Axion-driven Hybrid Inflation over a Barrier

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Cosmic Inflation

- Inflation

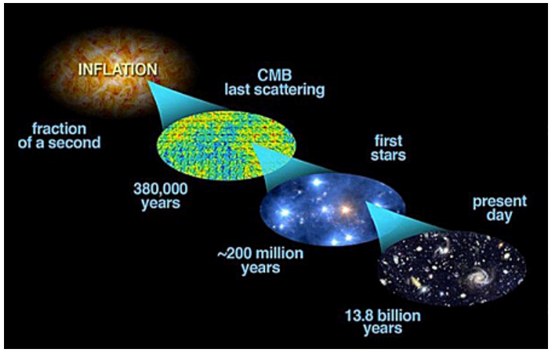
Essential part of the standard cosmological model

- 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 eta problem

  → A powerful way is to impose a **SYMMETRY**

- 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, $\phi \to \phi$ +constant, presumably broken by non-perturbative effects

  → Naturally very light

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

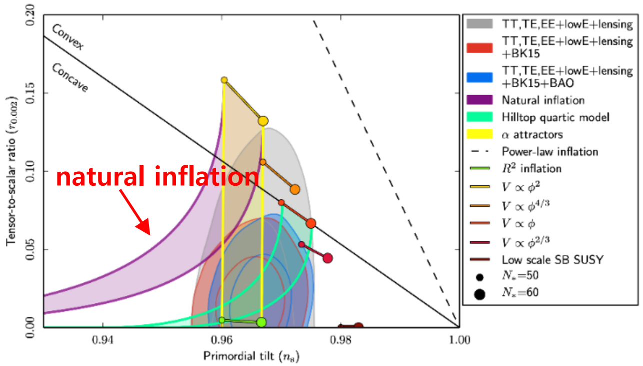
Size of the potential is finite, and insensitive to the decay constant

- Natural inflation

Freese, Frieman, Olinto 1990

Minimal setup for axion-driven inflation

- Marginally consistent with the recent Planck observations on CMB



$$n_s \approx 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

$$r = \frac{A_t}{A_s} \approx 8\left(\frac{V'}{V}\right)^2$$

- Trans-Planckian decay constant

  → Quantum gravity effects, $\left(\frac{f}{m_{\rm Pl}}\right)^n$ with $n > 0$, may spoil the field theoretic description

Inflation with multiple axions to get $f \gg$ (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

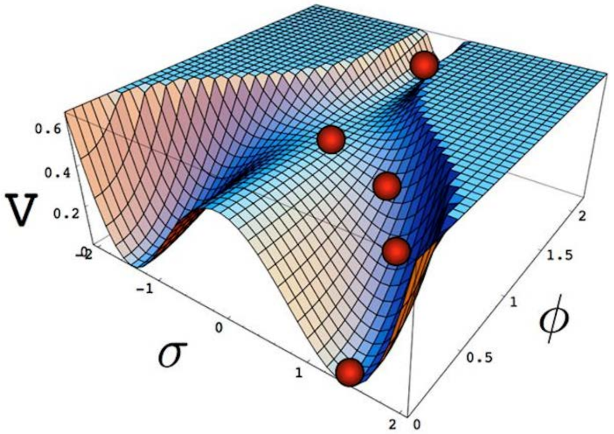
- Hybrid inflation

Linde 1993

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

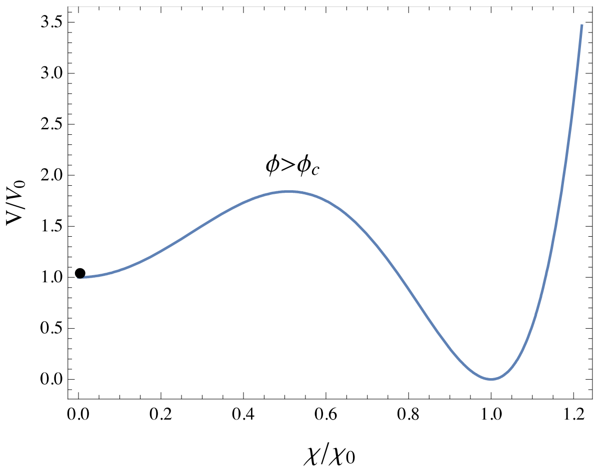
Field contents

- Axion ϕ as an inflaton

  → Naturally flat potential due to shift symmetry

- Complex waterfall field χ various options

  → $U(1)_\chi$ to forbid a dangerous tadpole



Potential barrier along the waterfall direction

- Traps χ at the origin
- Disappears when ϕ reaches a critical value → a waterfall transition

