Axion-driven Hybrid Inflation over a Barrier

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Contents

1. Inflation
2. Model
3. Cosmological Dynamics - Inflation
4. Cosmological Dynamics - Dark Matter
5. Conclusions
Cosmic Inflation
1. Inflation

- Inflation
  
  Essential part of the standard cosmological model
  
  - Initial conditions for the hot big-bang evolution of the universe
    → Homogenous, isotropic, spatially flat universe
  
  - Quantum fluctuations during inflation
    → CMB temperature fluctuations, and inhomogeneous distribution of galaxies

Slow-roll inflation: Unusually flat potential

- Stability against radiative corrections and quantum gravity effects
  → A powerful way is to impose a SYMMETRY
1. Inflation

- Axion

Appealing candidate for an inflaton

- Nambu-Goldstone boson associated with spontaneously broken U(1)
  - Flat direction in the absence of explicit U(1) breaking
  - Periodic: $\phi = \phi + 2\pi f$ with generally $f = U(1)$ breaking scale
- Shift symmetry, $\phi \rightarrow \phi + \text{constant}$, presumably broken by non-perturbative effects
  $\rightarrow$ Naturally very light

$$V = V_0 + M^4 \cos\left(\frac{\phi}{f}\right) + \cdots$$

Size of the potential is finite, and insensitive to the decay constant
1. Inflation

- Natural inflation
  Freese, Frieman, Olinto 1990

  Minimal setup for axion-driven inflation
  - Marginally consistent with the recent Planck observations on CMB

  ![Image of inflation diagram]

  \[ n_s \approx 1 + 2 \frac{V'}{V} - 3 \left(\frac{V''}{V}\right)^2 \]
  \[ r = \frac{A_1}{A_0} \approx 8 \left(\frac{V'}{V}\right)^2 \]

- Trans-Planckian decay constant
  → Quantum gravity effects, \( \left(\frac{f}{m_{Pl}}\right)^n \) with \( n > 0 \), may spoil the field theoretic description

Inflation with multiple axions to get \( f \gg (\text{symmetry breaking scale}) \)

- Alignment
  Kim, Nilles, Peloso 2004
  Choi, Kim, Yun 2014, Higaki, Takahashi 2014

- Clockwork mechanism
  Choi, Im 2015, Kaplan, Rattazzi 2015

See talk by Kiwoon Choi
Model
2-1. Hybrid Inflation

- **Hybrid inflation**
  - End of inflation triggered by a waterfall transition
    - Slow-rolling inflaton
    - Instability of a waterfall field triggered by the inflaton

\[
V(\sigma, \phi) = \frac{1}{4\lambda} (M^2 - \lambda \sigma^2)^2 + \frac{m^2}{2} \phi^2 + \frac{g^2}{2} \phi^2 \sigma^2
\]
2-2. Model

- Axion-induced hybrid inflation over a barrier

  Field contents
  - Axion $\phi$ as an inflaton
    $\rightarrow$ Naturally flat potential due to shift symmetry
  - Complex waterfall field $\chi$ various options
    $\rightarrow U(1)_{\chi}$ to forbid a dangerous tadpole

Potential barrier along the waterfall direction
- Traps $\chi$ at the origin
- Disappears when $\phi$ reaches a critical value $\rightarrow$ a waterfall transition

Barrier can still be an important ingredient of slow-roll inflation.
2-2. Model

- Simple model

Scalar potential

\[
V(\phi, \chi) = V_0 + \mu_{\text{eff}}^2(\phi)|\chi|^2 - \lambda|\chi|^4 + \frac{1}{\Lambda^2}|\chi|^6 + U(\phi)
\]

- Inflaton-dependent waterfall mass parameter and potential

\[
\mu_{\text{eff}}^2(\phi) = m^2 - \mu^2 \cos \left( \frac{\phi}{f} + \alpha \right)
\]

\[
U(\phi) = M^4 \cos \left( \frac{\phi}{f} \right)
\]

- \( V_0 \) fixed by the condition \( V = 0 \) at the true vacuum
2-2. Model

- **Simple model**

  Parameter space of our interest

  \[ m^4 < \mu^4 \ll M^4 \ll V_0 \]

  - Scale of inflation: \( H_{\text{inf}} \sim \sqrt{\frac{V_0}{m_{\text{Pl}}^2}} \) where \( V_0 \sim \lambda^3 \Lambda^4 \)
  
  - Scale of the waterfall transition: \( \mu \) and \( m \)

**Role of the barrier**

→ Separation of the scale of inflation and the scale of waterfall transition

→ Wide allowed range of \( f \) and \( H_{\text{inf}} \)

*Ross, German 2010, Ross, German, Vazques 2016*

Case without a barrier: Hybrid natural inflation

- No separation of the two scales
2-2. Model

- **Tunneling over a barrier**

  Tunneling rate
  - Tunneling rate \( \propto e^{-S_E} \)
    - \( S_E \): Euclidean action of \( \chi \) evaluated on a bounce solution
  
