Mutli-field Open Inflation
and
the Effect of Interaction

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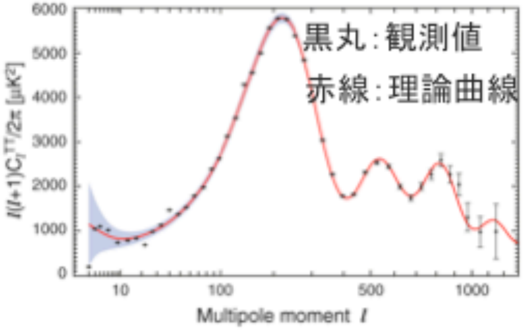
Motivations

Slow-roll inflation and beyond

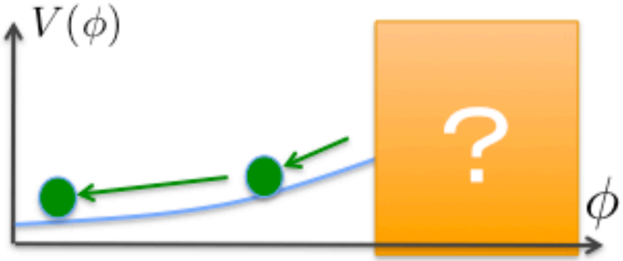

http://lambda.gsfc.nasa.gov

☐ Slow-roll inflation is satisfactory

- Solution of
  - Horizon problem
  - Flatness problem
  - Monopole problem
- Prediction of power spectrum → very good agreement!!

☐ Slow-roll inflation is unsatisfactory

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



String landscape

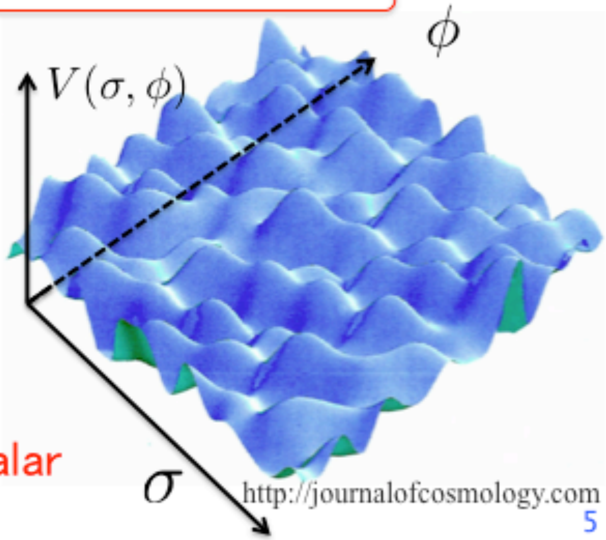
- String theory can implement a setting for slow-roll inflation
  - scalar field
  - flat potential

