Effective field theory of waterfall in hybrid inflation

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Based on JG and M. Mylova, to appear soon

Outline

Why inflation?

Inflation can provide otherwise finely tuned initial conditions

Hot big bang	Inflation
Horizon problem	Single causal patch
Flatness problem	Locally flat
Monopole problem	Diluted away
Initial perturbations	Quantum fluctuations

Predictions of inflation are consistent with recent observations

Why effective field theory?

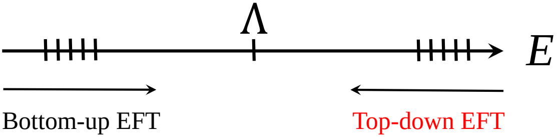
- $E_{\text{inflation}}\,(\sim 10^{15}\ \text{GeV?}) \gg E_{\text{LHC}} = 14\ \text{TeV}$
- Hundreds of inflation models in the market
- Universality of EFT is very powerful

Why hybrid inflation?

- (Relatively) realized easily
- Rich structure and phenomenology
- Connections to particle physics

Effective field theory of inflation?

EFT is such a powerful tool and we can build EFT of inflation



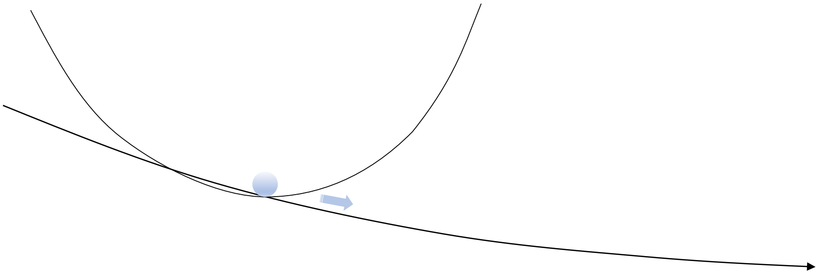
- Bottom-up: T-trans broken, spatial diff preserved (Cheung et al. 2008)
- Top-down: Heavy dof ($\gg \Lambda$) integrated out (Achucarro et al. 2011, 2012)

We adopt top-down EFT to integrate fluc of waterfall field

How hybrid inflation proceeds

Inflation is occurring…

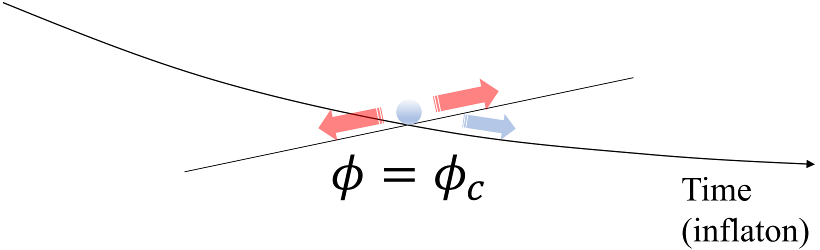
How hybrid inflation proceeds



Inflation is still occurring…

How hybrid inflation proceeds

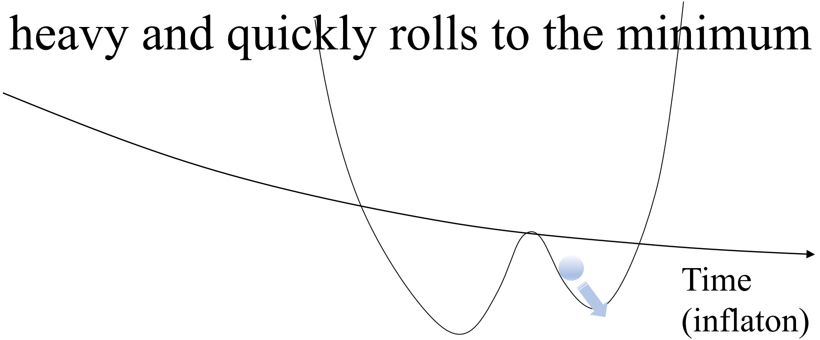
The direction orthogonal to the inflaton becomes massless



