Alternative-to-Inflation Scenarios from DHOST Cosmology

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Inflationary cosmology

A period of time before the hot big bang during which the universe undergoes exponential expansion, which is the leading paradigm of early universe cosmology.

Advantages

1. Solve the flatness, horizon and monopole problems
2. Provide a mechanism for the formation of Large Scale Structure through primordial fluctuations
3. The near de-Sitter expansion predicts a near scale invariant power spectrum of density perturbations
4. Predict small amounts of primordial non-Gaussianities

Why searching for alternative paradigm

- provides a possible solution to initial singularity problem and Trans-Planckian problem encountered in inflationary scenario.
- Alternative scenarios may provide distinctively phenomenology compared to inflation.
- We may look out of the paradigm of inflation to judge whether these solutions are economical or artificial, to measure the success of inflation.

Examples of early universe scenarios

We may classify the models of early universe cosmology through the evolution of the scale factor $a(t)$.

- Bounce cosmology: The universe starts with a contraction period ($H < 0$), followed by an expansion period ($H > 0$).
- Genesis cosmology: The universe starts in a quasi-Minkovskian configuration ($H \simeq 0$ but not 0), then transits to an expansion period ($H > 0$). Also named as "Emergent universe scenario" or "Slow expansion/contraction".

One exemplified Bounce cosmology model

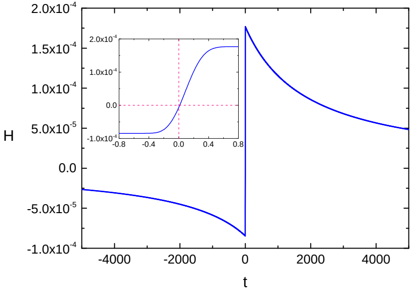

Figure 1: Cosmological evolution of a bounce cosmology model from [1].

One exemplified Galileon Genesis model

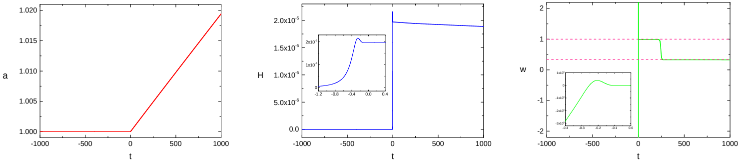

Figure 2: The background dynamics of an emergent universe model from [9].

Challange: NEC Violation

The equation-of-state parameter for the dominated matter content:

$$w = -1 - \frac{2\dot{H}}{3H^2} \ , \tag{1}$$

When the universe transit from a non-expanding state ($H < 0$ or $H \to 0$) to an expanding state $H > 0$, w will approach to $-\infty$, the Null Energy Condition(NEC) is violated.

NEC violation is a generic challange for alternative-to-inflation scenarios.

Constructing alternative scenarios in scalar tensor theory

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- However, there always exists gradient instabilities (sound speed of scalar perturbations becomes negative) within the framework of ghost condensation.
- It is believed that within the framework Horndeski/Galileon theory [2, 3], which is the extension of ghost condensation theory, NEC can be stably violated, resulting in a healthy alternative model.

Horndeski/Galileon Theory

The most general scalar tensor theory with equation of motion up to second order, hence no ghost DoF.

$$L_H = \sum_{i=2}^{5} c_i L_i \ , \tag{2}$$

where $X \equiv 1/2(\partial\phi)^2$ and

$$L_2 = G_2(\phi, X) \ , \ L_3 = G_3(\phi, X)\Box\phi \ ,$$

$$L_4 = G_4(\phi, X)R - 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - \phi^{\mu\nu}\phi_{\mu\nu}\right] \ ,$$

$$L_5 = G_5 G_{\mu\nu}\phi^{\mu\nu} + \frac{G_{5,X}}{3}\left[(\Box\phi)^3 - 3\Box\phi\phi^{\mu\nu}\phi_{\mu\nu} + 2\phi^{\mu\nu}\phi_{\mu\sigma}\phi^{\sigma}_{\nu}\right] \ .$$

No-go theorem for Horndeski theory

The Null Energy Condition cannot be stably violated in Horndeski theory, there will be either ghost degree of freedom or a gradient instability.

