Effective theory approach to multi-field inflation

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Outline

Why inflation?

Hot big bang

- Horizon problem
- Flatness problem
- Monopole problem
- Initial perturbations

Inflation

- Single causal patch
- Locally flat
- Diluted away
- Quantum fluctuations

1. Initial conditions for hot big bang
2. A certain amount of expansion is required:

$$\text{Number of } e\text{-folds} : N = \log\left(\frac{a_e}{a_i}\right) \sim 60 \text{ is necessary}$$

3. Consistent with most recent observations
4. Typically driven by inflaton with a specific potential $V(\phi)$

Why multi-field inflation?

- Theoretical challenges: building models from particle physics
  1. No inflaton in SM: BSM (Bezrukov & Shaposhnikov 2008: Higgs = inflaton?)
  2. Many scalar fields
  3. Many inflaton candidates
- Observational opportunities: new data ahead
  1. Both particle physics (LHC) and cosmology (a lot)
  2. Constraining / detecting new cosmological signatures ↔ constraining high energy physics
  3. All in next 10 - 15 years

We have both theoretical and observational motivations

Why EFT for multi-field inflation?

- $E_{\text{inflation}}(\sim 10^{15}\ \text{GeV?}) \gg E_{\text{LHC}} = 14\ \text{TeV}$
- Are various corrections important? No idea
- Control over our ignorance: universality of EFT

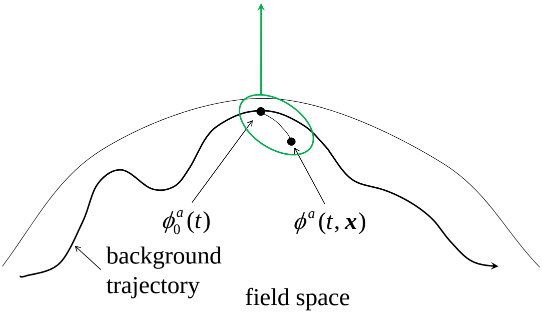
For multi-field inflation... (single-field EFT: Burgess, Lee & Trott 2009)

- Trajectory along the lightest direction
- If the trajectory is...
  1. straight: identical to single field case by field redefinition
  2. curved: 1 more d.o.f. and different from single field case
- Effects of heavy physics are there

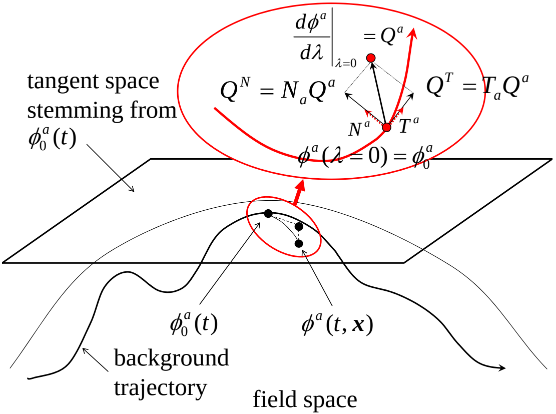
Can we apply EFT to find universal features of "heavy" physics?

Decomposing perturbation

How to describe **departure** from homogeneous background?



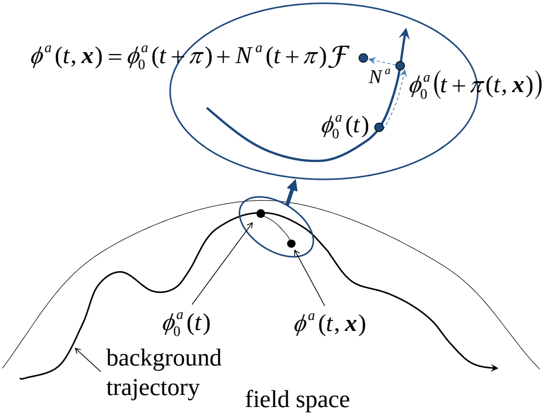
Decomposing perturbation



1. Tangent / perp to the BG trajectory: Traditional approach

(Gong & Tanaka 2011)

Decomposing perturbation



1. Tangent / perp to the BG trajectory: Traditional approach

   (Gong & Tanaka 2011)

2. Along / perp to the BG trajectory: Symmetry of the action

   (Achucarro et al. 2012a)

Family of background solutions

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm Pl}^2}{2}R + \mathscr{L}^{(M)}\left(\phi^a,\partial_\mu\phi^a\right)\right]$$

