Effective field theories for multi-field inflation

Jinn-Ouk Gong

Ewha Womans University
Seoul 03760, Korea

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Outline

1. Introduction
2. EFT for multi-field inflation: Adiabatic study
    - How to construct top-down EFT
    - Validity of EFT
    - Correlation of correlation functions
3. Benchmark scenario for non-adiabaticity: Hybrid inflation
    - Multi-field dynamics in hybrid inflation
    - Regimes of different EFTs
    - Construction of EFT
    - Effects of quantum corrections
4. Conclusions

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 multi-field inflation?

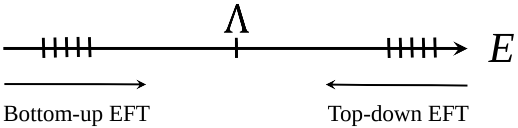
- No inflaton candidate in the standard model (cf. Higgs?)
- Typically BSM contains a number of scalar fields
- Rich phenomenologies, detectable signatures

We have both theoretical and observational motivations

Why effective field theory for inflation?

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

cf. S. Mukohyama's talk on Tue



Universal features of heavy physics?

Why bothering EFT description?

Observations prefer smooth inflation with large enough regime

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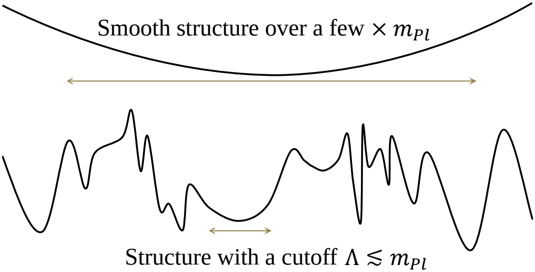
Observations prefer smooth inflation with large enough regime

$$\mathscr{L}_{\text{eff}}[\phi] = \underbrace{\mathscr{L}_0[\phi]}_{\text{smooth}} + \underbrace{\sum_n c_n \frac{\mathscr{O}_n[\phi]}{\Lambda^{n-4}}}_{\text{EFT allows these}}$$



EFT introduces sub-cutoff structure: **tension with observations**

What kind of EFT?

Single field inflation
in Einstein gravity

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Single (multi) field inflation
No gravity effect
Symmetry principles
(Senatore et al.)

effective

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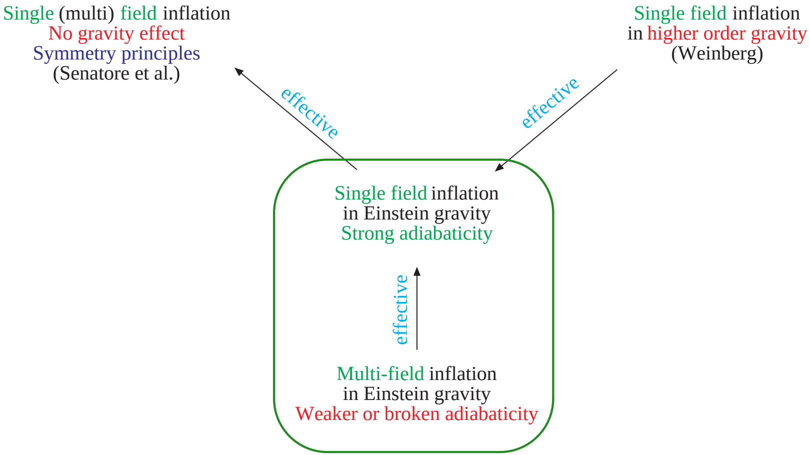
Multi-field inflation
in Einstein gravity
Weaker or broken adiabaticity

What kind of EFT?



