One-Loop Effective Action for Nonminimal Natural Inflation Model

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Outline

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1. Motivations
2. Covariant Effective Action at One-Loop
3. Results
4. Current and Future Works

Motivations

- At energies much below Planck scale (inflation era $\approx 10^{15}$ GeV; $\ll 10^{19}$GeV) QFT in Curved Spacetime is a preferred tool to study quantized fields in presence of gravity.
  - Well tested in case of quantum fields in curved background: black holes, large scale structure formation, etc.
  - Works as a low energy limit to very high energy theories like Quantum Gravity and String Theory.

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    - Works as a low energy limit to very high energy theories like Quantum Gravity and String Theory.
- Recently, there has been an increasing interest in studying quantized gravity using QFT in curved spacetime [2, 3].
    - Quantum corrections even at low energies (i.e. inflation era) could give rise to observable cosmological effects

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  - Works as a low energy limit to very high energy theories like Quantum Gravity and String Theory.
- Recently, there has been an increasing interest in studying quantized gravity using QFT in curved spacetime [2, 3].
  - Quantum corrections even at low energies (i.e. inflation era) could give rise to observable cosmological effects
- We use the DeWitt-Vilkovisky's effective action formalism for our calculations [1]
  - Gauge and Background field Independent result
  - Expansion in orders of $\hbar$ corresponds to loop expansion (S-matrix elements).

Nonminimal Natural Inflation

- Our objective is to study one-loop corrections to cosmological models
  1. evaluation of one-loop effective action using symbolic computation packages
  2. Renormalization: identifying counterterms
  3. studying relevant effects: corrections to potential, observables, etc.

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- Our objective is to study one-loop corrections to cosmological models
  1. evaluation of one-loop effective action using symbolic computation packages
  2. Renormalization: identifying counterterms
  3. studying relevant effects: corrections to potential, observables, etc.
- As a first step, we consider the recently proposed nonminimal natural inflation model [5]

$$S = \int d^4x \sqrt{|g|} \left[\frac{1}{2} M_P^2 \gamma(\phi)^2 R - \frac{1}{2} g^{\mu\nu} \partial_\nu \phi \partial_\nu \phi - V(\phi) \right]$$

where,

$$V(\phi) = \Lambda^4 \Big[1 + \cos(\phi/f) \Big] \qquad \gamma(\phi)^2 \equiv 1 + \alpha \left[1 + \cos\left(\frac{\phi}{f}\right) \right]$$

Nonminimal Natural Inflation

- The nonminimal term $\gamma(\phi)$ introduces a new dimensionless parameter α that *gives rise to n_s and r values well within 95% C.L. region from combined Planck 2018+BAO+BK14 data* [5]
- Interesting feature is that $f \simeq M_p$ (for $0.48 \leq \alpha < 0.5$)
  - during inflation, ϕ is also sub-planckian

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- For simplicity, we consider terms upto second order in ϕ

$$S = \int d^4x\sqrt{|g|}\left[\frac{(2+4\alpha)R}{\kappa^2} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\Lambda^4}{2f^2}\phi^2 - \frac{\alpha}{\kappa^2 f^2}\phi^2 R - 2\Lambda^4\right]$$

- For further convenience in setting up computation, we ignore for now the $2\Lambda^4$ term.

Outline

Effective Action Calculation

- As a toy model, we consider the ϕ^4 theory with non-minimal coupling to gravity

$$S = \int d^4x \sqrt{|g|} \left[-\frac{2R}{\kappa^2} + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi + \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\xi}{2}\phi^2 R \right]$$

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- The quantization of a theory $S[\varphi]$ with fields φ^i is performed about a classical background $\bar{\varphi}^i$: $\varphi^i = \bar{\varphi}^i + \zeta^i$, where ζ^i is the quantum part.
- In our case, $\varphi^i = \{g_{\mu\nu}, \phi\}$; $\bar{\varphi}^i = \{\eta_{\mu\nu}, \bar{\phi}\}$ $\eta_{\mu\nu} \longrightarrow$ Minkowski metric; and, $\zeta^i = \{\kappa h_{\mu\nu}, \delta\phi\}$

