Primordial non-Gaussianities in general modified gravitational models of inflation

Antonio De Felice

Tokyo University of Science [Yukawa Inst. – 21 March 2011]

with Shinji Tsujikawa [1103.1172]

Tokyo University of Science

also Mizuno, Yamaguchi

Introduction

- Which model of inflation

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- Search for large NG

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- More general scalar-tensor theories?

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$$\mathcal{L} = \frac{M_{\rm pl}^2}{2} F(\phi) R + P(\phi, X) - \xi(\phi)\mathcal{G} - G(\phi, X)\Box\phi$$

EOMs

- Expansion of $\mathcal{L}$ at first order (or 0th order)

$$E_1 \equiv 3M_{\rm pl}^2 F H^2 + 3M_{\rm pl}^2 H\dot{F} + P - 2XP_{,X} - 24H^3\dot{\xi} - 6H\dot{\phi}XG_{,X} + 2XG_{,\phi} = 0\,,$$

$$E_2 \equiv 3M_{\rm pl}^2 F H^2 + 2M_{\rm pl}^2 H\dot{F} + 2M_{\rm pl}^2 F\dot{H} + M_{\rm pl}^2\ddot{F} + P - 16H^3\dot{\xi} - 16H\dot{H}\dot{\xi} - 8H^2\ddot{\xi}$$
$$- G_{,X}\dot{\phi}^2\ddot{\phi} - G_{,\phi}\dot{\phi}^2 = 0\,,$$

$$E_3 \equiv (P_{,X} + 2XP_{,XX} + 6H\dot{\phi}G_{,X} + 6H\dot{\phi}XG_{,XX} - 2XG_{,\phi X} - 2G_{,\phi})\ddot{\phi}$$
$$+ (3HP_{,X} + \dot{\phi}P_{,\phi X} + 9H^2\dot{\phi}G_{,X} + 3\dot{H}\dot{\phi}G_{,X} + 3H\dot{\phi}^2 G_{,\phi X} - 6HG_{,\phi} - G_{,\phi\phi}\dot{\phi})\dot{\phi}$$
$$- P_{,\phi} - 6M_{\rm pl}^2 H^2 F_{,\phi} - 3M_{\rm pl}^2\dot{H}F_{,\phi} + 24H^4\xi_{,\phi} + 24H^2\dot{H}\xi_{,\phi} = 0$$

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- Use them to simplify expanded action
- Not independent: $\dot{\phi}E_3 + \dot{E}_1 + 3H(E_1 - E_2) = 0$

2nd order Lag

- Introduce ADM metric for scalars in uniform field gauge ($\delta\phi = 0$)

$$ds^2 = -\left[(1+\alpha)^2 - a^{-2}e^{-2\mathcal{R}}(\partial\psi)^2\right]\,dt^2 + 2\partial_i\psi\,dt\,dx^i + a^2 e^{2\mathcal{R}} d\vec{x}^2$$

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- Action becomes

$$\mathcal{L}_2 = a^3\left[-3w_1\dot{\mathcal{R}}^2 + \frac{2w_1}{a^2}\dot{\mathcal{R}}\partial^2\psi - \frac{w_2}{a^2}\alpha\partial^2\psi - \frac{2w_1}{a^2}\alpha\partial^2\mathcal{R}\right.$$
$$\left. + 3w_2\,\alpha\,\dot{\mathcal{R}} + \frac{1}{3}w_3\alpha^2 + \frac{w_4}{a^2}\,\partial_i\mathcal{R}\,\partial_i\mathcal{R}\right]$$

Notes on $\mathcal{L}_2$

- Coefficients

$$
\begin{aligned}
w_1 &\equiv M_{\rm pl}^2\,F - 8H\,\dot{\xi}\,,\\
w_2 &\equiv M_{\rm pl}^2(2HF+\dot{F}) - 2\dot{\phi}XG_{,X} - 24H^2\dot{\xi}\,,\\
w_3 &\equiv -9M_{\rm pl}^2FH^2 - 9M_{\rm pl}^2H\dot{F} + 3(XP_{,X}+2X^2P_{,XX}) + 144H^3\dot{\xi}\\
&\quad + 18H\dot{\phi}(2XG_{,X}+X^2G_{,XX}) - 6(XG_{,\phi}+X^2G_{,\phi X})\,,\\
w_4 &\equiv M_{\rm pl}^2F - 8\ddot{\xi}
\end{aligned}
$$