High dimensionality

many physical degrees of freedom

Integration out of high energy physics

Non-trivial structure of vacuum



http://journalofcosmology.com

- String theory implies
  - multi-field
  - quantum tunneling

We will study inflation with multi-scalar field and quantum tunneling

Multi-field open inflation

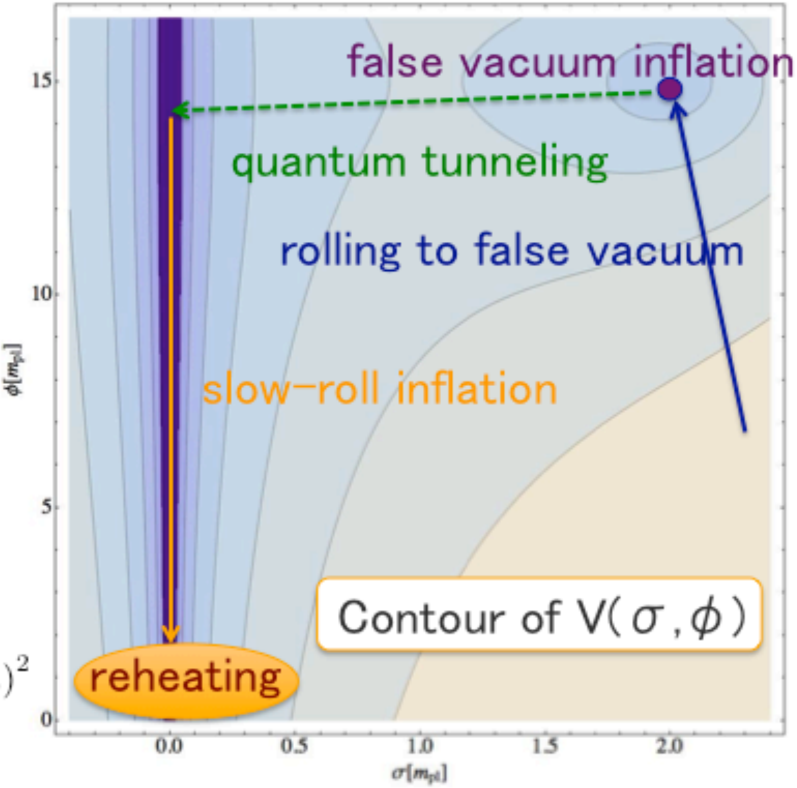
Scenario

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

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

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

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



Contour of V(σ , ϕ)

Review of CDL instanton

(tunneling = 1st order transition = bubble nucleation)

Single scalar field tunneling with gravity

→ **Coleman–De Luccia instanton(1980)**

under O(4)–symmetry

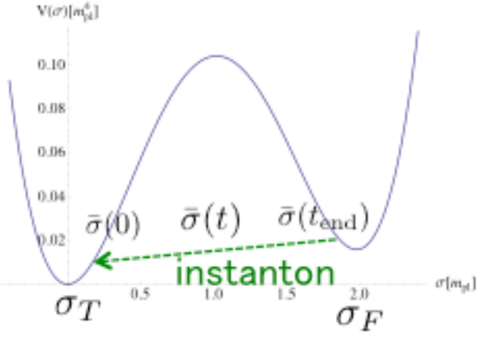
- Euclidean metric $ds_E^2 = dt^2 + a^2(t)\left(d\chi^2 + \sin^2\chi d\Omega^2\right)$
- Euclidean action $S_E[\sigma,a] = 2\pi^2 \int dt a^3 \left[\frac{1}{2}\dot{\sigma}^2 + V(\sigma) - \frac{3}{m_{pl}^2}\left(\frac{\dot{a}^2}{a^2} + \frac{1}{a^2}\right)\right]$

↓ non–trivial classical path

instanton $\bar{\sigma}(t), \bar{a}(t)$

$\bar{a}(0) = \bar{a}(t_{\text{end}}) = 0$

$\bar{\sigma}(0) \sim \sigma_T \quad \bar{\sigma}(t_{\text{end}}) \sim \sigma_F$



- decay rate $\frac{\text{(tuuneling probability)}}{\text{(unit volume)(unit time)}} = O\left(V(\sigma)\right) \times \exp\left(-S_E \underbrace{[\bar{\sigma},\bar{a}]}_{\text{instanton}} + S_E \underbrace{[\sigma_F, a_F]}_{\text{trivial path at false vacuum}}\right)$
- evolution inside bubble
  - metric $ds^2 = -dt^2 + a^2(t)\left(dr^2 + \sinh^2 r d\Omega^2\right)$ → open universe
  - initial conditions (at t=0)
    $\sigma(0) = \bar{\sigma}(0) \qquad a(0) = 0$

- evolution is same as the usual open universe

Multi-field tunneling with gravity

- Multi-field extension of Coleman-De Luccia instanton
  - instanton $\bar{\sigma}(t), \bar{\phi}(t), \bar{a}(t)$

instanton is a solution for these equations

EOMs

$$\frac{\ddot{\bar{a}}}{\bar{a}} + \frac{1}{3m_{pl}^2}\left(\dot{\bar{\sigma}}^2 + \dot{\bar{\phi}}^2 + V(\bar{\sigma}, \bar{\phi})\right) = 0$$

$$\ddot{\bar{\sigma}} + 3\frac{\dot{\bar{a}}}{\bar{a}}\dot{\bar{\sigma}} - V_{\sigma}(\bar{\sigma}, \bar{\phi}) = 0$$

$$\ddot{\bar{\phi}} + 3\frac{\dot{\bar{a}}}{\bar{a}}\dot{\bar{\phi}} - V_{\bar{\phi}}(\bar{\sigma}, \bar{\phi}) = 0$$

boundary conditions

$$\bar{a}(0) = \bar{a}(t_{\text{end}}) = 0.$$

$$\dot{\bar{\sigma}}(0) = \dot{\bar{\sigma}}(t_{\text{end}}) = 0$$

$$\dot{\bar{\phi}}(0) = \dot{\bar{\phi}}(t_{\text{end}}) = 0$$

$$\dot{\bar{a}}(0) = -\dot{\bar{a}}(t_{\text{end}}) = 1$$

  - decay rate

$$\frac{(\text{tuuneling probability})}{(\text{unit volume})(\text{unit time})} = O\left(V(\sigma, \phi)\right) \times \exp\left(-S_E\left[\bar{\sigma}, \bar{\phi}, \bar{a}\right] + S_E\left[\sigma_F, \phi_F, a_F\right]\right)$$