"Waterfall" phase transition

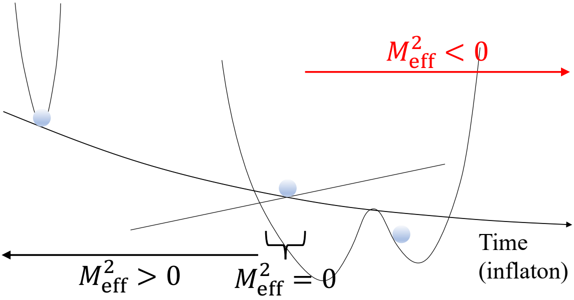
How hybrid inflation proceeds

Very soon the waterfall field becomes heavy and quickly rolls to the minimum



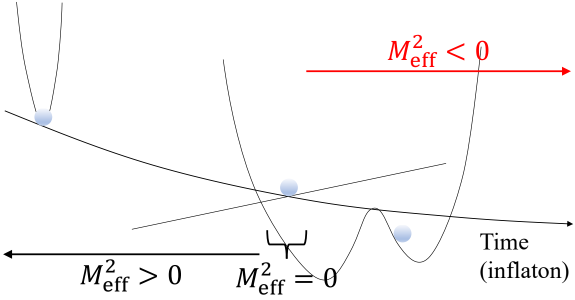
Regimes of different waterfall masses

Let M_{eff}^2 the effective mass squared of the waterfall field χ



- $\phi > \phi_c$: $M_{\text{eff}}^2 > 0$ so is trapped at $\chi = 0$
- $\phi = \phi_c$: $M_{\text{eff}}^2 = 0$ and waterfall transition occurs
- $\phi < \phi_c$: $M_{\text{eff}}^2 < 0$ and is tachyonic

Regimes of different EFTs



- $M^2_{\rm eff} > 0$: χ is integrated out, we get CW-type (Burgess, Cline, Holman 2003)
- $M^2_{\rm eff} = 0$: log diverges, resummed using CS eq (e.g. Peskin & Schroeder)
- $M^2_{\rm eff} < 0$: Just shift the background χ_0 when $V_{\rm eff}$ is minimized?

How to compute the effective potential

We take standard steps for one-loop corrected effective potential

1. 2-field potential $V(\phi,\chi) = \underbrace{V_{\rm inf}(\phi)}_{=\frac{1}{2}m^2\phi^2} + \frac{\lambda}{4}\left(\frac{M^2}{\lambda} - \chi^2\right)^2 + \frac{1}{2}g^2\phi^2\chi^2$
2. Expand $\chi = \chi_0 + \delta\chi$ with $\langle\chi\rangle = \chi_0$, and integrate over $\delta\chi$
3. Regularize divergences

One-loop corrected effective potential

With $M_{\text{eff}}^2 \equiv g^2\phi^2 - M^2$, we find one-loop corrected potential for χ_0

$$V_{\text{eff}}(\chi) = -\frac{1}{2}\left|M_{\text{eff}}^2(\phi)\right|\chi_0^2 + \frac{\lambda}{4}\chi_0^4 + \frac{1}{4(4\pi)^2}\left[-\left|M_{\text{eff}}^2(\phi)\right| + 3\lambda\chi_0^2\right]^2\left\{\log\left[\frac{-\left|M_{\text{eff}}^2(\phi)\right| + 3\lambda\chi_0^2}{\Lambda^2}\right] - \frac{3}{2}\right\}$$

Imaginary corrections to V_{eff}

V_{eff} is valid as long as the log remains small: $|\chi_0| = |M_{\text{eff}}| / \sqrt{3\lambda}$
(N.B. VEV of $\chi = \pm|M_{\text{eff}}|/\sqrt{\lambda}$)

$$V_{\text{eff}} \supseteq \frac{1}{4(4\pi)^2}\left[-\left|M_{\text{eff}}^2(\phi)\right| + 3\lambda\chi_0^2\right]^2 \left\{ i\pi + \log\left[\frac{\left|M_{\text{eff}}^2(\phi)\right| - 3\lambda\chi_0^2}{\Lambda^2}\right] - \frac{3}{2} \right\}$$

Imaginary part of V_{eff} is related to vacuum decay rate (Weinberg and Wu, 1987)