$\rightarrow$ invariant under $x^\mu \rightarrow x^\mu + \xi^\mu$ for constant ξ^μ

Given a set of BG solutions $\phi_0^a(t)$ and $a(t)$, a family of solutions

$$\begin{aligned}\phi_0^{a\prime}(t) &= \phi_0^a(t+\Delta\mathscr{T})\\ a'(t) &= a(t+\Delta\mathscr{T}) + \Delta\mathscr{R}\end{aligned}$$

Parametrizing perturbations (3 scalar d.o.f.) as

$$\begin{aligned}\phi^a(t,\boldsymbol{x}) &= \phi_0^a(t+\pi) + N^a(t+\pi)\mathscr{F}\\ \gamma_{ij} &= a^2(t+\pi)e^{2\mathscr{R}}\delta_{ij}\end{aligned}$$

Non-trivial solutions: $\pi =$constant, $\mathscr{R} =$constant, $\mathscr{F} = 0$ (Cheung et al. 2008)

Gauge transformation of π and $\mathscr{R}$

Single field case for clarity: at linear order

$$
\begin{aligned}
\phi = \phi_0 + \delta\phi \quad &\leftrightarrow \quad \delta\phi = \dot{\phi}_0\pi \quad \underset{\hat{t}=t+\xi^0}{\longrightarrow} \quad \widehat{\delta\phi} = \dot{\phi}_0\left(\pi - \xi^0\right) \\
\gamma_{ij} = a^2\left(1+2\varphi\right)\delta_{ij} \quad &\leftrightarrow \quad \varphi = H\pi + \mathscr{R} \quad \underset{\hat{t}=t+\xi^0}{\longrightarrow} \quad \widehat{\varphi} = H\left(\pi - \xi^0\right) + \mathscr{R}
\end{aligned}
$$

$\widehat{\pi} = \pi - \xi^0$: π =Goldstone boson associated with $t \to \widehat{t} = t + \xi^0$

1. Comoving gauge: $\widehat{\delta\phi} = 0 \to \varphi_{\delta\phi} = \mathscr{R}$
   - $\mathscr{R}$ is gauge invariant
   - $\widehat{\mathscr{R}}$ shares the same properties as the original $\mathscr{R}$
2. Flat gauge: $\gamma_{ij} = a^2(t)\delta_{ij} \to \widehat{\pi} = -\mathscr{R}/H$
   - $\widehat{\pi}$ does not share the same properties as the original π
   - Not original π in both cases

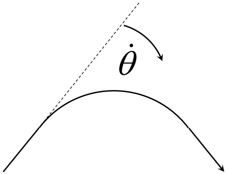
Comoving gauge is privileged!

Effective single field theory: recipe

1. Write the action in terms of $\mathscr{R}$ (along traj) and $\mathscr{F}$ (off traj)
2. Integrate out $\mathscr{F}$: $e^{S_{\text{eff}}[\mathscr{R}]} = \int [D\mathscr{F}] e^{S[\mathscr{R},\mathscr{F}]}$
   $\left[= \text{equiv to plugging linear sol: } \left(-\Box + M_{\text{eff}}^2\right)\mathscr{F} = -2\dot\theta\left(\dot\phi_0/H\right)\dot{\mathscr{R}}\right]$
3. Effective single field action $S_{\text{eff}}[\mathscr{R}]$
4. ☺

Effects of heavy physics in "speed of sound"

$$c_s^{-2} \equiv 1 + \frac{4\dot\theta^2}{M_{\text{eff}}^2} \quad \left(\dot\theta : \text{ angular velocity of traj}\right)$$



Single field theory with non-trivial c_s^2: Footprint of heavy physics

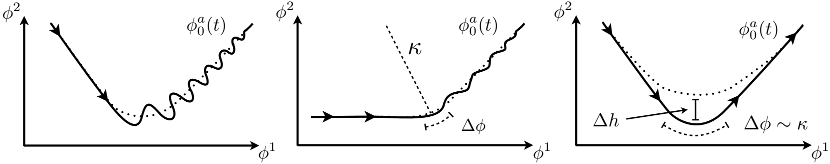
(Achucarro et al. 2012a)

$\mathscr{F}$ borrows kinetic energy of $\mathscr{R}$ → progagation speed c_s reduced

"Effective field theory"