  - initial conditions inside bubble

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

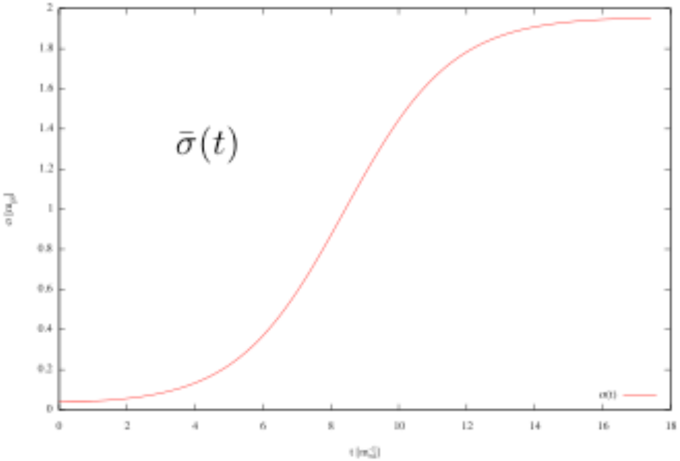
evolve as an open Friedmann universe

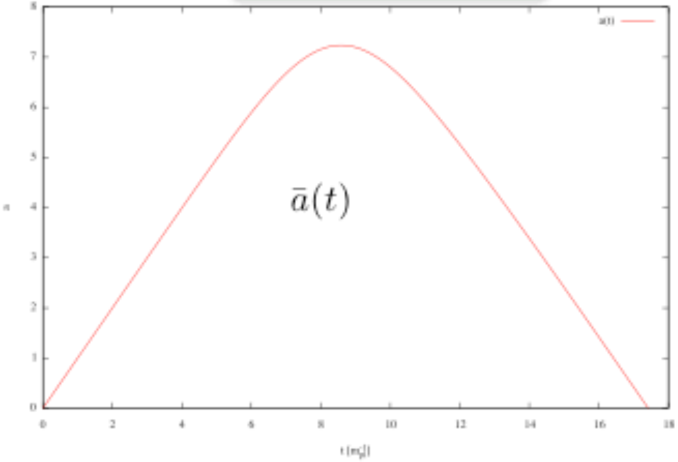
We will

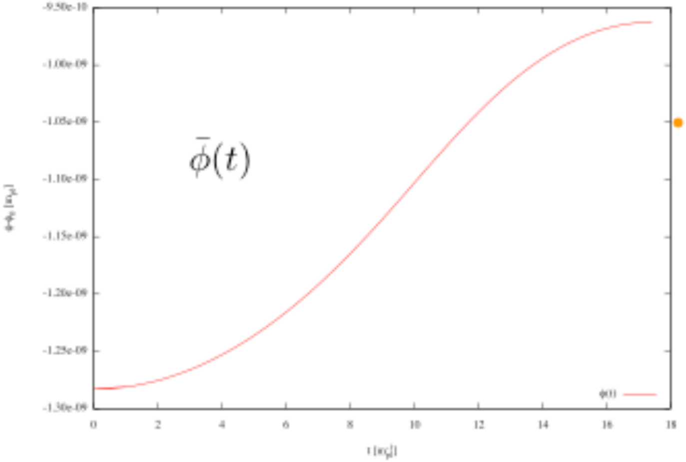
1. construct a multi-field instanton
2. develop the universe inside bubble

