Parity Violation in the Effective Field Theory of Inflation

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Summary/overview

- quick review of the Effective Field Theory of Inflation (EFTI)
- parity violation and splitting of the two graviton helicities
- consequences for CMB power spectra
- tensor power spectrum and higher-order correlation functions:
    1. bispectra involving tensors
    2. effect on CMB angular three-point functions
    3. what is the largest effect?

Effective Field Theory of Inflation

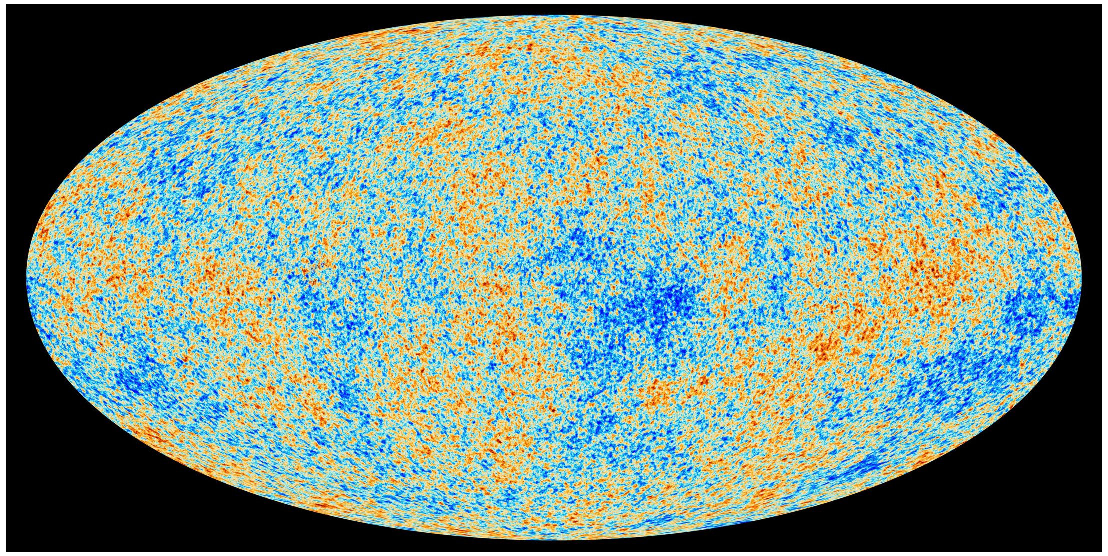
Cheung et al. (2007)

- inflation: epoch of accelerated expansion that smoothly connects to the Hot Big Bang
- there is a clock that describes this evolution: we are interested in its perturbations

EFTI: effective theory for these perturbations!

- give an effective action in terms of some free coefficients
- constrain them from observations as in collider experiments!

fit specific models to these constraints!



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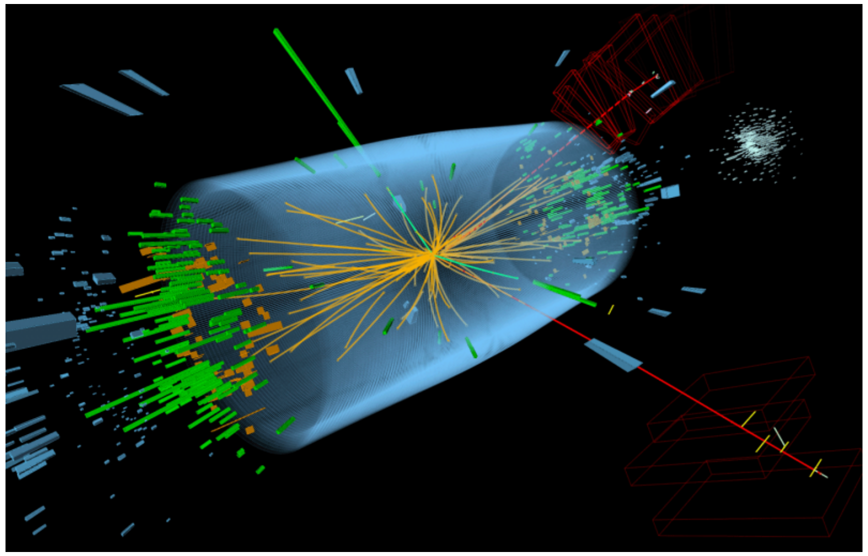