The theorem is proven to be true for bounce cosmology, genesis cosmology and Lorentzian wormhole [5, 6, 7, 8].

Solve the gradient instability: DHOST theory

- It is natural to guess if extending the Horndeski theory could evade the no-go theorem. However, modifying Horndeski action will lead to a higher order equation of motion, and generally it will result in the Ostrogradsky instability [11], where unexpectional ghost DoF appears.
- For scalar tensor theories with higher derivatives, the action should be in certain form to avoid the Ostrogradsky ghost. This kind of theory is dubbed as Degenerate Higher Order Scalar Tensor(DHOST) theory [12, 13, 14, 15].
- In our work [1, 9], we will show that specific DHOST theory can break the no-go theorem, and hence solve the gradient instability problem.

The most general action of scalar tensor theory with derivative up to second order is

$$S = \int d^4x\sqrt{-g}\left(f_2 R + C^{\mu\nu\rho\sigma}_{(2)}\phi_{\mu\nu}\phi_{\rho\sigma}\right) \equiv \int d^4x\sqrt{-g}\sum_{i=1}^{5} a_i L_i^{(2)} \ ,$$

with

$$L_1^{(2)} = \phi_{\mu\nu}\phi^{\mu\nu} \ , \ L_2^{(2)} = (\Box\phi)^2 \ , \ L_3^{(2)} = (\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu} \ ,$$

$$L_4^{(2)} = \phi_{\mu}\phi^{\mu\rho}\phi_{\rho\nu}\phi^{\nu} \ , \ L_5^{(2)} = (\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2 \ .$$

To evade the Ostrogradsky ghost, the form of $a_i = a_i(\phi, X)$ is constrained.

DHOST action in our model

In our work [1, 9], we use a Horndeski action

$$\mathcal{L}_H = K(\phi, X) + G(X)\Box\phi \ , \tag{3}$$

developed in [4, 10] to build up a bounce/Genesis cosmology, then merge it with the DHOST action, which is taken to be

$$\mathcal{L}_D = \frac{R}{2}f - \frac{f}{4X}\left(L_1^{(2)} - L_2^{(2)}\right) + \frac{f - 2Xf_X}{4X^2}\left(L_4^{(2)} - L_3^{(2)}\right) \ , \tag{4}$$

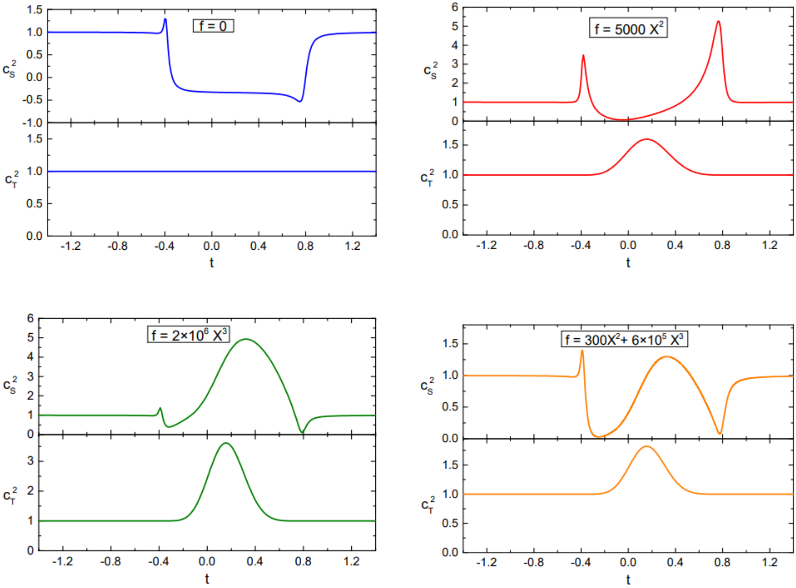
$f = f(\phi, X)$. The action (4) is of type ${}^{(2)}N - II$ DHOST theory, so the merge of $\mathcal{L}_D$ and $\mathcal{L}_H$ doesn't introduce ghost degree of freedom. Besides, when $f = f(X)$, the action (4) doesn't change the background dynamics.

