar{\sigma},\bar{\phi},\bar{a}] - S_E[\sigma_F,\phi_F,a_F]$

(Coleman and De Luccia, 1980)

- multi-field instanton

$\bar{\sigma}(t), \bar{\phi}(t), \bar{a}(t)$ ⇒ $B = B[\bar{\sigma},\bar{\phi},\bar{a}]$

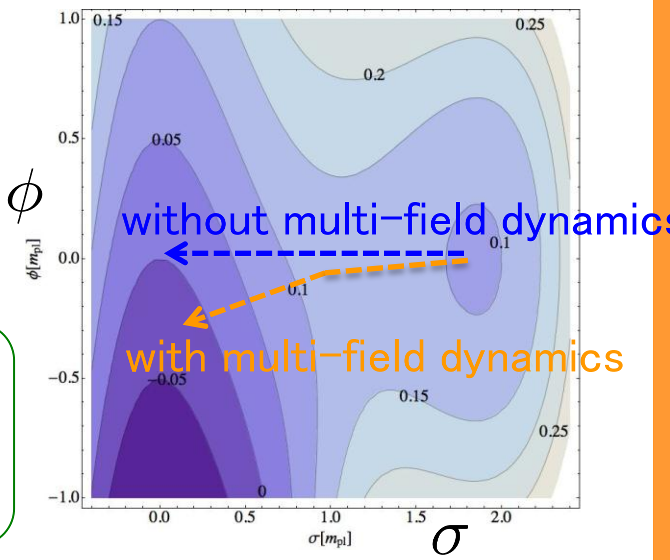
- instanton when neglecting dynamical freedom of φ

$\bar{\sigma}_0(t), \bar{\phi}_0(t), \bar{a}_0(t)$

  - staying at false vacuum $\bar{\phi}_0(t) = \phi_F$
  - single field instanton for $V_0(\sigma) = V(\sigma,\phi_F)$ $\quad \bar{\sigma}_0(t), \bar{a}_0(t)$

⇒ $B_0 = B[\bar{\sigma}_0,\bar{\phi}_0,\bar{a}_0]$

- $B-B_0$ comes from the multi-field dynamics effect



Contour of V(σ ,φ)

Multi-field dynamics effect on decay rate

$$B[\bar{\sigma},\bar{\phi},\bar{a}] = S_E\left[\bar{\sigma},\bar{\phi},\bar{a}\right] - S_E\left[\sigma_F,\phi_F,a_F\right]$$

- decay rate $\propto e^{-B[\bar{\sigma},\bar{\phi},\bar{a}]}$
- difference of B due to multi-field dynamics $B - B_0$

$$V(\sigma,\phi) = V_{\rm tun}(\sigma) + V_{\rm infl}(\sigma,\phi)$$

$$V_{\rm tun}(\sigma) = \alpha\sigma^2\left\{(\sigma-\sigma_0)^2 + M_V^2\right\}$$

$$V_{\rm infl}(\sigma,\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\beta}{2}\sigma^2(\phi-\phi_0)^2$$

