Non-singular bounce in non-local gravity

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The problem

- **The initial singularity problem is the problem with most cosmological solutions that they hit a singularity approaching the time when Universe had begun**

- **Reformulation of gravity in terms of other models makes it looking like a strong coupling regime still not providing a reasonable resolution for the singular behaviour**

- **Standard ways to avoid a singularity meets another may be even more serious problem of ghosts**

- **These ghosts are related to higher derivatives in for example $F(R)$ models which feature non-singular bouncing solutions**

- **Is there a way around of ghosts?**

Model

Biswas, Koivisto, Mazumdar, 2010

Bulatov, Biswas, A.K., Mazumdar, Vernov to appear

$$S = \int d^4x \sqrt{-g}\left(\frac{R}{16\pi G_N} + \frac{c}{2} R\mathcal{F}(\Box)R + \dots\right)$$

This describes the modification of gravity expected from the closed String Field Theory. There are deep reasons to have operators like in the above mentioned model in SFT

This model features an exact solution

$$H = \lambda \tanh(\lambda t)$$

in the presence of the cosmological constant and some amount of radiation for a specific $\mathcal{F}(\Box)$.

Other solutions which can be easily constructed are $H = H_0 t$ and $H = H_0/t$.

Model (continued)

To give some feeling of what we are dealing with the trace equation is

$$\sum_{n=1}^{\infty} f_n \sum_{l=0}^{n-1} \left(\partial_\mu \Box^l R \partial^\mu \Box^{n-1-l} R + 2\Box^l R \Box^{n-l} R \right) + 6\Box \mathcal{F}(\Box) R = \frac{R}{8\pi G_N c} + \frac{4}{c}\Lambda$$

and it (really not obviously) has the following exact solution

$$a = a_0 \cosh(\lambda t) \;\Rightarrow\; H = \lambda \tanh(\lambda t)$$

Here a is the scale factor of the spatially flat FRW metric. And yes, we always discuss 4 dimensions.

The latter exact solution is the manifestly non-singular bouncing solution moreover with a de Sitter late time asymptotic

Model (continued)

The previous action is equivalent to the following one

$$S = \int d^4x\sqrt{-g}\left(R\left(\frac{1}{16\pi G_N} + \Psi\right) - \Psi\frac{1}{\mathcal{F}(\Box)}\Psi + \dots\right)$$

The important property here is the non-minimal coupling of a scalar field to gravity.

Model without the non-minimal coupling was intensively studied

The principal point here is the operator $\mathcal{F}(\Box)$ which may contain any (infinite) degrees of the box operator making the action non-local but at the same time giving a way to evade Ostrogradski ghosts in the spectrum

The main objective of our work in progress is to analyse the cosmological perturbations and find out what is new compared to the Einstein gravity.

In the literature

Aref'eva (2004 and on), Joukovskaya, A.K., Vernov, ... in application to the late time universe and in particular to the crossing of the phantom divide

A.K., Vernov, ... developed the cosmological perturbations and analysis of particular models is the work in progress

Barnaby, Biswas, Cline, Nunes, ... (2005 and on) in application to the models of inflation and some particular non-gaussianity mainly from p-adic strings

Biswas, Brandenberger, Koivisto, Mazumdar, Siegel, ... (2005 and on) proposed some non-local generalization of the Einstein action motivated by the String Field theory

Linearization and Localization

We can make a further transformation and eliminate the non-minimal coupling of the scalar field to gravity but the price for this is that the $\mathcal{F}(\Box)$ will gain a dependence on Ψ and the entanglement of the scalar field and gravity will be more complicated

If however we are interested in some vacuum constant solution $\Psi_0 \equiv \mathrm{const}$ then we can write down a linearisation around such a point $\Psi = \Psi_0 + \tau$ and then the action becomes

$$S = \int d^4x \sqrt{-\bar{g}} \left(\frac{\bar{R}}{16\pi G_N} + \tau \mathcal{K}(\bar{\Box}) \tau + \dots \right)$$

This action was studied and the main results are the way to make it local and complete analysis of cosmological perturbations

A.K., Vernov (2009 and 2010) and Galli, A.K (2010)

Summary and Outlook

- **Non-local generalization of gravity is presented and several exact solutions are constructed**
- **At least one solution manifestly has a non-singular bouncing behaviour**
- **Perturbations are studied in a simplified model which is one of the regime of the originally proposed gravity modification**
- **Perturbations around the given solutions is the question of primary concern now**
- **As the preliminary result it seems possible to formulate conditions on the non-local operator such that ghosts are absent and perturbations do not destroy the background behaviour**

Thank you for listening!