Effective Field Theory of Inflation

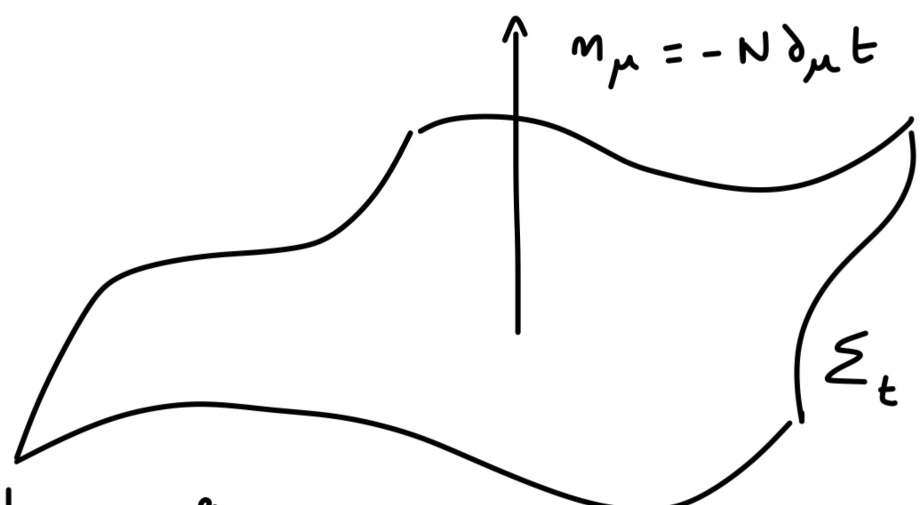
Important! Among the EFT coefficients there is the background evolution

What we know about $H(t)$ comes from measuring correlation functions

E.g.: $\langle \zeta(\vec{k})\zeta(\vec{k}')\rangle' \sim \frac{H^2}{\varepsilon}$; $\langle \gamma(\vec{k})\gamma(\vec{k}')\rangle' \sim H^2$ → constrain $H^2, \varepsilon, \eta, \ldots$

How do we write the Lagrangian?

- time diffeomorphisms are broken because the clock defines a preferred slicing
- unitary gauge: we can write all terms that break time diff.s but preserve spatial diff.s



$h_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

- diff.-invariant operators
  $\mathcal{L} \supset R,\ R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}, \ldots$
- operators constructed from n_μ
  $\mathcal{L} \supset \delta g^{00},\ \delta K_{\mu\nu}\delta K^{\mu\nu}, \ldots$
- coefficients are functions of time
  $\mathcal{L} \supset f(t)\cdot\delta g^{00}, \ldots$

Effective Field Theory of Inflation

FLRW background has a maximally symmetric slicing

- we can write perturbations in a way that respects residual gauge symmetries
- the action contains a finite number of tadpoles plus terms quadratic in perturbations

$$\mathcal{L} = \underbrace{\frac{M_p^2}{2}\left(R + 2\dot{H} g^{00} - 2(3H^2 + \dot{H})\right)}_{\text{tadpoles: fixed by background evolution}} + \underbrace{\sum_{n=2}^{+\infty} \frac{M_n^4(t)}{n!}(g^{00}+1)^n - \sum_{n=2}^{+\infty} \frac{\bar{M}_n^2(t)}{n!}(\delta K_\mu{}^\mu)^n + \dots}_{\text{higher order operators: different effects on n-point correlators}}$$