Our focus

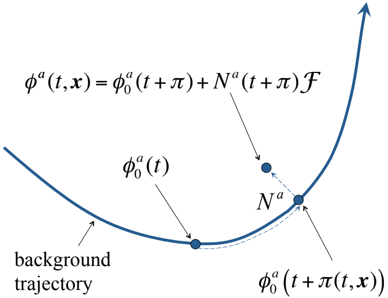
Adiabatic EFT recipe

☺ Recipe for top-down EFT ☺

1. Write the action in terms of $\mathscr{R}$ (along traj) and $\mathscr{F}$ (off traj)
2. Integrate out $\mathscr{F}$: $e^{S_\text{eff}[\mathscr{R}]} = \int [D\mathscr{F}] e^{S[\mathscr{R},\mathscr{F}]}$
3. Effective single field action $S_\text{eff}[\mathscr{R}]$

More about recipe 1

1. Write the action in terms of $\mathscr{R}$ (along traj) and $\mathscr{F}$ (off traj)



- $\mathscr{R}$: Curvature (or adiabatic) pert, related to π by $\mathscr{R} = -H\pi$
- $\mathscr{F}$: "Orthogonal" to the trajectory and hence to $\mathscr{R}$

More about recipe 2

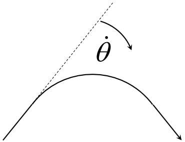
2. Integrate out $\mathscr{F}$: $e^{S_{\rm eff}[\mathscr{R}]} = \int [D\mathscr{F}] e^{S[\mathscr{R},\mathscr{F}]}$

Equivalent to plugging the (linear) solution of $\mathscr{F}$ back to the action

$$\underbrace{\left(-\Box + M_{\rm eff}^2\right)\mathscr{F}}_{\text{From quadratic terms purely in } \mathscr{F}} = \underbrace{-2\dot\theta\frac{\dot\phi_0}{H}\dot{\mathscr{R}}}_{\text{From the interaction with } \mathscr{R}:\ S_2 \supset \int d^4x\left(-2\dot\theta\frac{\dot\phi_0}{H}\dot{\mathscr{R}}\mathscr{F}\right)}$$

$\dot\theta$: angular velocity of trajectory

$\dot\theta = 0$: Straight, single field
$\dot\theta \neq 0$: Any deviations appear

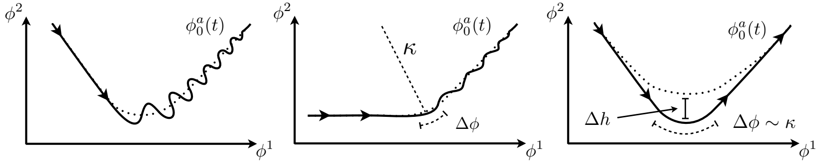


Q: Is replacing the solution of $\mathscr{F}$ always **valid**?

More about recipe 2, cont: Validity of EFT

Truncation in $\Box/M_{\rm eff}^2$: Non-local → higher derivative theory

$$\mathscr{F} = \frac{-2\dot\theta\left(\dot\phi_0/H\right)}{-\Box+M_{\rm eff}^2}\dot{\mathscr{R}} = \frac{-2\dot\theta\left(\dot\phi_0/H\right)}{M_{\rm eff}^2}\left[1+\frac{\Box}{M_{\rm eff}^2}+\cdots\right]\dot{\mathscr{R}}$$



Valid for "adiabatic trajectory": $M_{\rm eff}^2$ is most important, or

$$\left|\frac{\ddot\theta}{\dot\theta}\right| \ll M_{\rm eff} \to \frac{\dot\theta^2}{M_{\rm eff}^2} \gg 1 \text{ is OK } (\textbf{strong turn})$$

More about recipe 3

3. Effective single field action $S_{\text{eff}}[\mathscr{R}]$

$$S_{\text{eff}}[\mathscr{R}] = \int d^4x a^3 \epsilon m_{\text{Pl}}^2 \left[\left(1 + \frac{4\dot{\theta}^2}{M_{\text{eff}}^2} \right) \dot{\mathscr{R}}^2 + \cdots \right]$$

Effects of heavy physics in "speed of sound"

$$c_s^{-2} \equiv 1 + \frac{4\dot{\theta}^2}{M_{\text{eff}}^2} \quad (\gg 1, \text{ possibly})$$

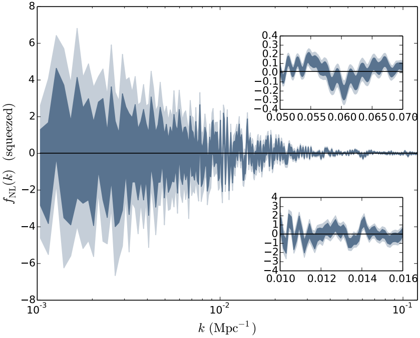
Manifest correlation between 2- & 3-point functions