EFT origin of our action

The action (4), when $f = f(X)$, corresponds to EFT operator $\delta K \delta g^{00}$ and $R^{(3)}\delta g^{00}$, which contribute only to the sound speed of scalar perturbation. Certain such operators are found to be able to remove the gradient instability in bounce cosmology [16, 17].

Hence, we believe the action (4) can help to build a healthy alternative-to-inflation model.

Solve gradient instability in bounce cosmology [1]



Solve gradient instability in emergent universe [9]

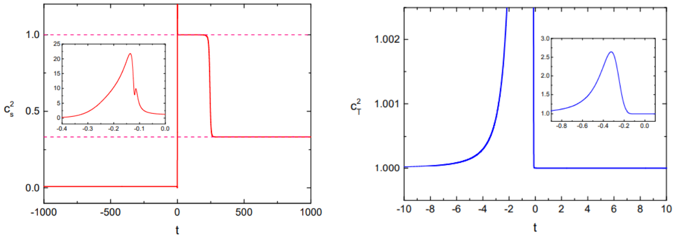


Figure 3: The dynamics of the sound speed of scalar and tensor perturbation c_s^2 and c_t^2 as a function of cosmic time t. The DHOST function is taken to be $f = 0.004X + 0.18X^2$.

Phenomenology of DHOST cosmology with $f = f(X)$

Main results: the DHOST action has negligible impact on the evolution of scalar/tensor perturbations. So the introduction of DHOST terms will not influence the predictions of observational signals [18].

Reason: the DHOST action has non-trivial contribution only during the transition period which is generically very quick, so its effect is restricted by the short duration of the transition period.

Conclusion: DHOST action (4) can serve as a mechanism to change the propogating speed of primordial perturbation, without altering the other physics.

Ongoing Project

The phenomenology of DHOST cosmology with $f = f(X)$ is limited: it only affect c_s^2 in limited region. We are searching for new phenomenons with a generic DHOST coupling $f(\phi, X)$.

We find in [1] that a DHOST coupling of the form $f(\phi) = e^{-a\phi^2}(1 - e^{-b\phi^2})$ can stably generate more than one bounce phase. It is interesting to study how to build up a multiple bounce cosmology with certain $f(\phi, X)$.

Besides, since conventional bounce and Genesis models give a blue scalar spectra, we wish to study whether certain $f(\phi)$ can help to acquire a scale invariant density spectrum.

Summary

- Alternative-to-inflation scenarios commonly require NEC violation, which generically leads to ghost and gradient instabilities.
- We introduce a type of DHOST action and construct stable cosmological models in bounce and Genesis scenarios.
- The DHOST coupling $f = f(X)$ provides negligible phenomenos. We expect new phenomenons for a more general DHOST coupling $f = f(\phi, X)$.

Thanks for your Attention

- A. Ilyas, M. Zhu, Y. Zheng, Y. F. Cai and E. N. Saridakis, "DHOST Bounce," JCAP **09**, 002 (2020) doi:10.1088/1475-7516/2020/09/002 [arXiv:2002.08269 [gr-qc]].
- G. W. Horndeski, "Second-order scalar-tensor field equations in a four-dimensional space," Int. J. Theor. Phys. **10**, 363 (1974). doi:10.1007/BF01807638
- C. Deffayet, X. Gao, D. A. Steer and G. Zahariade, "From k-essence to generalised Galileons," Phys. Rev. D **84**, 064039 (2011) doi:10.1103/PhysRevD.84.064039 [arXiv:1103.3260 [hep-th]].
- Y. F. Cai, D. A. Easson and R. Brandenberger, "Towards a Nonsingular Bouncing Cosmology," JCAP **1208**, 020 (2012)

doi:10.1088/1475-7516/2012/08/020 [arXiv:1206.2382 [hep-th]]

M. Libanov, S. Mironov and V. Rubakov, "Generalized Galileons: instabilities of bouncing and Genesis cosmologies and modified Genesis," JCAP **08**, 037 (2016) doi:10.1088/1475-7516/2016/08/037 [arXiv:1605.05992 [hep-th]].