Unitary gauge: $h_{ij} = a^2 e^{2\zeta} (e^\gamma)_{ij}\ ;\ \gamma_{ii} = 0\ ;\ \partial_i \gamma_{ij} = 0$

Helicity splitting

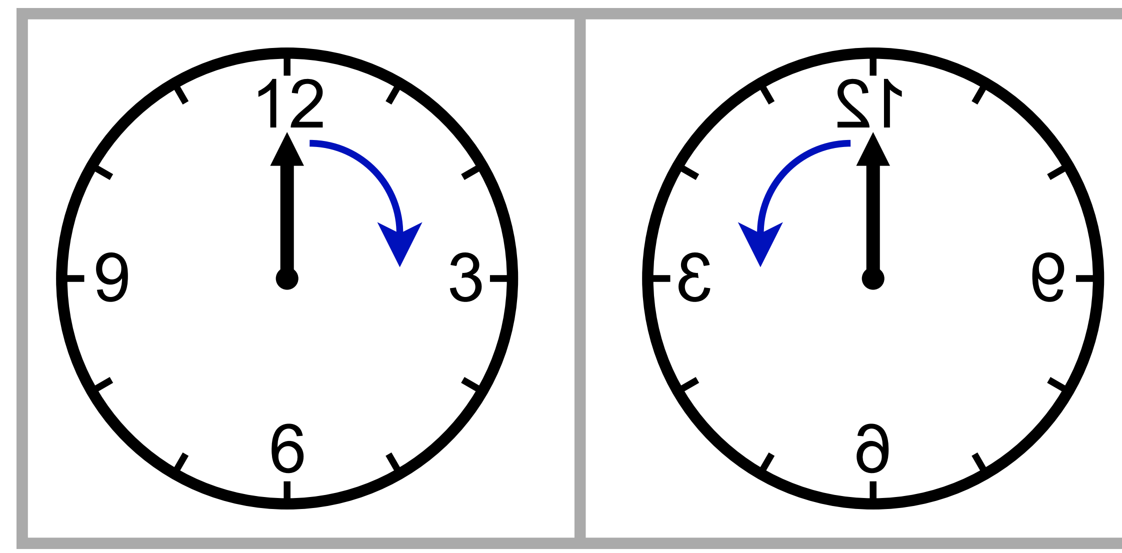
At leading order in derivatives $P_\gamma(k)$ is fixed by $H(t)$ Creminelli et al. (2014)

$$\mathcal{L}[\gamma] = \int d^4x \, \frac{M_P^2}{2} R \; ; \; \mathcal{L}_{\gamma\gamma} = \sum_{s=L,R} \frac{M_P^2}{2} \int d\eta \frac{d^3k}{(2\pi)^3} a^2 \left[|\gamma_s'|^2 - k^2 |\gamma_s|^2 \right]$$

➡ the two chiralities $\gamma^R = \dfrac{\gamma^+ - i\gamma^\times}{\sqrt{2}}$, $\gamma^L = \dfrac{\gamma^+ + i\gamma^\times}{\sqrt{2}}$ have the same power spectrum

Indeed ➡ $\gamma^R \xrightarrow{\mathcal{P}} \gamma^L \; ; \; \gamma^L \xrightarrow{\mathcal{P}} \gamma^R$

$$\mathcal{L}^R_{\gamma\gamma} \xrightarrow{\mathcal{P}} \mathcal{L}^L_{\gamma\gamma} \; ; \; \mathcal{L}^L_{\gamma\gamma} \xrightarrow{\mathcal{P}} \mathcal{L}^R_{\gamma\gamma}$$



if $\mathcal{P}$ is preserved ➡ $\mathcal{L}_{\gamma\gamma} \xrightarrow{\mathcal{P}} \mathcal{L}_{\gamma\gamma}$

$$\Rightarrow \mathcal{L}^R_{\gamma\gamma} = \mathcal{L}^L_{\gamma\gamma}$$

define: $r = \dfrac{P^L_\gamma + P^R_\gamma}{P_\zeta}$; $\chi = \dfrac{P^L_\gamma - P^R_\gamma}{r P_\zeta}$ ➡ $\chi = 0$ if parity is a symmetry