Effective Action Calculation

- The 1-loop effective action is given by

$$\Gamma = -\ln \int [d\zeta] \exp \left[\zeta^i \zeta^j \left(S_{,ij}[\bar{\varphi}] - \bar{\Gamma}^k_{ij} S_{,k}[\bar{\varphi}] \right) + \frac{1}{2\sigma} \chi^2_\beta \right] - \ln \det Q_{\alpha\beta}[\bar{\varphi}]$$

  as $\sigma \longrightarrow 0$ (Landau-DeWitt gauge).
  - $S_{,i}$ and $S_{,ij}$ are first and second functional derivative w.r.t the fields $(g_{\mu\nu}, \phi)$ at background $(\eta_{\mu\nu}, \bar{\phi})$, respectively.
  - $\bar{\Gamma}^k_{ij}$ are Vilkovisky-DeWitt connections. ensure covariance
  - χ_β is the gauge condition for the GCT symmetry.
  - $Q_{\alpha\beta}$ is the ghost term that appears during quantization.

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  - χ_β is the gauge condition for the GCT symmetry.
  - $Q_{\alpha\beta}$ is the ghost term that appears during quantization.
- For convenience, we write the exponential in the first term of Γ as,

$$\begin{aligned} \exp[\cdots] &= \exp\left(\tilde{S}[\bar{\varphi}^0] + \tilde{S}[\bar{\varphi}^1] + \tilde{S}[\bar{\varphi}^2] + \tilde{S}[\bar{\varphi}^3] + \tilde{S}[\bar{\varphi}^4]\right) \\ &\equiv \exp(\tilde{S}_0 + \tilde{S}_1 + \tilde{S}_2 + \tilde{S}_3 + \tilde{S}_4) \end{aligned}$$

Effective Action Calculation

- Treating $\tilde{S}_1, ..., \tilde{S}_4$ terms as perturbative, the final contribution to Γ at each order of $\bar{\varphi}$ is:

$$\begin{aligned}
\mathcal{O}(\bar{\varphi}) &= 0 \\
\mathcal{O}(\bar{\varphi}^2) &= \langle \tilde{S}_2 \rangle - \frac{1}{2} \langle \tilde{S}_1^2 \rangle \\
\mathcal{O}(\bar{\varphi}^3) &= 0 \\
\mathcal{O}(\bar{\varphi}^4) &= \langle \tilde{S}_4 \rangle - \langle \tilde{S}_1 \tilde{S}_3 \rangle + \mathcal{O}(\kappa^4) - \ln \det Q_{\alpha\beta}
\end{aligned}$$

- The correlators are calculated using Wick's theorem and basic propagator relations

$$\langle h_{\mu\nu}(x) h_{\rho\sigma}(x') \rangle = G_{\mu\nu\rho\sigma}(x.x'); \quad \langle \delta\phi(x) \delta\phi(x') \rangle = G(x, x')$$

$$\langle h_{\mu\nu}(x) \delta\phi(x') \rangle = 0$$

Outline

Results

- $\tilde{S}_0$:

$$\frac{1}{2} m^2 \left(\delta\phi^1\right)^2 + \frac{1}{2} \delta\phi^1{}_{,a} \delta\phi^{1,a} + h^{1ab} h^1{}_a{}^c{}_{,b,c} - \frac{h^{1ab} h^1{}_a{}^c{}_{,b,c}}{\alpha} - h^{1a}{}_a h^{1bc}{}_{,b,c} + \frac{h^{1a}{}_a h^{1bc}{}_{,b,c}}{\alpha} - \frac{1}{2} h^{1ab} h^1{}_{ab}{}^{,c}{}_{,c} + \frac{1}{2} h^{1a}{}_a h^{1b}{}_b{}^{,c}{}_{,c} - \frac{h^{1a}{}_a h^{1b}{}_b{}^{,c}{}_{,c}}{4\alpha}$$