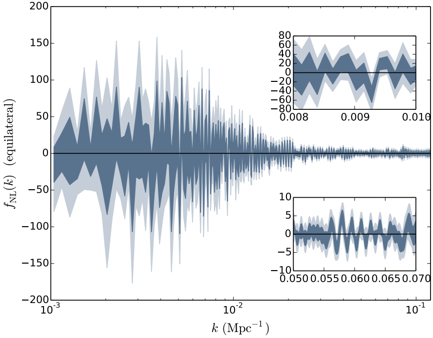
Since the (deviation from scale-inv) $P_{\mathscr{R}}$ is specified by c_s, we can find c_s in terms of $P_{\mathscr{R}}$ and 3-pt fct is **completely fixed** by 2-pt fct

$$f_{\rm NL}(k_1,k_2,k_3) = c_0^\Delta(\boldsymbol{k})\log P_{\mathscr{R}} + c_1^\Delta(\boldsymbol{k})\frac{d\log P_{\mathscr{R}}}{d\log k} + c_2^\Delta(\boldsymbol{k})\frac{d^2\log P_{\mathscr{R}}}{d\log k^2}$$

We only need precise measurement on $\mathscr{P}_{\mathscr{R}}(k)$

Reconstructed 3-pt function directly from CMB data





Marginal 2σ hints in the 3-pt fct at $k \sim 0.014$ Mpc^{-1} and 0.06 Mpc^{-1}

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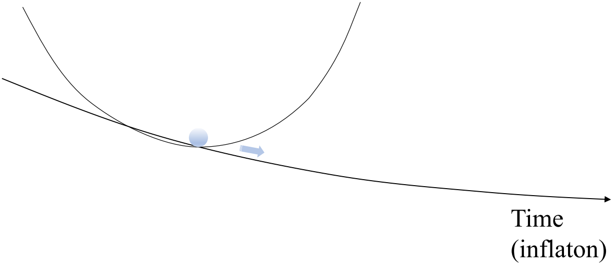
Why hybrid inflation?

- (Relatively) realized easily, e.g. in SUSY / SUGRA
- Connections to particle physics
- Rich structure and phenomenology

How hybrid inflation proceeds

Inflation is occurring…

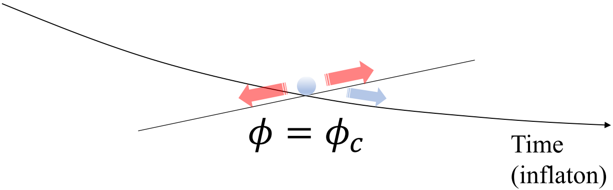
How hybrid inflation proceeds



Inflation is still occurring…

How hybrid inflation proceeds

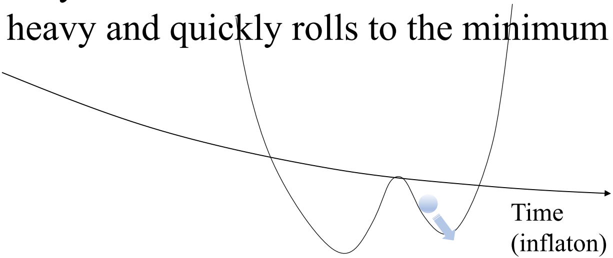
The direction orthogonal to
the inflaton becomes massless



“Waterfall” phase transition

How hybrid inflation proceeds

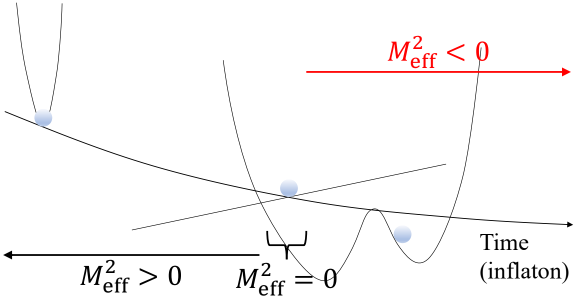
Very soon the waterfall field becomes heavy and quickly rolls to the minimum