Quantum tunneling

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







solution for EOMs and boundary conditions

↕

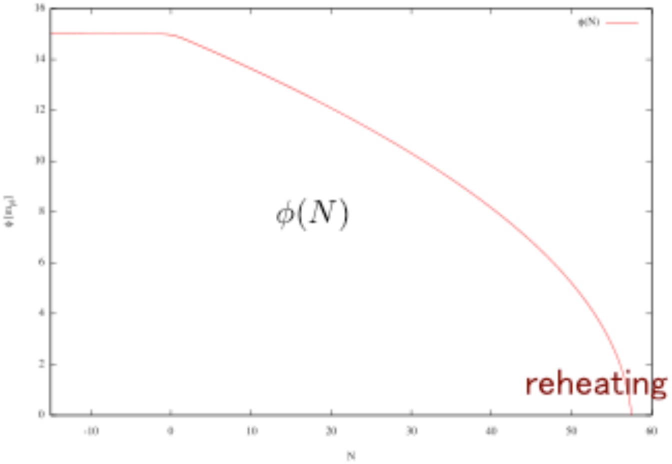
- numerically obtained multi−field instanton
- inflaton ϕ moves but a little
- initial condition for a nucleated bubble
  $\sigma(0) = \bar{\sigma}(0) \qquad \phi(0) = \bar{\phi}(0) \qquad a(0) = 0$

Evolution after tunneling

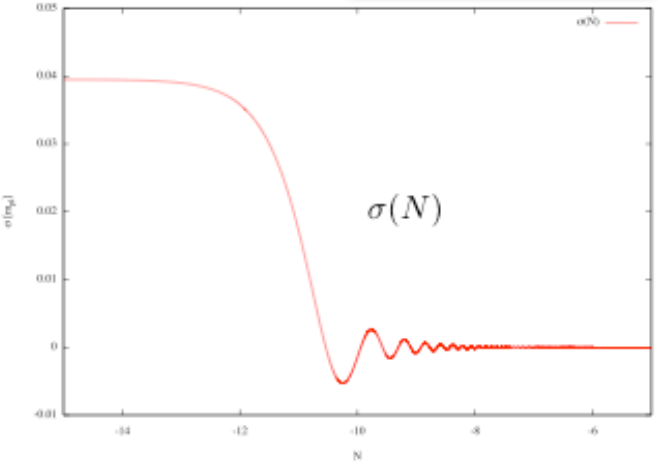
$\alpha = 0.1$ $\beta = 0.01$

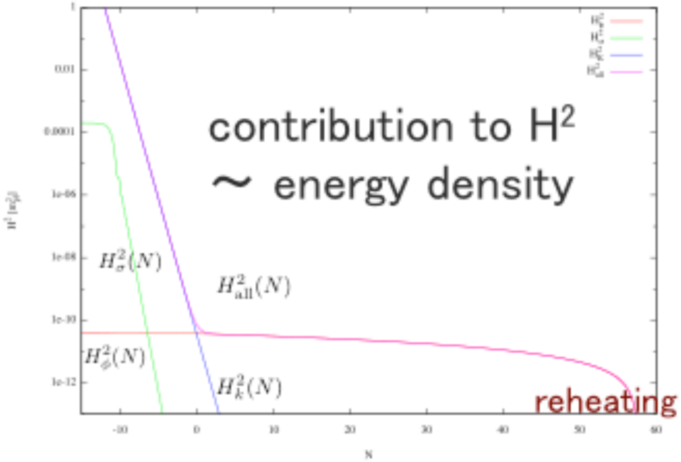
$\sigma_0 = 2m_{pl}$ $m_\phi = 10^{-6}m_{pl}$

$M_V = 0.2m_{pl}$ $\phi_0 = 15m_{pl}$



reheating





contribution to H^2

～ energy density

reheating

- initial conditions

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

- e–folds

$N = \ln\left(a(t)/\underline{a_i}\right)$ scale factor at the beginning of inflation

starting from curvature dominant universe

➡ potential energy win against the curvature

➡ slow–roll inflation for ～60 e–folds

Realization of open inflation scenario!!

Interaction effect on decay rate

decay rate and interaction effect

Q. Does an interaction effect make decay rate larger, or smaller?

- potential

$$V(\sigma,\phi) = V^{(0)}(\sigma) + \underline{V_{\rm int}(\sigma,\phi)} \qquad (V_{\rm int}(\sigma,\phi_F) = 0)$$

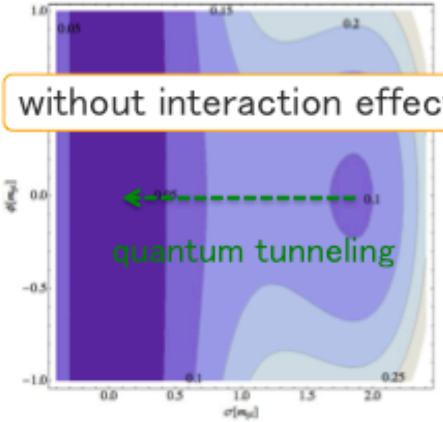
interaction part

$\partial V_{\rm int}(\sigma,\phi_F)/\partial\phi = 0$ ➡ $\bar{\phi}(t) = \phi_F$ without interaction effect