- $\tilde{S}_1$:

$$\frac{1}{2} m^2 \kappa \delta\phi^1 h^{1a}{}_a \phi - \frac{1}{4} m^2 \kappa \nu \delta\phi^1 h^{1a}{}_a \phi - \frac{1}{2} \kappa \delta\phi^1 h^{1b}{}_b \partial_a\partial^a\phi + \frac{1}{4} \kappa \nu \delta\phi^1 h^{1b}{}_b \partial_a\partial^a\phi - \frac{1}{2} \kappa \delta\phi^1 h^{1b}{}_{b,a} \partial^a\phi + \frac{\kappa \omega \delta\phi^1 h^{1b}{}_{b,a} \partial^a\phi}{2\alpha} + \kappa \delta\phi^1 \partial^a\phi h^1{}_a{}^b{}_{,b} - \frac{\kappa \omega \delta\phi^1 \partial^a\phi h^1{}_a{}^b{}_{,b}}{\alpha} + \kappa \xi \delta\phi^1 \phi h^{1ab}{}_{,a,b} - \kappa \xi \delta\phi^1 \phi h^{1a}{}_a{}^{,b}{}_{,b} + \kappa \delta\phi^1 h^1{}_{ab} \partial^b\partial^a\phi$$

Results

- $\tilde{S}_2$:

$$
\begin{aligned}
&-\frac{1}{8} m^2 \kappa^2\, h^{1}{}_{ab}\, h^{1ab}\, \phi^2 + \frac{1}{16} m^2 \kappa^2\, h^{1a}{}_{a}\, h^{1b}{}_{b}\, \phi^2 + \frac{1}{4} \lambda \phi^2 \left(\delta\phi^1\right)^2 - \frac{1}{8} m^2 \kappa^2 \nu \phi^2 \left(\delta\phi^1\right)^2 - \\
&\frac{1}{8} \kappa^2 \nu \xi\, h^{1}{}_{bc}\, h^{1bc}\, \phi\, \partial_a\partial^a\phi + \frac{1}{16} \kappa^2 \nu \xi\, h^{1b}{}_{b}\, h^{1c}{}_{c}\, \phi\, \partial_a\partial^a\phi + \frac{3}{8} \kappa^2 \nu \xi\, \phi \left(\delta\phi^1\right)^2 \partial_a\partial^a\phi - \\
&\frac{1}{8} \kappa^2\, h^{1}{}_{bc}\, h^{1bc}\, \partial_a\phi\, \partial^a\phi + \frac{1}{16} \kappa^2 \nu\, h^{1}{}_{bc}\, h^{1bc}\, \partial_a\phi\, \partial^a\phi - \frac{1}{8} \kappa^2 \nu \xi\, h^{1}{}_{bc}\, h^{1bc}\, \partial_a\phi\, \partial^a\phi + \frac{1}{16} \kappa^2\, h^{1b}{}_{b}\, h^{1c}{}_{c}\, \partial_a\phi\, \partial^a\phi - \\