- 2-field dynamics is essential, and cannot be integrated out
- At the heart of our picture lies the classical approximation
- **Q: Does the classical approximation remain valid?**

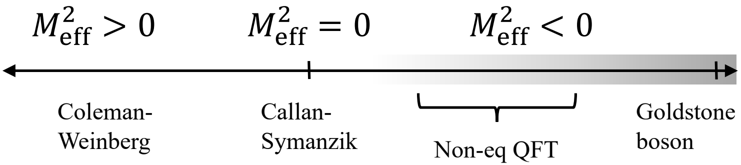
Regimes of different waterfall masses

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



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

Regimes of different EFTs



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

How to compute the effective potential

We take standard steps for one-loop corrected effective potential

1. 2-field potential $V(\phi,\chi) = \underbrace{V_{\rm inf}(\phi)}_{=\frac{1}{2}m^2\phi^2} + \frac{\lambda}{4}\left(\frac{M^2}{\lambda} - \chi^2\right)^2 + \frac{1}{2}g^2\phi^2\chi^2$

   (so that $M_{\rm eff}^2 \equiv g^2\phi^2 - M^2$)
2. Expand $\chi = \chi_0 + \delta\chi$ with $\langle\chi\rangle = \chi_0$, and integrate over $\delta\chi$
3. Regularize divergences

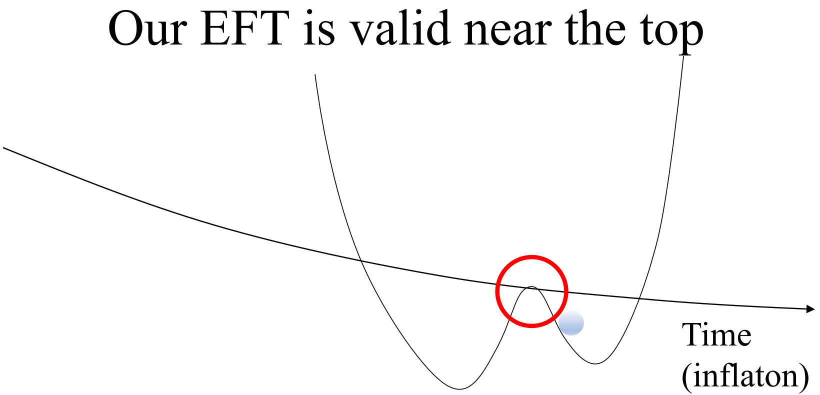
One-loop corrected effective potential

$$V_{\rm eff}(\chi) = -\frac{1}{2}\left|M^2_{\rm eff}(\phi)\right|\chi_0^2 + \frac{\lambda}{4}\chi_0^4$$

$$+\frac{1}{4(4\pi)^2}\left[-\left|M^2_{\rm eff}(\phi)\right|+3\lambda\chi_0^2\right]^2\left\{\underbrace{\log\left[\frac{-\left|M^2_{\rm eff}(\phi)\right|+3\lambda\chi_0^2}{\Lambda^2}\right]}_{=i\pi+\log\left[\frac{\left|M^2_{\rm eff}(\phi)\right|-3\lambda\chi_0^2}{\Lambda^2}\right]}-\frac{3}{2}\right\}$$

- $V_{\rm eff}$ is valid as long as the $|\chi_0| \lesssim |M_{\rm eff}|/\sqrt{3\lambda}$ (N.B. Min at $\chi_0 = \pm|M_{\rm eff}|/\sqrt{\lambda}$)
- As waterfall begins ($\chi_0 \sim 0$), log is imaginary but remains small
- $\Im V_{\rm eff}$ is related to vacuum decay rate (Weinberg and Wu, 1987)

Validity of our EFT



Consistency check

1. Is backreaction to gravity under control? YES
2. Does the BG field grow exponentially? YES (those up to $k < m$)
3. Is the slow-roll maintained at the beginning?