...continue

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- No mass term for $\mathcal{R}$
- $\psi = -L_1\mathcal{R} + \chi$, $\partial^2\chi = a^2 Q\mathcal{R}/w_1$

Reduced $\mathcal{L}_2$

- Action reduces to

$$\mathcal{L}_2 = a^3 Q \left[\dot{\mathcal{R}}^2 - \frac{c_s^2}{a^2} (\partial \mathcal{R})^2 \right]$$

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$$c_s^2 \equiv \frac{3(2w_1^2w_2H - w_2^2w_4 + 4w_1\dot{w}_1w_2 - 2w_1^2\dot{w}_2)}{w_1(4w_1w_3 + 9w_2^2)}$$

Third order action

- After expanding and integrating by parts

$$
\begin{aligned}
\mathcal{L}_3 = a^3 \{ & a_1\,\alpha^3 + \alpha^2\,(a_2\,\mathcal{R} + a_3\,\dot{\mathcal{R}} + a_4\,\partial^2\mathcal{R}/a^2 + a_5\partial^2\psi/a^2) \\
& + \alpha\,[a_6\,\partial_i\mathcal{R}\partial_i\psi/a^2 + a_7\,\dot{\mathcal{R}}\mathcal{R} + a_8\,\dot{\mathcal{R}}\partial^2\mathcal{R}/a^2 \\
& + a_9\,(\partial_i\partial_j\psi\partial_i\partial_j\psi - \partial^2\psi\partial^2\psi)/a^4 + \frac{a_{10}}{a^4}(\partial_i\partial_j\psi\partial_i\partial_j\mathcal{R} - \partial^2\psi\partial^2\mathcal{R}) \\
& + a_{11}\,\mathcal{R}\,\partial^2\psi/a^2 + a_{12}\,\dot{\mathcal{R}}\,\partial^2\psi/a^2 + a_{13}\,\mathcal{R}\,\partial^2\mathcal{R}/a^2 + a_{14}\,(\partial\mathcal{R})^2/a^2 \\
& + a_{15}\dot{\mathcal{R}}^2] + b_1\,\dot{\mathcal{R}}^3 + b_2\,\mathcal{R}\,(\partial\mathcal{R})^2/a^2 + b_3\dot{\mathcal{R}}^2\,\mathcal{R} + c_1\,\dot{\mathcal{R}}\partial_i\mathcal{R}\partial_i\psi/a^2 \\
& + c_2\dot{\mathcal{R}}^2\partial^2\psi/a^2 + c_3\dot{\mathcal{R}}\,\mathcal{R}\,\partial^2\psi/a^2 \\
& + (d_1\dot{\mathcal{R}} + d_2\mathcal{R})\,(\partial_i\partial_j\psi\partial_i\partial_j\psi - \partial^2\psi\partial^2\psi)/a^4 + d_3\partial_i\mathcal{R}\partial_i\psi\,\partial^2\psi/a^4 \}
\end{aligned}
$$

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$$\mathcal{L}_3 = a^3\{A_1\dot{\mathcal{R}}^3 + A_2\dot{\mathcal{R}}^2\partial^2\mathcal{R}/a^2 + A_3\dot{\mathcal{R}}^2\partial^2\psi/a^2 + A_4\mathcal{R}\dot{\mathcal{R}}^2$$
$$+ (A_5\dot{\mathcal{R}} + A_6\mathcal{R})(\partial_i\partial_j\psi\partial_i\partial_j\psi - \partial^2\psi\partial^2\psi)/a^4$$
$$+ \frac{A_7}{a^4}\dot{\mathcal{R}}(\partial_i\partial_j\psi\partial_i\partial_j\mathcal{R} - \partial^2\psi\partial^2\mathcal{R}) + \frac{A_8}{a^2}\mathcal{R}(\partial\mathcal{R})^2 + \frac{A_9}{a^4}\partial_i\mathcal{R}\partial_i\psi\,\partial^2\psi\}$$