Truncation in $\Box/M_{\rm eff}^2$ when feeding back the sol of $\mathscr{F}$:

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



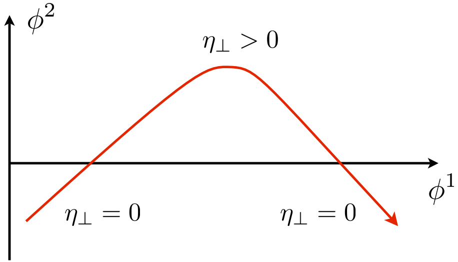
Valid for "adiabatic traj": $|\Box\mathscr{F}| \ll M_{\rm eff}^2|\mathscr{F}|$ $\left(\left|\ddot\theta/\dot\theta\right| \ll M_{\rm eff}\right) \rightarrow$
Creation of heavy quanta suppressed (Achucarro et al. 2012b)

EFT remains valid even for $c_s^{-2} = 1 + \dfrac{4\dot\theta^2}{M_{\rm eff}^2} \gg 1$ (strong turn)

Modelling effective speed of sound

A smooth turn in otherwise straight trajectory in 2-field system

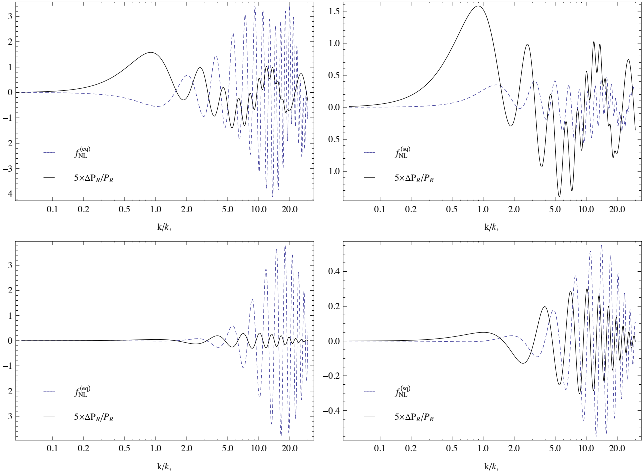
(Achucarro et al. 2011a, 2013)



$$\frac{1}{c_s^2} = 1 + u_{\max}\left[\tanh\left(\frac{N-N_i}{\delta N}\right) - \tanh\left(\frac{N-N_f}{\delta N}\right)\right]$$

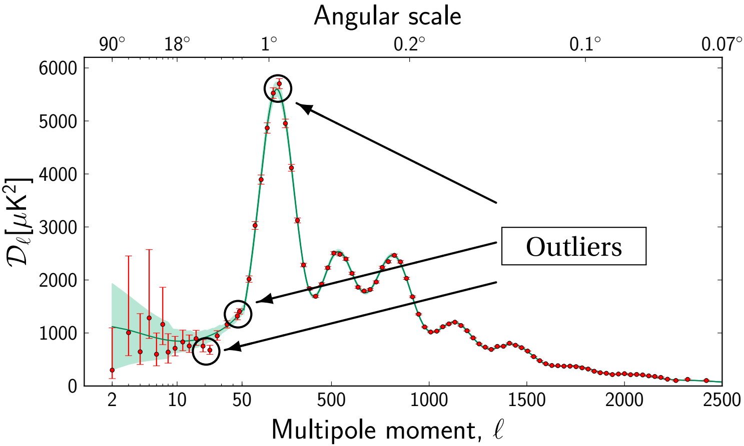
Power spectrum $\mathscr{P}_{\mathscr{R}}$ and bispectrum $B_{\mathscr{R}}$ are completely correlated

Correlation of correlation functions



(Achucarro et al. 2013)

PLANCK 2013 data



We may have already observed the signatures?

(Meerburg & Spergel 2013, see also Hazra, Shafieloo & Smoot 2013)

Conclusions

1. Prescription of perturbations
   - Goldstone language : Time translational symmetry
   - Constant solution : Constrained derivative structure
   - Comoving gauge is privileged
2. Effective single field theory
   - Integrating out the heavy isocurvature modes
   - Identical to plugging the full solution of the isocurvature modes
   - Single field theory with non-trivial c_s^2
3. Phenomenology of multi-field system
   - Highly non-trivial features in the correlation functions
   - Oscillations in the power spectrum
   - Bispectrum: Local + equilateral, scale dependence$\cdots$