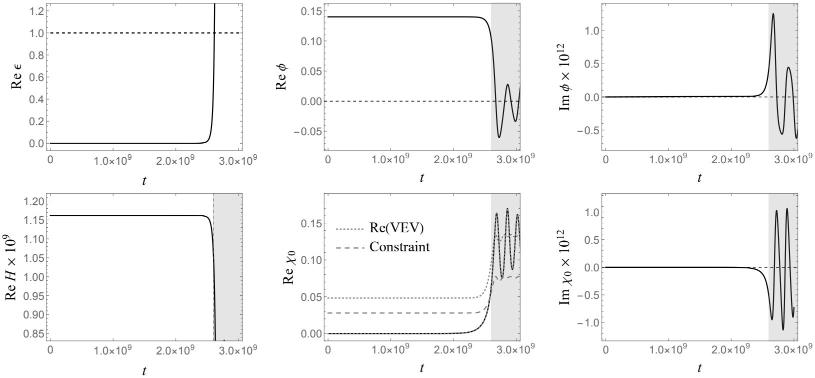
$$\frac{m}{g} \gtrsim \frac{M}{4\sqrt{\pi}}$$

Otherwise, $\delta\chi$ dominates and **classical approx breaks down**

Example 1: SR inflation after waterfall transition

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

$$\lambda = 5\times10^{-14}\,,\ g = 2\times10^{-7}\,,\ M = 3\times10^{-8}\,m_{\rm Pl}\,,\ m = 8\times10^{-12}\,m_{\rm Pl}$$

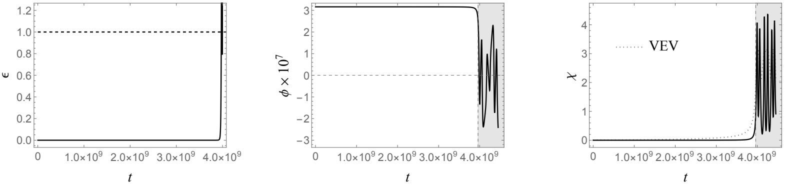


No significant effects at all

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 $\phi = \phi_c$

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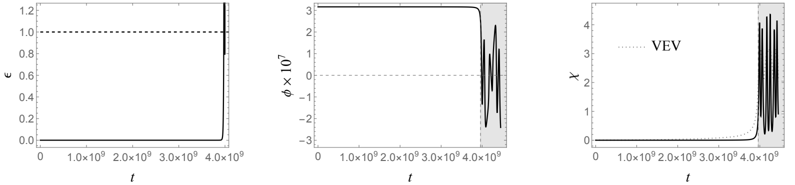

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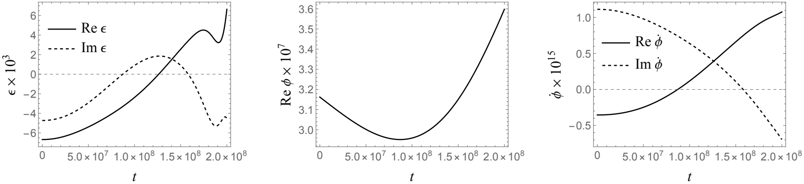
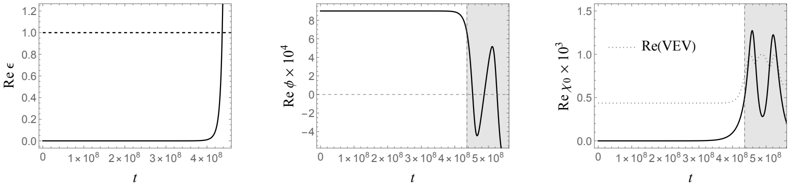


Quantum effects dominate from the beginning

Example 3: Constraint enforced

We impose $\phi < M/g$ and $m/g > M/(4\sqrt{\pi})$:

$$\lambda = 10^{-8}\,,\ g = 10^{-4}\,,\ M = 10^{-7}m_{\rm Pl}\,,\ m = 10^{-11}m_{\rm Pl}$$



Classical approximation is valid

Conclusions

- EFT is a powerful tool, for (multi-field) inflation too
- Adiabatic EFT for multi-field inflation
  - Bottom-up and top-down approaches
  - Universal features described in the speed of sound
  - Correlation of correlation functions
- Broken adiabaticity: EFT for hybrid inflation
  - Different regimes of hybrid inflation allows different EFTs
  - Breakdown of EFT when quantum effects dominate
  - Classical considerations are never enough