&\frac{1}{32} \kappa^2 \nu\, h^{1b}{}_{b}\, h^{1c}{}_{c}\, \partial_a\phi\, \partial^a\phi + \frac{1}{16} \kappa^2 \nu \xi\, h^{1b}{}_{b}\, h^{1c}{}_{c}\, \partial_a\phi\, \partial^a\phi - \frac{1}{16} \kappa^2 \nu \left(\delta\phi^1\right)^2 \partial_a\phi\, \partial^a\phi + \frac{3}{8} \kappa^2 \nu \xi \left(\delta\phi^1\right)^2 \partial_a\phi\, \partial^a\phi + \\
&\frac{\kappa^2 \omega^2 \left(\delta\phi^1\right)^2 \partial_a\phi\, \partial^a\phi}{4\alpha} + \frac{1}{2} \kappa^2 \xi\, h^{1ab}\, \phi^2\, h^{1c}{}_{c,a,b} - \frac{1}{8} \kappa^2 \xi \phi^2\, h^{1c}{}_{c,b}\, h^{1a}{}_{a}{}^{,b} + \frac{1}{2} \kappa^2\, h^{1}{}_{a}{}^{c}\, h^{1}{}_{bc}\, \partial^a\phi\, \partial^b\phi - \\
&\frac{1}{4} \kappa^2 \nu\, h^{1}{}_{a}{}^{c}\, h^{1}{}_{bc}\, \partial^a\phi\, \partial^b\phi + \frac{1}{2} \kappa^2 \nu \xi\, h^{1}{}_{a}{}^{c}\, h^{1}{}_{bc}\, \partial^a\phi\, \partial^b\phi - \frac{1}{4} \kappa^2\, h^{1}{}_{ab}\, h^{1c}{}_{c}\, \partial^a\phi\, \partial^b\phi + \frac{1}{8} \kappa^2 \nu\, h^{1}{}_{ab}\, h^{1c}{}_{c}\, \partial^a\phi\, \partial^b\phi - \\
&\frac{1}{4} \kappa^2 \nu \xi\, h^{1}{}_{ab}\, h^{1c}{}_{c}\, \partial^a\phi\, \partial^b\phi - \frac{1}{2} \kappa^2 \xi \phi^2\, h^{1ab}{}_{,a}\, h^{1}{}_{b}{}^{c}{}_{,c} + \frac{1}{2} \kappa^2 \xi \phi^2\, h^{1a}{}_{a}{}^{,b}\, h^{1}{}_{b}{}^{c}{}_{,c} - \kappa^2 \xi\, h^{1ab}\, \phi^2\, h^{1}{}_{a}{}^{c}{}_{,b,c} + \\
&\frac{1}{4} \kappa^2 \xi\, h^{1a}{}_{a}\, \phi^2\, h^{1bc}{}_{,b,c} + \frac{1}{2} \kappa^2 \nu \xi\, h^{1}{}_{a}{}^{c}\, h^{1ab}\, \phi\, \partial_c\partial_b\phi - \frac{1}{4} \kappa^2 \nu \xi\, h^{1a}{}_{a}\, h^{1bc}\, \phi\, \partial_c\partial_b\phi + \\
&\frac{1}{2} \kappa^2 \xi\, h^{1ab}\, \phi^2\, h^{1}{}_{ab}{}^{,c}{}_{,c} - \frac{1}{4} \kappa^2 \xi\, h^{1a}{}_{a}\, \phi^2\, h^{1b}{}_{b}{}^{,c}{}_{,c} - \frac{1}{4} \kappa^2 \xi \phi^2\, h^{1}{}_{ac,b}\, h^{1ab,c} + \frac{3}{8} \kappa^2 \xi \phi^2\, h^{1}{}_{ab,c}\, h^{1ab,c}
\end{aligned}
$$