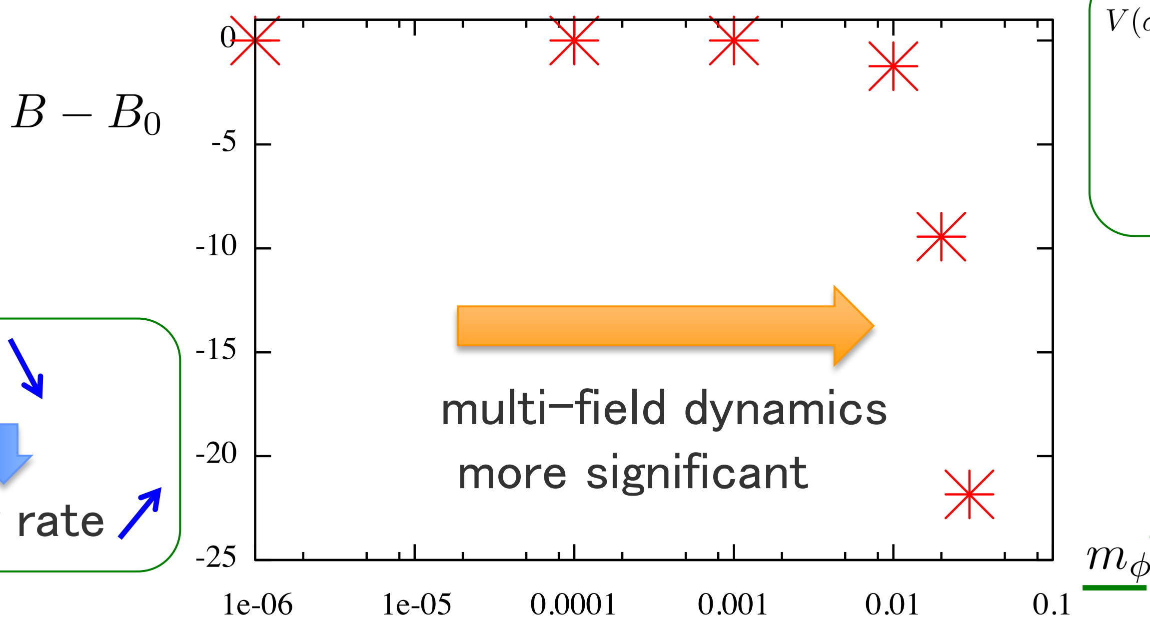
$\alpha = 0.1$ $\beta = 0.01$

$\sigma_0 = 2m_{pl}$ $\phi_0 = 15m_{pl}$

$M_V = 0.2m_{pl}$

B ↘

decay rate ↗



A. The multi-field dynamics make decay rate larger!!

Decomposition of energy density in the universe after tunneling

- Hubble parameter $H^2 = \frac{1}{3m_{pl}^2}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\sigma}^2 + V(\sigma,\phi)\right) + \frac{1}{a^2}$
- inflaton φ $H_\phi^2 = \frac{1}{3m_{pl}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\sigma_T,\phi)\right)$
- tunneling field σ $H_\sigma^2 = \frac{1}{3m_{pl}^2}\left(\frac{1}{2}\dot{\sigma}^2 + V(\sigma,\phi) - V(\sigma_T,\phi)\right)$
- curvature $H_k^2 = \frac{1}{a^2}$

m_ϕ dependence of the system

m_φ changes not only the strength of interaction but also the non-interaction part

$$V(\sigma,\phi) = V_{\text{tun}}(\sigma) + V_{\text{infl}}(\sigma,\phi)$$
$$V_{\text{tun}}(\sigma) = \alpha\sigma^2\left\{(\sigma-\sigma_0)^2 + M_V^2\right\}$$
$$V_{\text{infl}}(\sigma,\phi) = \frac{1}{2}\underline{m_\phi^2}\phi^2 + \frac{\beta}{2}\sigma^2(\phi-\phi_0)^2$$

$\alpha = 0.1$ $\beta = 0.01$
$\sigma_0 = 2m_{pl}$
$M_V = 0.2m_{pl}$ $\phi_0 = 15m_{pl}$

different m_φ → different

$$V_0(\sigma) = V(\sigma,\phi_F)$$
$$\bar{\sigma}_0(t), \bar{\phi}_0(t), \bar{a}_0(t)$$
$$B_0 = B[\bar{\sigma}_0, \bar{\phi}_0, \bar{a}_0]$$

large m_φ → large $V_0(\sigma_F)$

→ small V''/H^2

	B	B_0	ΔB
$m_\phi = 10^{-6}m_{pl}$	12109.11	12109.11	0.00
$m_\phi = 10^{-4}m_{pl}$	12108.10	12108.10	0.00
$m_\phi = 10^{-3}m_{pl}$	12008.71	12008.71	0.00
$m_\phi = 10^{-2}m_{pl}$	6328.61	6329.83	-1.23
$m_\phi = 2\times10^{-2}m_{pl}$	2196.44	2205.89	-9.44
$m_\phi = 3\times10^{-2}m_{pl}$	844.13	865.98	-21.84

- in the case of the very large m_φ, there may exist only a Hawking-Moss instanton

(barrier is effectively small)