- decay rate

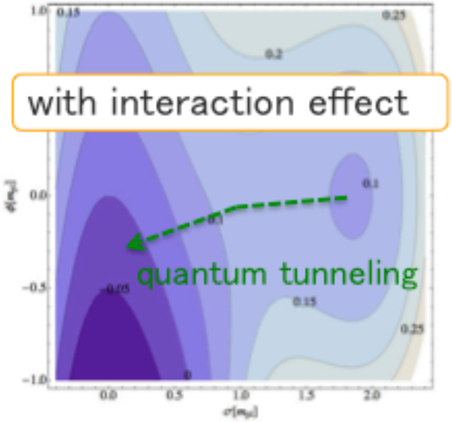
$$\frac{(\text{tuuneling probability})}{(\text{unit volume})(\text{unit time})} = O\left(V(\sigma,\phi)\right) \times \exp\left(-S_E\left[\bar{\sigma},\bar{\phi},\bar{a}\right] + S_E\left[\sigma_F,\phi_F,a_F\right]\right)$$

changing $V_{\rm int}$ with $V^{(0)}$ fixed ➡ $V_{\rm int}$ dependence of decay rate



without interaction effect

quantum tunneling



with interaction effect

quantum tunneling

Decay rate dependence on interaction

- potential ansatz

$$V^{(0)}(\sigma): \text{fixed} \qquad V_{\text{int}}(\sigma,\phi) = \begin{cases} \lambda(\phi-\phi_F) & \sigma \sim \sigma_T \\ \dfrac{m_{\phi F}^2}{2}(\phi-\phi_F)^2 & \sigma \sim \sigma_F \end{cases}$$

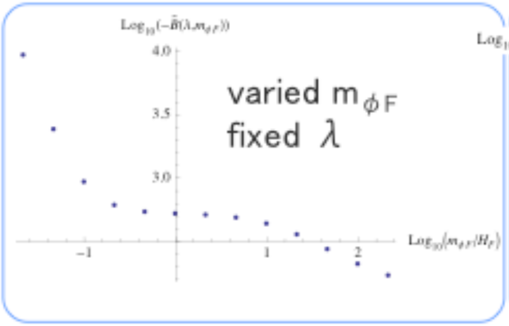
- indicator of decay rate

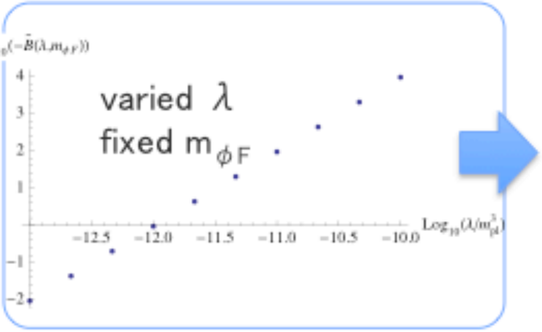
$$\tilde{B}\left(m_{\phi,F},\lambda\right) = -\left(-S_E\left[\bar{\sigma},\bar{\phi},\bar{a}\right] + S_E\left[\sigma_F,\phi_F,a_F\right]\right)\Big|_{m_{\phi,F},\lambda} + \underbrace{\left(-S_E\left[\bar{\sigma},\bar{\phi},\bar{a}\right] + S_E\left[\sigma_F,\phi_F,a_F\right]\right)\Big|_{m_{\phi,F},\lambda=0}}_{}$$

action without interaction effect (independent of m$_{\phi,F}$)

$\tilde{B}$ ↘ ➡ decay rate ↗

- results





➡

$\tilde{B} < 0$

λ ↗

$\tilde{B}$ ↘ ⬅ $m_{\phi,F}$ ↘

A. The interaction effect make decay rate larger!!

interpretation : tunneling to a lower energy state

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

- For a certain potential, a multi-field instanton can be obtained and open inflation is realized

- The effects of interaction make decay rate larger because of tunneling to a lower energy state

Discussions

- Initial state of the universe is different from Bunch-Davies vacuum because of tunneling
- Calculation of Non-Gaussianity from this effect and comparison with observation such as PLANCK is a future work

- Tunneling field experiences damped oscillation after tunneling
- Interaction with tunneling field may cause some features in inflaton power spectrum