Results

- $\tilde{S}_3$:

$$\frac{1}{12}\kappa\lambda\,\delta\phi^{1}\,h^{1a}{}_{a}\,\phi^{3}-\frac{1}{24}\kappa\lambda\nu\,\delta\phi^{1}\,h^{1a}{}_{a}\,\phi^{3}$$

- $\tilde{S}_4$:

$$-\frac{1}{96}\kappa^{2}\lambda\,h^{1}{}_{ab}\,h^{1ab}\,\phi^{4}+\frac{1}{192}\kappa^{2}\lambda\,h^{1a}{}_{a}\,h^{1b}{}_{b}\,\phi^{4}-\frac{1}{96}\kappa^{2}\lambda\nu\,\phi^{4}\left(\delta\phi^{1}\right)^{2}$$

Results

- Divergent part of $\langle \tilde{S}_1(x)\tilde{S}_1(x')\rangle$:

$$
\begin{aligned}
&-\frac{3\,\mathrm{i}\,m^4\kappa^2\phi^2}{16\pi^2}+\frac{\mathrm{i}\,m^4\alpha\kappa^2\phi^2}{16\pi^2}+\frac{3\,\mathrm{i}\,m^4\kappa^2\nu\phi^2}{16\pi^2}-\frac{\mathrm{i}\,m^4\alpha\kappa^2\nu\phi^2}{16\pi^2}-\frac{3\,\mathrm{i}\,m^4\kappa^2\nu^2\phi^2}{64\pi^2}+\frac{\mathrm{i}\,m^4\alpha\kappa^2\nu^2\phi^2}{64\pi^2}+\\
&\frac{3\,\mathrm{i}\,m^4\kappa^2\xi\phi^2}{8\pi^2}-\frac{3\,\mathrm{i}\,m^4\kappa^2\nu\xi\phi^2}{16\pi^2}-\frac{3\,\mathrm{i}\,m^4\kappa^2\xi^2\phi^2}{16\pi^2}+\frac{3\,\mathrm{i}\,m^2\kappa^2\phi\,\partial_a\partial^a\phi}{16\pi^2}-\frac{9\,\mathrm{i}\,m^2\kappa^2\nu\phi\,\partial_a\partial^a\phi}{32\pi^2}+\\
&\frac{3\,\mathrm{i}\,m^2\alpha\kappa^2\nu\phi\,\partial_a\partial^a\phi}{32\pi^2}+\frac{3\,\mathrm{i}\,m^2\kappa^2\nu^2\phi\,\partial_a\partial^a\phi}{32\pi^2}-\frac{\mathrm{i}\,m^2\alpha\kappa^2\nu^2\phi\,\partial_a\partial^a\phi}{32\pi^2}-\frac{3\,\mathrm{i}\,m^2\kappa^2\xi\phi\,\partial_a\partial^a\phi}{16\pi^2}+\frac{3\,\mathrm{i}\,m^2\kappa^2\nu\xi\phi\,\partial_a\partial^a\phi}{16\pi^2}-\\
&\frac{3\,\mathrm{i}\,m^2\kappa^2\xi^2\phi\,\partial_a\partial^a\phi}{16\pi^2}-\frac{\mathrm{i}\,m^2\kappa^2\omega\phi\,\partial_a\partial^a\phi}{8\pi^2}+\frac{\mathrm{i}\,m^2\kappa^2\omega^2\phi\,\partial_a\partial^a\phi}{16\pi^2\alpha}-\frac{\mathrm{i}\,\kappa^2\nu\phi\,\partial_a\partial^a\partial_b\partial^b\phi}{32\pi^2}+\frac{\mathrm{i}\,\alpha\kappa^2\nu\phi\,\partial_a\partial^a\partial_b\partial^b\phi}{32\pi^2}-\\
&\frac{\mathrm{i}\,m^2\alpha\kappa^2\phi\,\partial^a\partial_a\phi}{16\pi^2}+\frac{\mathrm{i}\,m^2\alpha\kappa^2\nu\phi\,\partial^a\partial_a\phi}{32\pi^2}+\frac{\mathrm{i}\,m^2\kappa^2\omega\phi\,\partial^a\partial_a\phi}{16\pi^2}-\frac{\mathrm{i}\,m^2\kappa^2\nu\omega\phi\,\partial^a\partial_a\phi}{32\pi^2}-\frac{\mathrm{i}\,\alpha\kappa^2\phi\,\partial^a\partial_b\partial^b\partial_a\phi}{16\pi^2}-\\
&\frac{\mathrm{i}\,\alpha\kappa^2\nu\phi\,\partial^a\partial_b\partial^b\partial_a\phi}{32\pi^2}+\frac{\mathrm{i}\,\kappa^2\omega\phi\,\partial^a\partial_b\partial^b\partial_a\phi}{16\pi^2}+\frac{\mathrm{i}\,\kappa^2\nu\omega\phi\,\partial^a\partial_b\partial^b\partial_a\phi}{32\pi^2}+\frac{\mathrm{i}\,\kappa^2\xi\phi\,\partial^a\partial^b\partial_b\partial_a\phi}{12\pi^2}+\frac{\mathrm{i}\,\alpha\kappa^2\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{16\pi^2}+\\
&\frac{\mathrm{i}\,\kappa^2\nu\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{8\pi^2}-\frac{\mathrm{i}\,\alpha\kappa^2\nu\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{16\pi^2}-\frac{3\,\mathrm{i}\,\kappa^2\nu^2\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{64\pi^2}+\frac{\mathrm{i}\,\alpha\kappa^2\nu^2\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{64\pi^2}-\frac{\mathrm{i}\,\kappa^2\xi\phi\,\partial_b\partial^b\partial_a\partial^a\phi}{48\pi^2}
\end{aligned}
$$

- Divergent part of $\langle \tilde{S}_2\rangle$:

$$
-\frac{\mathrm{i}\,m^2\lambda\phi^2}{32\pi^2}+\frac{\mathrm{i}\,m^4\kappa^2\nu\phi^2}{64\pi^2}-\frac{\mathrm{i}\,m^2\kappa^2\nu\phi\,\partial_a\partial^a\phi}{128\pi^2}+\frac{\mathrm{i}\,m^2\kappa^2\omega^2\phi\,\partial_a\partial^a\phi}{32\pi^2\alpha}
$$