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

- Simple model

Scalar potential

positive

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

cutoff scale

- Inflaton-dependent waterfall mass parameter and potential

c.f. Graham, Kaplan, Rajendran 2015

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

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

- V_0 fixed by the condition $V = 0$ at the true vacuum

- Simple model

Parameter space of our interest

$$m^4 < \mu^4 \ll M^4 \ll V_0$$

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

Role of the barrier

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

→ Wide allowed range of f and $H_{\rm inf}$

Ross, German 2010, Ross, German, Vazques 2016

Case without a barrier: Hybrid natural inflation

- No separation of the two scales

Tunneling over a barrier

Tunneling rate

- Tunneling rate $\propto e^{-S_E}$

  insensitive to the $|\chi|^6$ term

  - S_E: Euclidean action of χ evaluated on a bounce solution

  In the region with $\mu_{\rm eff}^2 > 2H_{\rm inf}^2$, Coleman-De Luccia bounce: $S_E > \frac{8\pi^2}{3\lambda}$ Shkerin, Sibiryakov 2015

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

- Viable inflation

$$\mu^2 \gg H_{\rm inf}^2$$

→ Heavy enough χ to be initially fixed at the origin

→ Exponentially suppressed tunneling until ϕ 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

2-3. UV Completion

- UV completion

Hidden QCD with $U(1)_\chi$ charged quarks

$$m_u u u^c + y\chi u^c d + y'\chi^* u d^c + m_d d d^c + \frac{1}{16\pi^2}\frac{\phi}{f} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

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

contribution from a closed waterfall loop

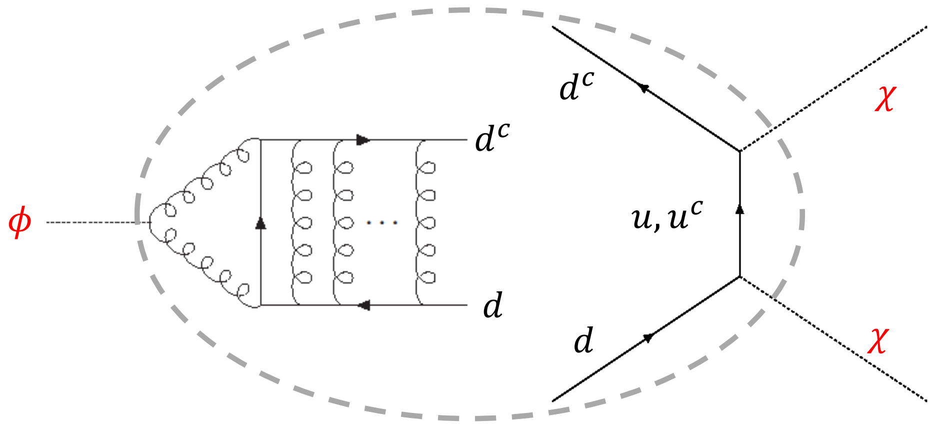
$$\left(\frac{yy'}{m_u}|\chi|^2 + m_d + \delta m_d\right) d d^c + \frac{1}{16\pi^2}\frac{\phi}{f} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