Observational consequences

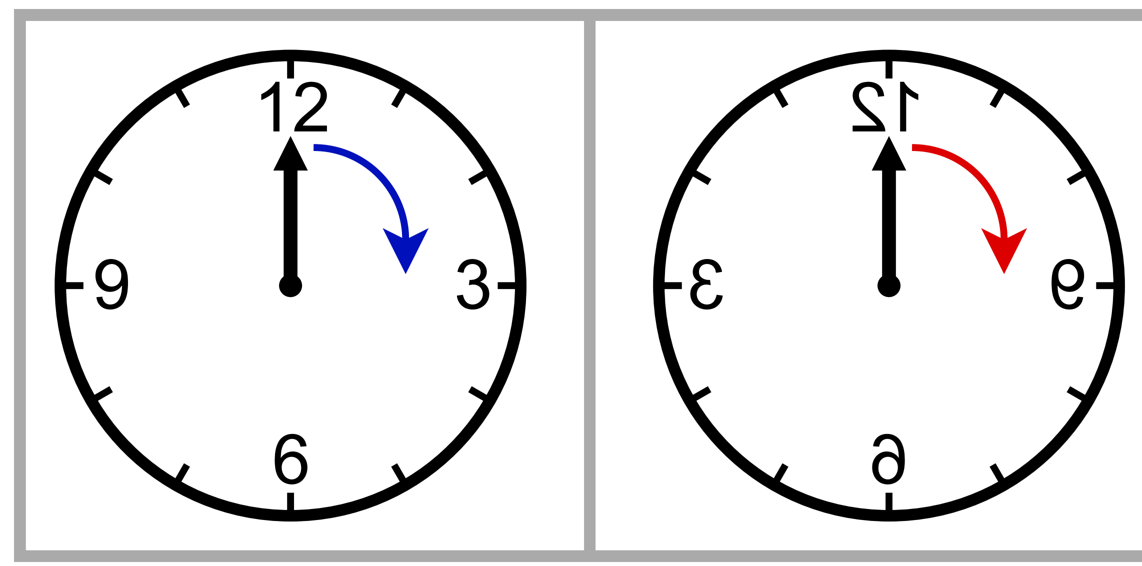
What happens if parity is broken?

- non-vanishing TB , EB angular correlators

$$C_\ell^{X_1 X_2} = 2\pi \int_0^{+\infty} \frac{dk}{k} \, \Delta_\ell^{X_1}(k) \, \Delta_\ell^{X_2}(k) \, r \, \chi \, P_\zeta(k)$$

for $X_1 X_2 = TB, EB$

(it goes to 0 as $r \to 0$)



e.g. Cabella et al. (2007), Gubitosi et al. (2009), Gluscevic & Kamionkowski (2010), Gruppuso et al. (2012), Kaufman et al. (2014), Kahniashvili et al. (2014), Galaverni et al. (2015), Molinari et al. (2016), Gerbino et al. (2016), Thorne et al. (2018)...

- let's see what happens in the EFTI!

Parity violation in the EFTI

How do we break parity? **Take operators involving the volume form** $\varepsilon_{\mu\nu\rho\sigma}$ **!**

Some examples:

- four-dimensional Chern-Simons term `e.g. Lue et al. (1999), Bartolo & Orlando (2017)`

$$\mathcal{L} \supset f(t)\,\epsilon^{\mu\nu\alpha\beta} R^{\sigma}{}_{\rho\alpha\beta} R^{\rho}{}_{\sigma\mu\nu} \qquad \left(\epsilon^{\mu\nu\alpha\beta} = -\sqrt{-g}\,\varepsilon^{\mu\nu\rho\sigma}\right)$$

1. fourth order in derivatives: naïvely, effect will be suppressed by H^2/Λ^2

2. $\epsilon^{\mu\nu\alpha\beta} R^{\sigma}{}_{\rho\alpha\beta} R^{\rho}{}_{\sigma\mu\nu} = \partial_\mu K^\mu$ ➤ integrate by parts: only H/Λ !