We can trust V_{eff} as long as its imaginary part is small

Slow-roll initial conditions

Standard lore:

We expect SR inflation until $\phi = \phi_c$, and ends immediately

Imposing small log as a part of our initial conditions, we find

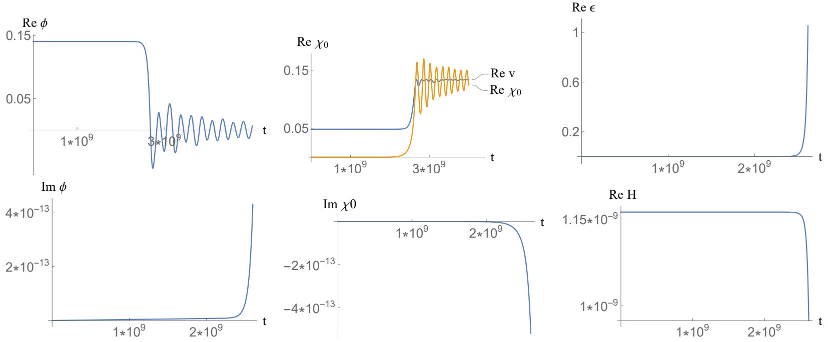
$$\dot{\phi} = \frac{1}{3H}\left[m^2\phi + \underbrace{\frac{g^2M^2\phi}{16\pi^2} - \frac{g^4\phi^3}{16\pi^2}}_{\text{more suppressed}} + i\underbrace{\left(-\frac{g^2M^2\phi}{16\pi} + \frac{g^4\phi^3}{16\pi}\right)}_{\text{than these terms}}\right]$$

For the 1st term to compensate this suppression, we impose

$$g < \frac{4m\sqrt{\pi}}{M} \quad \text{and} \quad \phi < \frac{M}{g}$$

Example 1: SR inflation after waterfall transition

SR inflation proceeds after waterfall transition (Clesse 2011, Kodama et al 2011)

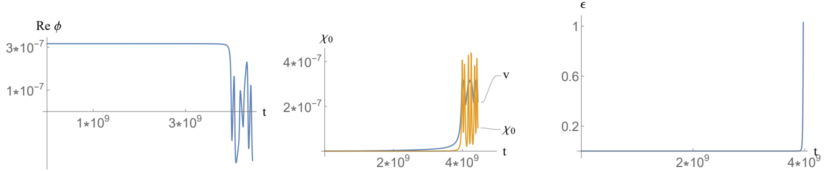


No significant effects at all

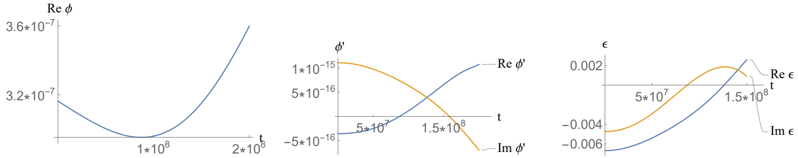
Example 2: Immediate end after waterfall transition

Standard result we expect from long time ago (Linde 1994)

$$\lambda = 10^{-1}, g = 10^{-1/2}, M = 10^{-7} m_{\rm Pl}, m = 10^{-16} m_{\rm Pl}$$



Without quantum effects, inflation ends immediately after $\phi = \phi_c$



Quantum effects dominate from the beginning

Example 2: Immediate end after waterfall transition (cont)

Tried another set of parameters (Linde 1994)

$$\lambda = 1\,, g = 1\,, M = 10^{-3} m_{\rm Pl}\,, m = 5 \times 10^{-8} m_{\rm Pl}$$

Still, quantum effects dominate from the beginning

To impose SR initial conditions at the beginning of waterfall

$$g < 7 \times 10^{-9} \quad \to \quad \phi_c \gg m_{\rm Pl}$$

SR inflation continues after χ settles at VEV (not very interesting!)

Conclusions

- EFT is a powerful tool, for inflation too
- Different regimes of hybrid inflation allows different EFTs
- We have considered EFT of waterfall in hybrid inflation
  1. Effects of quantum corrections are manifest
  2. Breakdown of EFT when quantum effects dominate
  3. Classical considerations are never enough