Post-Inflationary String Cosmology
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Shift-Symmetric Adiabatic Modes

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Introduction and outline

• Inflation: some primordial data, many models.

• Idea: understand the role of symmetries (exact or approximate) without relying on specific UV models and the consequences/constraints for observables.

• A simple case: shift-symmetry in single-clock inflation.
Assuming an exact shift-symmetry provides specific relations among correlation functions.
Can we understand whether it is exact or broken?

• Results: new adiabatic modes and soft-theorems in shift-symmetric theories.

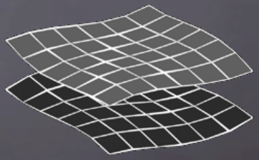
EFT for single-field cosmology

[Creminelli, Luty, Nicolis, Senatore '06], [Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore '08]

- Irrespective of what is really driving the evolution at microscopic level, one can capture the low-energy physics just in terms of symmetry breaking patterns.

- The system can be thought of as being equipped with a "clock" $\Phi(t)$ scanning the status of the Universe, defining a privileged time-slicing.

Exact symmetries: $x^i \to x^i + \xi^i(t, \vec{x})$.
Broken symmetries: $t \to t + \xi^0(t, \vec{x})$.



EFT for single-field cosmology

[Creminelli, Luty, Nicolis, Senatore '06], [Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore '08]

- The residual symmetries (spatial diffs) enforce the following action

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \mathcal{L}\left(R_{\mu\nu\rho\sigma}, g^{00}, K_{\mu\nu}, \nabla_\mu; t\right) .$$

- Because of the breaking of time diffs, it exhibits 3 d.o.f.: 2 graviton helicities + 1 scalar mode (use a Stückelberg transformation to make it explicit).

- The action for perturbations can be found expanding around FRW

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}\vec{x}^2 .$$

- At this level, no input either from inflation (this is really the EFT of single-clock cosmology!) or from additional symmetries.

EFT for single-field inflation

[Creminelli, Luty, Nicolis, Senatore ’06], [Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore ’08]

- Neglecting for the moment higher-derivative operators,

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R + \sum_{n=0}^{\infty} \frac{M_n(t)}{n!} \left(g^{00} + 1 \right)^n \right] .$$

- $M_0 = -M_{\rm Pl}^2(3H^2 + 2\dot{H})$ and $M_1 = M_{\rm Pl}^2 \dot{H}$ are fixed by the background.

- Yet there is infinite freedom because the coefficients $M_{n\geq 2}(t)$ can be in principle *arbitrary* functions of time.
(E.g. in $P(X)$, with $X = -g^{\mu\nu}\partial_\mu \Phi \partial_\nu \Phi$, M_n are *not* necessarily constant.)

Shift-symmetry in the EFT of inflation

[Finelli, Goon, Pajer, L.S. *in progress*]

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{M_{\mathrm{Pl}}^2}{2} R + \sum_{n=0}^{\infty} \frac{M_n(t)}{n!} \left(g^{00}+1\right)^n \right] .$$

- Imposing a shift-symmetry for the *clock*, $\Phi \to \Phi + c$, fixes the time-dependence of *all* free coefficients.

Shifting the clock is equivalent to performing a specific t-shift:

$$t \to t + \Delta t \,, \qquad \Delta t \equiv \frac{c}{\dot{\Phi}(t)} + \ldots$$

As a result

$$\boxed{X\dot{M}_n - n\dot{X}M_n + \dot{X}M_{n+1} = 0 \,.}$$

- We are simply imposing that, after the time re-parametrization

$$t \to \Phi\left(t(\phi)\right) = \Phi(\phi) = \phi \,,$$

there is no explicit ϕ-dependence in the action

$$S = \int \mathrm{d}\phi \, \mathrm{d}^3\vec{x} \sqrt{-g} \, \mathcal{L}\left(R_{\mu\nu\rho\sigma}, g^{00}, K_{\mu\nu}, \nabla_\mu ; \cancel{\phi}\right)$$

Shift-symmetry in the EFT of inflation

[Finelli, Goon, Pajer, L.S. *in progress*]

- The condition

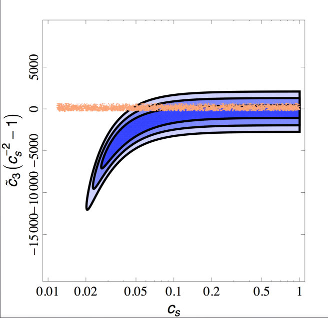
$$X\dot{M}_n - n\dot{X}M_n + \dot{X}M_{n+1} = 0$$

is simply telling us that all M_n are specific functions of the slow-roll parameters.