- Using $\alpha = L_1\dot{\mathcal{R}}$

$$\mathcal{L}_3 = a^3\{A_1\dot{\mathcal{R}}^3 + A_2\dot{\mathcal{R}}^2\partial^2\mathcal{R}/a^2 + A_3\dot{\mathcal{R}}^2\partial^2\psi/a^2 + A_4\mathcal{R}\dot{\mathcal{R}}^2 + (A_5\dot{\mathcal{R}} + A_6\mathcal{R})\left(\partial_i\partial_j\psi\partial_i\partial_j\psi - \partial^2\psi\partial^2\psi\right)/a^4 + \frac{A_7}{a^4}\dot{\mathcal{R}}(\partial_i\partial_j\psi\partial_i\partial_j\mathcal{R} - \partial^2\psi\partial^2\mathcal{R}) + \frac{A_8}{a^2}\mathcal{R}(\partial\mathcal{R})^2 + \frac{A_9}{a^4}\partial_i\mathcal{R}\partial_i\psi\,\partial^2\psi\}$$

- Replace $\psi = -L_1\mathcal{R} + a^2\mathcal{X}/w_1$, with $\partial^2\mathcal{X} = Q\dot{\mathcal{R}}$

- Using $\alpha = L_1 \dot{\mathcal{R}}$

$$\mathcal{L}_3 = a^3 \{ A_1 \dot{\mathcal{R}}^3 + A_2 \dot{\mathcal{R}}^2 \partial^2 \mathcal{R}/a^2 + A_3 \dot{\mathcal{R}}^2 \partial^2 \psi / a^2 + A_4 \mathcal{R} \dot{\mathcal{R}}^2 + (A_5 \dot{\mathcal{R}} + A_6 \mathcal{R}) (\partial_i \partial_j \psi \partial_i \partial_j \psi - \partial^2 \psi \partial^2 \psi)/a^4 + \frac{A_7}{a^4} \dot{\mathcal{R}} (\partial_i \partial_j \psi \partial_i \partial_j \mathcal{R} - \partial^2 \psi \partial^2 \mathcal{R}) + \frac{A_8}{a^2} \mathcal{R} (\partial \mathcal{R})^2 + \frac{A_9}{a^4} \partial_i \mathcal{R} \partial_i \psi \, \partial^2 \psi \}$$

- Replace $\psi = -L_1 \mathcal{R} + a^2 \mathcal{X}/w_1$, with $\partial^2 \mathcal{X} = Q \dot{\mathcal{R}}$
- Rewrite $\mathcal{L}_3 = a^3 f_1 + a f_2 + f_3/a$ [Collins '11]

Final step

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$$
\begin{aligned}
L_3 = \int d^3x \Big\{ & a^3 \mathcal{C}_1 M_{\rm pl}^2 \mathcal{R}\dot{\mathcal{R}}^2 + a\,\mathcal{C}_2 M_{\rm pl}^2 \mathcal{R}(\partial\mathcal{R})^2 + a^3 \mathcal{C}_3 M_{\rm pl} \dot{\mathcal{R}}^3 \\
& + a^3 \mathcal{C}_4 \dot{\mathcal{R}}(\partial_i \mathcal{R})(\partial_i \mathcal{X}) + a^3 (\mathcal{C}_5/M_{\rm pl}^2) \partial^2 \mathcal{R} (\partial \mathcal{X})^2 \\
& + a\mathcal{C}_6 \dot{\mathcal{R}}^2 \partial^2 \mathcal{R} + (\mathcal{C}_7/a) \left[\partial^2 \mathcal{R} (\partial \mathcal{R})^2 - \mathcal{R}\partial_i\partial_j(\partial_i\mathcal{R})(\partial_j\mathcal{R}) \right] \\
& + a(\mathcal{C}_8/M_{\rm pl}) \left[\partial^2\mathcal{R}\partial_i\mathcal{R}\partial_i\mathcal{X} - \mathcal{R}\partial_i\partial_j(\partial_i\mathcal{R})(\partial_j\mathcal{X}) \right] \\
& + \mathcal{F}_1 \frac{\delta \mathcal{L}_2}{\delta \mathcal{R}}\bigg|_1 \Big\}
\end{aligned}
$$