T. Kobayashi, "Generic instabilities of nonsingular cosmologies in Horndeski theory: A no-go theorem," Phys. Rev. D **94**, no.4, 043511 (2016) doi:10.1103/PhysRevD.94.043511 [arXiv:1606.05831 [hep-th]].

R. Kolevatov and S. Mironov, "Cosmological bounces and Lorentzian wormholes in Galileon theories with an extra scalar field," Phys. Rev. D **94**, no.12, 123516 (2016) doi:10.1103/PhysRevD.94.123516 [arXiv:1607.04099 [hep-th]].

S. Akama and T. Kobayashi, "Generalized multi-Galileons, covariantized new terms, and the no-go theorem for nonsingular cosmologies," Phys. Rev. D **95**, no.6, 064011 (2017) doi:10.1103/PhysRevD.95.064011 [arXiv:1701.02926 [hep-th]].

A. Ilyas, M. Zhu, Y. Zheng and Y. F. Cai, "Emergent Universe and Genesis from the DHOST Cosmology," JHEP **01**, 141 (2021) doi:10.1007/JHEP01(2021)141 [arXiv:2009.10351 [gr-qc]].

P. Creminelli, A. Nicolis and E. Trincherini, "Galilean Genesis: An Alternative to inflation," JCAP **11**, 021 (2010) doi:10.1088/1475-7516/2010/11/021 [arXiv:1007.0027 [hep-th]].

R. P. Woodard, "Ostrogradsky's theorem on Hamiltonian instability," Scholarpedia **10**, no.8, 32243 (2015) doi:10.4249/scholarpedia.32243 [arXiv:1506.02210 [hep-th]].

J. Gleyzes, D. Langlois, F. Piazza and F. Vernizzi, "Healthy theories beyond Horndeski," Phys. Rev. Lett. **114**, no. 21, 211101 (2015)

A. Nicolis, R. Rattazzi and E. Trincherini, "The Galileon as a local modification of gravity," Phys. Rev. D **79**, 064036 (2009) doi:10.1103/PhysRevD.79.064036 [arXiv:0811.2197 [hep-th]].

D. Langlois and K. Noui, "Degenerate higher derivative theories beyond Horndeski: evading the Ostrogradski instability," JCAP **1602**, no. 02, 034 (2016) doi:10.1088/1475-7516/2016/02/034 [arXiv:1510.06930 [gr-qc]].

- J. Ben Achour, M. Crisostomi, K. Koyama, D. Langlois, K. Noui and G. Tasinato, “Degenerate higher order scalar-tensor theories beyond Horndeski up to cubic order,” JHEP **1612**, 100 (2016) doi:10.1007/JHEP12(2016)100 [arXiv:1608.08135 [hep-th]].
- Y. Cai, Y. Wan, H. G. Li, T. Qiu and Y. S. Piao, “The Effective Field Theory of nonsingular cosmology,” JHEP **01**, 090 (2017) doi:10.1007/JHEP01(2017)090 [arXiv:1610.03400 [gr-qc]].
- P. Creminelli, D. Pirtskhalava, L. Santoni and E. Trincherini, “Stability of Geodesically Complete Cosmologies,” JCAP **11**,

047 (2016) doi:10.1088/1475-7516/2016/11/047
[arXiv:1610.04207 [hep-th]].

M. Zhu, A. Ilyas, Y. Zheng, Y. F. Cai and E. N. Saridakis,
[arXiv:2108.01339 [gr-qc]].