But! Need rapidly varying f for large signal

- terms involving the Weyl tensor `e.g. Maldacena & Pimentel (2011)`

$$\mathcal{L} \supset \epsilon^{\mu\nu\alpha\beta} W_{\alpha\beta\gamma\delta} W^{\gamma\delta}{}_{\rho\sigma} W^{\rho\sigma}{}_{\mu\nu}$$

1. sixth order in derivatives: suppressed by H^4/Λ^4

2. contribution to three-point function is slow-roll suppressed `e.g. Soda et al. (2011)`

Parity violation in the EFTI

The contributions at lowest order in derivatives include the foliation: Creminelli et al. (2014)

- $\mathcal{L} \sim \alpha\, \varepsilon^{\mu\nu\rho\sigma} n_\mu (\nabla_\nu \delta K_{\rho\alpha}) \delta K^\alpha{}_\sigma$

- three-dimensional Chern-Simons term

$$\mathcal{L} \sim \beta \left[{}^{(3)}\Gamma^p_{iq}\, \partial_j\, {}^{(3)}\Gamma^q_{kp} + \frac{1}{3}\, {}^{(3)}\Gamma^p_{iq}\, {}^{(3)}\Gamma^q_{jr}\, {}^{(3)}\Gamma^r_{kp} \right] \epsilon^{ijk}$$

Both are third order in derivatives → suppressed by H/Λ !

Effect on the power spectrum

$$\delta \langle \gamma^R \gamma^R \rangle' = \frac{\beta \pi}{2} \frac{H}{\Lambda} \quad ; \quad \delta \langle \gamma^L \gamma^L \rangle' = - \frac{\beta \pi}{2} \frac{H}{\Lambda}$$

the contribution is not slow-roll suppressed (but only β contributes)

Parity violation in the EFTI

There are other terms that can enter at third order in derivatives:

- Gauss-Bonnet topological current: $J^{\alpha} = \epsilon^{\alpha\beta\gamma\delta}\,\epsilon_{\rho\sigma}{}^{\mu\nu}\,\Gamma^{\rho}{}_{\mu\beta}\left[\frac{1}{2}R^{\sigma}{}_{\nu\gamma\delta} + \frac{1}{3}\Gamma^{\sigma}{}_{\lambda\gamma}\Gamma^{\lambda}{}_{\nu\sigma}\right]$

➤ we can include J^0 in the Lagrangian! But **it preserves parity** (contains $\epsilon\cdot\epsilon$)

- recall that the four-dimensional Chern-Simons is given by $\partial_\mu K^\mu$, where

$$K^\mu = 2\,\epsilon^{\mu\alpha\beta\gamma}\left(\frac{1}{2}\Gamma^{\sigma}_{\alpha\nu}\,\partial_\beta\Gamma^{\nu}_{\gamma\sigma} + \frac{1}{3}\Gamma^{\sigma}_{\alpha\nu}\,\Gamma^{\nu}_{\beta\eta}\,\Gamma^{\eta}_{\gamma\sigma}\right)$$

➤ we can include K^0 in the Lagrangian! **It violates parity!**

⬇

Effect on the power spectrum: degenerate with β

But! It can contribute to higher-order correlation functions!

Effect on three-point functions and CMB

These operators contain both scalar and tensor perturbations at all orders

they contribute to three-point functions! E.g. $\langle \gamma\gamma\gamma \rangle$, $\langle \gamma\gamma\zeta \rangle$, $\langle \gamma\zeta\zeta \rangle$

There will be imprints on CMB bispectra!