Coefficients

- Time dependent dimensionless coeffs

$$\mathcal{C}_1 = \frac{Q}{M_{\rm pl}^2}\left[3 - \frac{L_1 H}{c_s^2}\left(3 + \frac{\dot{Q}}{HQ}\right) + \frac{d}{dt}\left(\frac{L_1}{c_s^2}\right)\right], \; \mathcal{C}_2 = \ldots$$

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- Negligible contribution [Maldacena '03; Arroja, Tanaka '11]

$$\mathcal{F}_1 = \frac{A_5}{w_1^2}\{(\partial_k\mathcal{R})(\partial_k\mathcal{X}) - \partial^{-2}\partial_i\partial_j[(\partial_i\mathcal{R})(\partial_j\mathcal{X})]\} + q_1\mathcal{R}\dot{\mathcal{R}}$$
$$+ \frac{A_7 - 2A_5L_1}{4w_1a^2}\{(\partial\mathcal{R})^2 - \partial^{-2}\partial_i\partial_j[(\partial_i\mathcal{R})(\partial_j\mathcal{R})]\}\,.$$

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- Consider $\mathcal{C}_i$ const, and dS $[\tau \approx -1/(aH)]$ for MS, $\tau_i \approx -\infty$ and $\tau_f \approx 0$. Extract the $f_{\rm NL}^{k_1=k_2=k_3}$

$$f_{\rm NL}^{\rm equil} = \frac{40}{9}\frac{M_{\rm pl}^2}{Q}\left[\frac{1}{12}\mathcal{C}_1 + \frac{17}{96 c_s^2}\mathcal{C}_2 + \frac{1}{72}\frac{H}{M_{\rm pl}}\mathcal{C}_3 - \frac{1}{24}\frac{Q}{M_{\rm pl}^2}\mathcal{C}_4 - \frac{1}{24}\left(\frac{Q}{M_{\rm pl}^2}\right)^2\mathcal{C}_5 + \frac{1}{36 c_s^2}\left(\frac{H}{M_{\rm pl}}\right)^2\mathcal{C}_6 - \frac{13}{96 c_s^4}\left(\frac{H}{M_{\rm pl}}\right)^2\mathcal{C}_7 - \frac{17}{192 c_s^2}\frac{H}{M_{\rm pl}}\frac{Q}{M_{\rm pl}^2}\mathcal{C}_8\right]$$

- Assuming slow-variation

$$f_{\rm NL}^{\rm equil} \simeq \frac{85}{324}\left(1-\frac{1}{c_s^2}\right) - \frac{10}{81}\frac{\lambda}{\Sigma} + \frac{55}{36}\frac{\epsilon_s}{c_s^2} + \frac{5}{12}\frac{\eta_s}{c_s^2} - \frac{85}{54}\frac{s}{c_s^2}$$
$$+ \frac{5}{162}\delta_F\left(1-\frac{1}{c_s^2}\right) - \frac{10}{81}\delta_\xi\left(2-\frac{29}{c_s^2}\right) + \frac{\delta_{GX}}{\epsilon_s}\left[\frac{20\,(1+\lambda_G)}{81} + \frac{65}{162c_s^2}\right]$$

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- Introduce $\Sigma = \frac{w_1(4w_1w_3+9w_2^2)}{12M_{\rm pl}^4}$, $\lambda_G \equiv XG_{,XX}/G_{,X}$ and

$$\delta_F \equiv \frac{\dot{F}}{HF},\ \delta_\xi \equiv \frac{H\dot{\xi}}{M_{\rm pl}^2F},\ \delta_{GX} \equiv \frac{\dot{\phi}XG_{,X}}{M_{\rm pl}^2HF},\ \epsilon_s \equiv \frac{Qc_s^2}{M_{\rm pl}^2F},\ s \equiv \frac{\dot{c}_s}{Hc_s}$$
$$\lambda \equiv F^2[X^2P_{,XX}+2X^3P_{,XXX}/3+\dot{\phi}H(XG_{,X}+5X^2G_{,XX}$$
$$+2X^3G_{,XXX})-2(2X^2G_{,\phi X}+X^3G_{,\phi XX})/3]$$

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