  In the region with \( \mu_{\text{eff}}^2 > 2H_{\text{inf}}^2 \), Coleman-De Luccia bounce: \( S_E > \frac{8\pi^2}{3\lambda} \)

  In the opposite region, Hawking-Moss instantons: \( S_E = \left( \frac{\mu_{\text{eff}}^2}{H_{\text{inf}}^2} \right)^2 \frac{8\pi^2}{3\lambda} \)

  - Viable inflation

  \( \mu^2 \gg H_{\text{inf}}^2 \)

  → Heavy enough \( \chi \) to be initially fixed at the origin
  → Exponentially suppressed tunneling until \( \phi \) reaches close to the critical value

  Bubble nucleation is possible at the end of inflation

  But, smooth \( U(1)_\chi \) phase transition due to quick disappearance of barrier

insensitive to the \(|\chi|^6\) term

Shkerin, Sibiryakov 2015
2-3. UV Completion

- **UV completion**

  Hidden QCD with $U(1)_χ$ charged quarks

  \[
  m_u u u^c + y χ u^c d + y' χ^* u d^c + m_d d d^c + \frac{1}{16\pi^2} \frac{φ}{f} G_{μν} \tilde{G}^{μν}
  \]

  - Confining scale in the range: $m_d \ll Λ_h \ll m_u$
  - At scales below $m_u$

  contribution from a closed waterfall loop

  \[
  \left( \frac{yy'}{m_u} |χ|^2 + m_d + δm_d \right) d d^c + \frac{1}{16\pi^2} \frac{φ}{f} G_{μν} \tilde{G}^{μν}
  \]

  Inflaton potential terms at low energy scales
  
  $→ μ$ and $M$ controlled by the hidden confining scale
2-3. UV Completion

- UV completion

Inflaton-dependent waterfall mass parameter

\[ \Rightarrow \mu^2 \cos \left( \frac{\phi}{f} + \alpha \right) |\chi|^2 \]

- Natural setup for the scale hierarchy: \( \mu^4 \ll M^4 \ll V_0 \)
- Small \( m \): required for the waterfall instability
  - Supersymmetry, or anthropic selection
Cosmological Dynamics

Inflation
3-1. Inflation

- **Inflation**
  - Inflation phase
    - Waterfall field trapped at the origin due to the barrier
    - Inflaton evolution: $V_0$, $M$, $f$

\[
V = V_0 + U(\phi) = V_0 + M^4 \cos\left(\frac{\phi}{f}\right)
\]

- Waterfall phase
  - Barrier disappears at

\[
\frac{\phi_c}{f} = \cos^{-1}\left(\frac{m^2}{\mu^2}\right) - \alpha
\]
3-1. Inflation

- Inflation
  Slow-roll parameters: \( \epsilon \equiv \frac{m_{pl}^2}{2} \left( \frac{V'}{V} \right)^2, \quad \eta \equiv m_{pl}^2 \frac{V''}{V} \)

  \( \rightarrow \epsilon \ll |\eta| \) as in natural inflation

- Cosmological observables: Let \( \theta \equiv \frac{\phi}{f} \)
  - Amplitude of power spectrum of curvature perturbation, and its spectral index
  - Tensor-to-scalar ratio of perturbation

\[
A_R = \frac{V_0}{24\pi^2 m_{pl}^4 \epsilon_*} \approx 2.0989^{+0.0296}_{-0.0292} \times 10^{-9}
\]
\[
n_R = 1 - 6\epsilon_* + 2\eta_* \approx 0.9656 \pm 0.0042, \quad r = 16\epsilon_* < 0.056,
\]

at the pivot scale horizon exit of the cosmological scales
3-1. Inflation

- Viable parameter region
  - Inflaton decay constant
    - From the spectral index
      \[ f \approx 7.6 \sqrt{\cos \theta_*} \left( \frac{M^4}{V_0} \right)^{1/2} m_{\text{Pl}} \]
      → Can be well below the Planck scale
  - Number of e-folds before the onset of waterfall phase transition
    \[ N \approx 58 \cos \theta_* \log \left[ \frac{\tan(\theta_c/2)}{\tan(\theta/2)} \right] \]
    → Inflaton value at the horizon exit \( (N \approx 60) \)
    \[ \theta_* \approx 0.71 \tan \left( \frac{\theta_c}{2} \right) - 0.16 \tan^3 \left( \frac{\theta_c}{2} \right) \]
    Need not very close to the hilltop of the potential
3-2. Inflaton Properties

- Inflaton properties
  - Inflaton mass and decay constant in terms of $H_{\text{inf}}$

\[
\begin{align*}
  f &\approx \frac{2 \times 10^5}{\tan \theta_*} H_{\text{inf}} \\
  m_\phi &\approx \frac{0.2}{\sqrt{\cos \theta_*}} H_{\text{inf}}
\end{align*}
\]