Inflaton potential terms at low energy scales

→ μ and M controlled by the hidden confining scale

- UV completion

Inflaton-dependent waterfall mass parameter



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

anomalous coupling to hidden gluons
→ mixing between ϕ and dd^c meson

effective coupling of dd^c to χ
mediated by heavy $u + u^c$

- 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

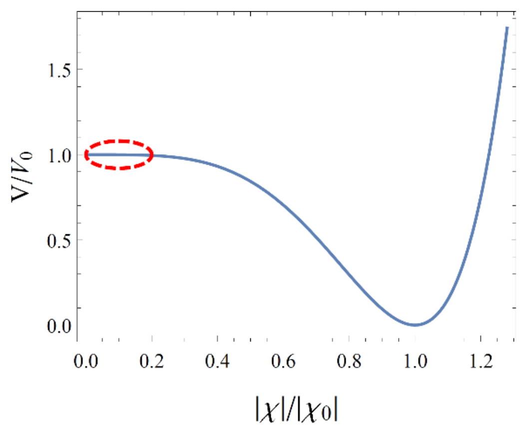
Inflation

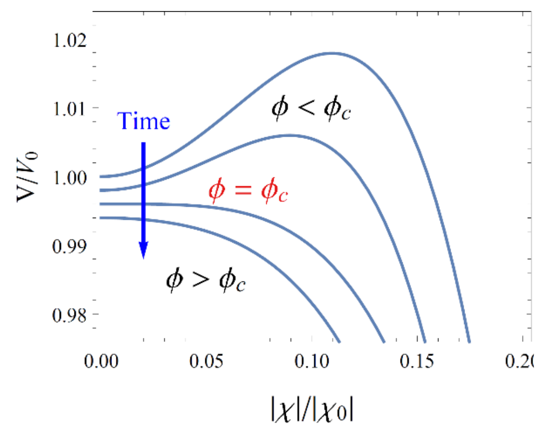
Inflation

- 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 $\frac{\phi_c}{f} = \cos^{-1}\left(\frac{m^2}{\mu^2}\right) - \alpha$





- Inflation

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

  → $\epsilon \ll |\eta|$ 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

$$
\begin{aligned}
A_{\mathcal{R}} &= \frac{V_0}{24\pi^2 m_{\rm Pl}^4 \epsilon_*} \approx 2.0989^{+0.0296}_{-0.0292} \times 10^{-9} \\
n_{\mathcal{R}} &= 1 - 6\epsilon_* + 2\eta_* \approx 0.9656 \pm 0.0042\,, \\
r &= 16\epsilon_* < 0.056\,,
\end{aligned}
$$

at the pivot scale horizon exit of the cosmological scales

- Viable parameter region
  - Inflaton decay constant

    - From the spectral index

$$f \simeq 7.6\sqrt{\cos\theta_*}\left(\frac{M^4}{V_0}\right)^{1/2} m_{\rm Pl}$$

→ Can be well below the Planck scale

  - Number of e-folds before the onset of waterfall phase transition

$$N \simeq 58\cos\theta_* \log\left[\frac{\tan(\theta_c/2)}{\tan(\theta/2)}\right]$$

→ 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

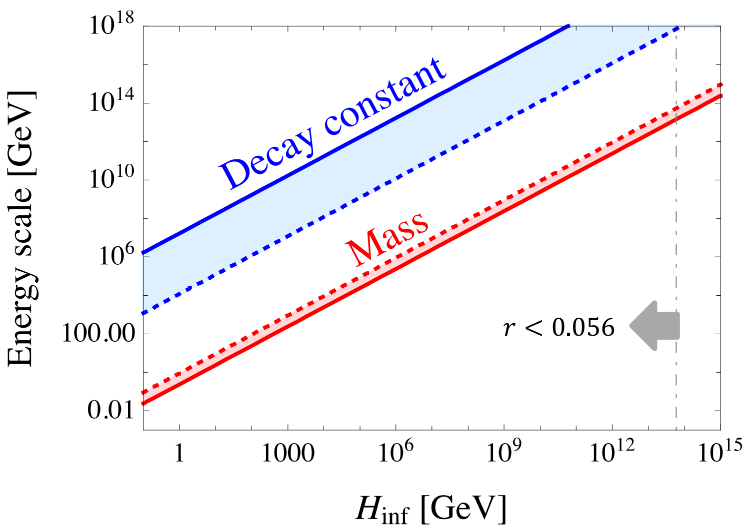
- Inflaton properties
  - Inflaton mass and decay constant in terms of $H_{\rm inf}$