- As a result:

$$\tilde{c}_3\left(c_s^{-2}-1\right) = \frac{1}{2}\left(3c_s^2 - 4 + c_s^{-2}\right) + \left(1 + c_s^{-2}\right)\frac{s}{2\varepsilon - \eta}\,.$$

- Relations among observables are more easily derived using Ward identities, without relying on perturbation theory.



Shift-symmetry in the EFT of inflation

[Finelli, Goon, Pajer, L.S. *in progress*]

- In particular, using the background conditions for M_0 and M_1, the equations of motion can be written as

$$\varepsilon\left[\eta - 2\varepsilon + 3\left(1 + c_s^2\right)\right] = 0\,,$$

where $\varepsilon \equiv -\dot{H}/H^2$ and $\eta \equiv \dot{\varepsilon}/(H\varepsilon)$.

- Two possible solutions:
  - $\varepsilon = 0$ (ghost condensate);
  - $\varepsilon \ll 1$, $\eta \simeq -3\left(1 + c_s^2\right)$ (ultra-slow-roll inflation).

- No standard "slow-roll" in pure $P(X)$-theories! Enforcing the shift symmetry requires higher-derivative operators...

Shift-symmetric Adiabatic Mode (SAM)

[Finelli, Goon, Pajer, L.S. *to appear*]

We discuss a new symmetry of the action for perturbations around FRW backgrounds:

> internal shift-symmetry
> (when the underlying UV-theory obeys $\Phi \to \Phi + c$)
> $+$
> large residual gauge transformations
> $=$
> Shift-symmetric Adiabatic Mode (SAM)

We follow the standard protocol:

- fix a gauge: $ds^2 = -(1+\delta N)^2 dt^2 + a^2 e^{2\zeta}\delta_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$;
- find a residual symmetry transformation which preserves the gauge $\delta\Phi = 0$: internal shift + diff with $\xi^\mu = (c/\dot{\Phi}, \lambda(t) x^i)$;
- demand that all equations of motion are satisfied at finite momentum, $q \neq 0$: $\lambda(t) = -c\int^t dt' \dot{H}(t')/\dot{\Phi}(t')$;
- the so generated configurations are the SAM's: $\Delta\zeta = c\left[H/\dot{\Phi} - \int^t dt' \dot{H}(t')/\dot{\Phi}(t')\right]$.

SAM's Ward identities

[Finelli, Goon, Pajer, L.S. *to appear*]

We computed the Ward identities associated to such a new symmetry, yielding the following soft theorem for inflationary correlators:

$$\left[\frac{H}{\dot{\Phi}} - \int^t \mathrm{d}t' \frac{\dot{H}(t')}{\dot{\Phi}(t')}\right] \lim_{\vec{q}\to 0} \frac{\langle \zeta_{\vec{q}} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \cdots \zeta_{\vec{k}_n} \rangle'}{P_\zeta(q)}$$
$$= \left[\frac{1}{\dot{\Phi}}\partial_t + \int^t \mathrm{d}t' \frac{\dot{H}(t')}{\dot{\Phi}(t')} \left(3(n-1) + \sum_{j=1}^n \vec{k}_j \cdot \frac{\partial}{\partial \vec{k}_j}\right)\right] \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \cdots \zeta_{\vec{k}_n} \rangle' \,.$$

The shift contribution becomes dominant in ultra-slowly rolling backgrounds, yielding for $n = 2$ the well-known prediction

$$f_{\mathrm{NL}} = \frac{5}{2}\,.$$

Conclusions

• Model independent results are precious in order to shed light on the microscopic realization of inflation.
We discussed the role of the shift symmetry in the EFT of inflation.

• The symmetries underlying soft theorems in attractor models are the residual asymptotic symmetries common to any FRW (Weinberg's adiabatic modes).
We introduced a new symmetry involving an internal shift, associated with SAM's.
We introduced a new class of soft theorems and discussed their implications in non-attractor models of inflation.