Results

- Final result for the divergent part of effective action $divp(\Gamma)$:

$$\frac{5}{16}\, i\, m^4 \kappa^2 \phi^2 - \frac{1}{4}\, i\, m^2 \lambda \phi^2 - \frac{3}{4}\, i\, m^4 \kappa^2 \xi \phi^2 + \frac{3}{4}\, i\, m^4 \kappa^2 \xi^2 \phi^2 + \frac{5}{16}\, i\, m^2 \kappa^2 \phi\, \partial_a \partial^a \phi + \frac{3}{4}\, i\, m^2 \kappa^2 \xi^2 \phi\, \partial_a \partial^a \phi - \frac{9}{16}\, i\, \kappa^2 \phi\, \partial_b \partial^b \partial_a \partial^a \phi - \frac{1}{4}\, i\, \kappa^2 \xi \phi\, \partial_b \partial^b \partial_a \partial^a \phi$$

- Matches with previous result in literature [Mackay and Toms, 2010]
- Higher order terms $\phi \Box^2 \phi$ indicate non-renormalizability. No counterterms
- Code implemented using xAct packages in Mathematica.
- The tadpole and self-interaction integrals are solved by-hand, and substituted in the code.

Some Partial Results[1]

- For the natural inflation model, the divergent part of effective action upto quadratic order in $\bar{\phi}$, not taking into account the constant term $(2\Lambda^4)$:

$$-\frac{3\, i\, \alpha\theta\, \Lambda^8\, \phi^2}{2\, f\theta^6} - \frac{6\, i\, \alpha\theta^2\, \Lambda^8\, \phi^2}{f\theta^6} - \frac{3\, i\, \alpha\theta^2\, \Lambda^8\, \phi^2}{f\theta^8\, \kappa^2} - \frac{5\, i\, \kappa^2\, \Lambda^8\, \phi^2}{16\, f\theta^4} - \frac{3\, i\, \alpha\theta\, \kappa^2\, \Lambda^8\, \phi^2}{2\, f\theta^4} - \frac{3\, i\, \alpha\theta^2\, \kappa^2\, \Lambda^8\, \phi^2}{f\theta^4} - \frac{i\, \kappa^4\, \Lambda^8\, \phi^2}{8\, f\theta^2} - \frac{3\, i\, \alpha\theta^2\, \Lambda^4\, \phi\, \partial_a\partial^a\phi}{f\theta^4} - \frac{3\, i\, \alpha\theta^2\, \Lambda^4\, \phi\, \partial_a\partial^a\phi}{f\theta^6\, \kappa^2} + \frac{9\, i\, \kappa^2\, \Lambda^4\, \phi\, \partial_a\partial^a\phi}{16\, f\theta^2} + \frac{7}{16}\, i\, \kappa^4\, \Lambda^4\, \phi\, \partial_a\partial^a\phi + \frac{i\, \alpha\theta\, \phi\, \partial_b\partial^b\partial_a\partial^a\phi}{2\, f\theta^2} - \frac{3}{16}\, i\, \kappa^2\, \phi\, \partial_b\partial^b\partial_a\partial^a\phi$$

- Contribution at quartic order in $\bar{\phi}$, upto κ^2 terms for the toy model (ϕ^4 theory):

$$\frac{7}{96}\, i\, m^2\, \kappa^2\, \lambda\, \phi^4 - \frac{1}{8}\, i\, m^2\, \kappa^2\, \lambda\, \xi\, \phi^4 - \frac{1}{48}\, i\, \kappa^2\, \lambda\, \phi^3\, \partial^a\partial_a\phi$$

[1] S. Aashish and S. Panda, under preparation

Outline

Current and Future Works

- Quartic order calculation under progress, to include contributions from ghost term.
- Effective action including the constant (Λ) term is being calculated
  - Complications arise due to non-zero poles in graviton propagator, giving rise to complicated loop integrals.
- Once the code is set up, we will apply it to different cosmological models.

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Thank You