Planck results

$A_{\mathcal{R}},\ n_{\mathcal{R}}$

$$f \approx \frac{2\times 10^5}{\tan\theta_*} H_{\rm inf}$$

$$m_\phi \approx \frac{0.2}{\sqrt{\cos\theta_*}} H_{\rm inf}$$

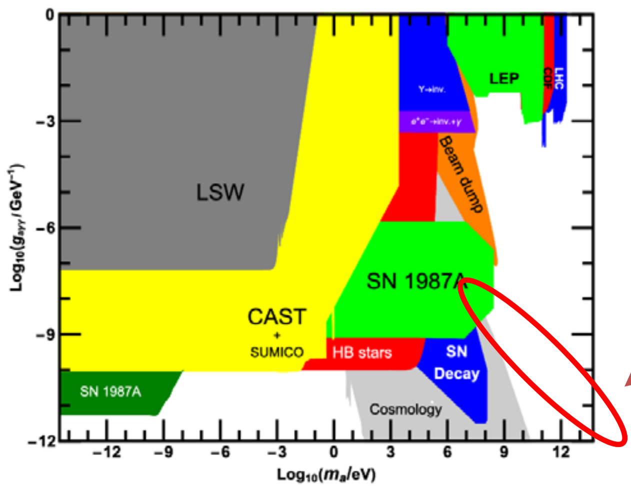


for θ_* between 0.01 (solid) and 1.5 (dotted)

- Inflaton properties

Support for experimental searches for ALP in a wide mass range

- Anomalous inflaton coupling to photons

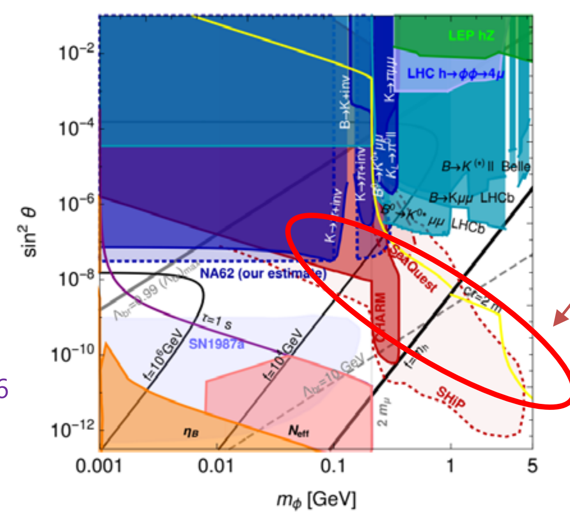


If coupled to photons,
Inflaton heavier than about 0.1GeV
to avoid too rapid cooling of stars

Our scenario: $f \sim 10^6 \times m_\phi$

Jaeckel, Spannowski 2015

- Inflaton coupling to the Higgs sector
  - Model-dependent inflaton-Higgs mixing



Case with $\theta_{\rm mix} \sim \frac{v}{f}$

Flacke, Frugiuele, Fuchs, Gupta, Perez 2016
Choi, Im 2016

3-3. Reheating

- Post-inflationary evolution

Rich phenomenology, but strong model-dependence

- Evolution of χ after the barrier disappears

  - Acquires a huge mass soon: $\mu \ll \Lambda$

  - Evolves insensitively to the inflaton evolution

- Reheating

  - Generally, very effective tachyonic preheating — Garcia-Bellido, Linde 1997; Copeland, Pascoli, Rajantie 2002

  - 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 — Auclair et al 2019; Garcia-Bellido, Figueroa 2007, Dufaux et al 2009

    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 $U(1)_\chi$ charged quarks

- Hidden quarks: Large masses proportional to χ_0 in the present universe

  → Can be heavier than the confining scale

- Such heavy quark case: no mesons formed

$$\mu^2 = 0 \quad \text{and} \quad M^4 = \Lambda_h^4$$

c.f. $\alpha = 0$ case: Im, KJS 2019

→ Inflaton stabilized at a CP conserving minimum

Inflation sector: accidental Z_2 symmetry, $\phi \to -\phi$

→ Z_2 makes the inflaton stable if it has no coupling to the SM

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

$$\Omega_\phi h^2 \sim 0.24\,\theta_c^2 \left(\frac{T_1}{\Lambda_h}\right)^n \left(\frac{f}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{T_{\mathrm{reh}}}{10^5\mathrm{GeV}}\right)$$

    - Otherwise, need the replacement T_{reh} with T_1

    Thus, the observed dark matter density in a wide range of f

- Waterfall sector

Wide allowed range of H_{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 Peccei, Quinn 1977

  - 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

$$\Omega_a h^2 \approx 0.54 \times \left(\frac{\Lambda_{\text{QCD}}}{400\text{MeV}} \right) \left(\frac{f_a}{10^{11}\text{GeV}} \right)^{1.19} \Rightarrow H_{\text{inf}} \lesssim \sqrt{\lambda} \times 10^4\,\text{GeV}$$

Hiramatsu, Kawasak, Saikawa, Sekiguchi 2012

- 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, …

Thank you for your interest!