Planck results

$A_R$, $n_R$

![Graph showing decay constant and mass vs. $H_{\text{inf}}$]

for $\theta_*$ between 0.01 (solid) and 1.5 (dotted)
3-2. Inflaton Properties

- Inflaton properties
  - Support for experimental searches for ALP in a wide mass range
    - Anomalous inflaton coupling to photons
      - If coupled to photons, Inflaton heavier than about 0.1GeV to avoid too rapid cooling of stars
        - Our scenario: \( f \sim 10^6 \times m_\phi \)

- Inflaton coupling to the Higgs sector
  - Model-dependent inflaton-Higgs mixing
    - Case with \( \theta_{\text{mix}} \sim \frac{v}{f} \)

Jaeckel, Spannowski 2015

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016
Choi, Im 2016
3-3. Reheating

- **Post-inflationary evolution**
  
  Rich phenomenology, but strong model-dependence
  
  - Evolution of \( \chi \) after the barrier disappears
    
    - Acquires a huge mass soon: \( \mu \ll \Lambda \)
    
    - Evolves insensitively to the inflaton evolution
  
  - **Reheating**
    
    - Generally, very effective tachyonic preheating
    
    - Subsequent heating up to a radiation-dominated regime
  
  - Cosmic strings from \( U(1)_\chi \) symmetry breaking
    
    - Can contribute to CMB temperature anisotropies
    
    - Can source gravitational waves
      
      \( 10^{-12} \) to 1 Hz for stable and metastable cosmic strings: LIGO, LISA
      
      1 to \( 10^{10} \) Hz for inhomogeneities from tachyonic preheating
  
  - **Nucleation of barriers at the end of inflation and their effects:** *work in progress*
Cosmological Dynamics

Dark Matter
4-1. Dark Matter- Inflaton

- Inflaton as dark matter
  
  Hidden QCD sector with $U(1)_x$ charged quarks
  
  - Hidden quarks: Large masses proportional to $\chi_0$ in the present universe
    $\rightarrow$ Can be heavier than the confining scale
  
  - Such heavy quark case: no mesons formed
    
    $\mu^2 = 0$ and $M^4 = \Lambda_h^4$
    
    $\rightarrow$ Inflaton stabilized at a CP conserving minimum
  
  Inflation sector: accidental $Z_2$ symmetry, $\phi \rightarrow -\phi$
  
  $\rightarrow Z_2$ makes the inflaton stable if it has no coupling to the SM

  c.f. $\alpha = 0$ case: Im, KJS 2019
4-1. Dark Matter- Inflaton

- **Inflaton as dark matter**
  - Inflaton coherent oscillation
    - Oscillation starts at \( T = T_1 \) when
    \[
    m_\phi(T_1) = 3H(T_1)
    \]
  - Inflaton relic density from misalignment
    - If oscillation starts before reheating ends
    \[
    \Omega_\phi h^2 \sim 0.24 \theta_c^2 \left( \frac{T_1}{\Lambda_h} \right)^n \left( \frac{f}{10^{11} \text{GeV}} \right)^2 \left( \frac{T_{\text{reh}}}{10^5 \text{GeV}} \right)
    \]
    - Otherwise, need the replacement \( T_{\text{reh}} \) with \( T_1 \)
      Thus, the observed dark matter density in a wide range of \( f \)
4-2. Dark Matter- PQ

- Waterfall sector
  Wide allowed range of $H_{\text{inf}}$ allows to connect it to the scale of new physics for BSM
  - $U(1)_\chi$ as Peccei-Quinn symmetry solving the strong CP problem
    - Waterfall phase = QCD axion
    - Cosmologically determined PQ scale (axion decay constant)
  \[
  f_a \approx \frac{3.8 \times 10^{11} \text{ GeV}}{\lambda^{1/4}} \left( \frac{H_{\text{inf}}}{10^4 \text{GeV}} \right)^{1/2}
  \]
  - Contribution of the QCD axion to dark matter
    - Domain-wall number = 1 to avoid the domain-wall problem
    - Axions from misalignment and more efficiently from domain-walls bounded by string
      \[
      \Omega_a h^2 \approx 0.54 \times \left( \frac{\Lambda_{\text{QCD}}}{400 \text{MeV}} \right) \left( \frac{f_a}{10^{11} \text{GeV}} \right)^{1.19} \quad H_{\text{inf}} \lesssim \sqrt{\lambda} \times 10^4 \text{GeV}
      \]
  - Also other possibilities: $U(1)_\chi$ as $U(1)_L$ or local $U(1)_{B-L}$
Conclusions
5. Conclusions

Axion-driven hybrid inflation over a barrier

- Essential role by a potential barrier which diminishes as the axion-like inflation evolves
  - Separation of the scales of inflation and waterfall transition

- Inflaton
  - Decay constant well below the Planck scale
  - Relation between its mass and decay constant in terms of inflation scale: ALP searches
  - Potential to contribute to dark matter

- Waterfall sector
  - Wide allowed range of the inflation scale
  - Possibility to resolve other SM puzzles, e.g. PQ scale determined cosmologically
  - Rich structures: Bubbles, cosmic strings, ...