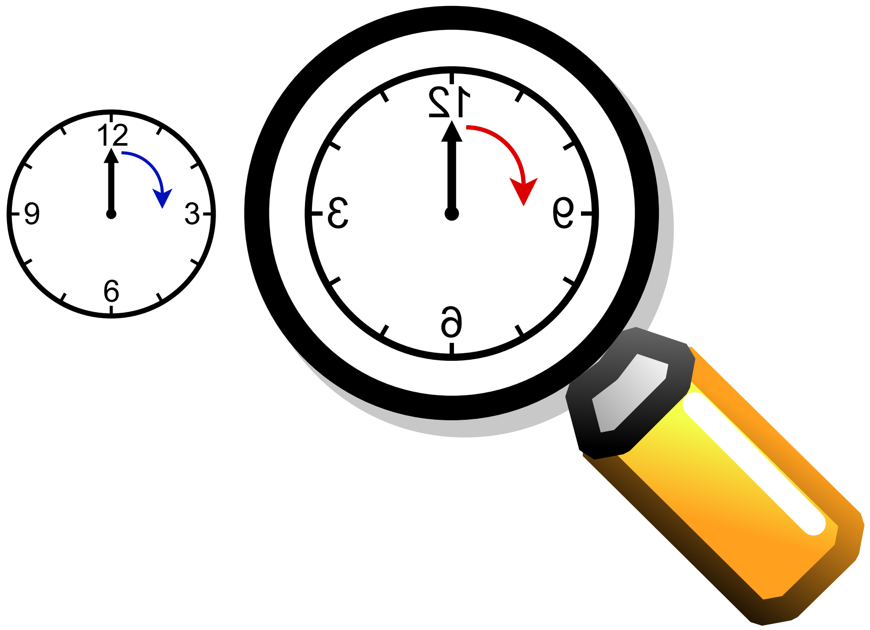
In a parity-preserving universe:

- $a^T_{\ell m} \xrightarrow{\mathcal{P}} (-1)^\ell \, a^T_{\ell m}$
- $a^E_{\ell m} \xrightarrow{\mathcal{P}} (-1)^\ell \, a^E_{\ell m}$
- $a^B_{\ell m} \xrightarrow{\mathcal{P}} (-1)^{\ell+1} \, a^B_{\ell m}$

e.g. $\langle a^T_{\ell_1 m_1} a^T_{\ell_2 m_2} a^B_{\ell_3 m_3} \rangle = 0$ if $\sum_n \ell_n = \text{even}$

this will not hold if parity is violated!

Looking for the largest possible signal



Which operators give the largest effect?

- focus on those with the lowest number of derivatives

- the naïve expectation is that the time dependence of the coefficients is small: focus on operators whose contribution to the correlation functions does not depend on that

Moreover ➔ if interested in correlators involving scalars, focus on operators involving the foliation directly!

Thanks!

Backup slides

Decoupling limit

In unitary gauge the scalar mode is eaten by the metric. We make it explicit via the Stueckelberg trick: do a broken time diffeomorphism $t \to t + \pi(t, \vec{x})$

Relation between π and ζ: $\zeta = -H\pi + \mathcal{O}(\text{slow-roll})$

Operators that break time diff.s will generate π, others won't

$$g^{00} \longrightarrow g^{\mu\nu}(\delta^0_\mu + \partial_\mu \pi)(\delta^0_\nu + \partial_\nu \pi) \quad \text{vs.} \quad R \longrightarrow R$$

For diff.-invariant operators, scalar interactions are generated only by the solution of the non-dynamical Einstein equations (the "constraints"), i.e. $g^{00} = g^{00}(\pi)$, $g^{0i} = g^{0i}(\pi)$

this solution is slow-roll suppressed, and the final contribution will be subleading!

Cheung et al. (2007a, 2007b)