ELTE

TTK

Semester report - I.: Connecting inflation and dark energy with particle physics

Particle and Nuclear Physics program

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2024/25

1 Introduction

There are two eras in cosmic history when the Universe was/is undergoing accelerated expansion. One is the early inflationary epoch, and the other is the behavior caused by dark energy today. Both of these can be modeled dynamically with scalar fields [1], although their connection to each other as well as to the scalars in particle physics is not yet understood.

In my work, I aim to make this connection clearer. Starting from Lagrangians endowed with meaning in the Standard Model, or its extensions, one can derive their effects on cosmic evolution. In temporal history, this translates to requiring sufficient e-foldings during inflation, and before the advent of the dark energy dominated era; while in terms of the spatial evolution the predicted power spectrum should match observations. In particular, the models to be studied are those with a spontaneous breaking of symmetry with one or two scalar fields, which can have a non trivial coupling to the curvature of spacetime [2].

2 Guided research

2.1 Temporal evolution

The temporal evolution of the universe tells us how many e-folds occured during inflation, as well as whether or not a dark-energy like behavior arises at the correct epoch in the late time limit. It also describes the background evolution when studying perturbations around the homogeneous metric.

From my previous studies, I have worked out the differential equations governing the temporal evolution for the single field model:

- With a minimal $\xi = 0$, or conformal $\xi = 1/6$ coupling to the curvature as $\xi\Phi^2 R$.
- With the inclusion of an a posteriori decay term in the Klein-Gordon equation, proportional to some decay width Γ.
- For an arbitrary potential energy, including a constant V_0 minimum value.

So far, I have successfully derived the same kind of equation system for a model with two scalar fields instead of one, with all the cases listed above. We are most interested in when both of these scalar fields can undergo spontaneous symmetry breaking, either one after another, or roughly at the same time, leading to the potential energy [3]:

$$V(\Phi, \mathcal{X}) = \lambda_\Phi(\Phi^2 - \Phi_0^2)^2 + \lambda_\mathcal{X}(\mathcal{X}^2 - \mathcal{X}_0^2)^2 + \lambda(\Phi^2 - \Phi_0^2)(\mathcal{X}^2 - \mathcal{X}_0^2)\,.$$

Preliminary simulations show that the system behaves in a similar way as is the case for a single scalar: a sufficient amount of e-folds can be obtained if the initial value of the fields, or at least one of them, is atop a local maximum in the potential. For the late time emergence of dark energy, further study is necessary, as the form of the potential obtained from particle physics is not disturbed by shifts of the nullpoint value.

2.2 Spatial evolution

To find stronger constraints on the parameters of the scalar fields (in this case, the vacuum expectation value), one has to take into consideration the observed inhomogeneities of the cosmos, and relate the predicted values in the model (for example, the spectral index n_s) to observational constraints. There are two ways to achieve this: the perturbation equations can be solved numerically, or the slow-roll approximation can be applied.

For the first of these methods, I familiarized myself with the Cosmic Linear Anisotropy Solving System (`CLASS`) code package [4]. With it, the spectral index n_s and scalar-tensor ratio r can be calculated both numerically as well as in the slow-roll approximation, for a single, minimally coupled scalar field. As a starting point, my aim was to verify the slow roll approximation for this case with the help of the numerical solutions. Currently, the spectral index n_s lines up between the two. The scalar-tensor ratio r_{k^*} taken at some pivot scale k^* differs, which needs to be resolved.

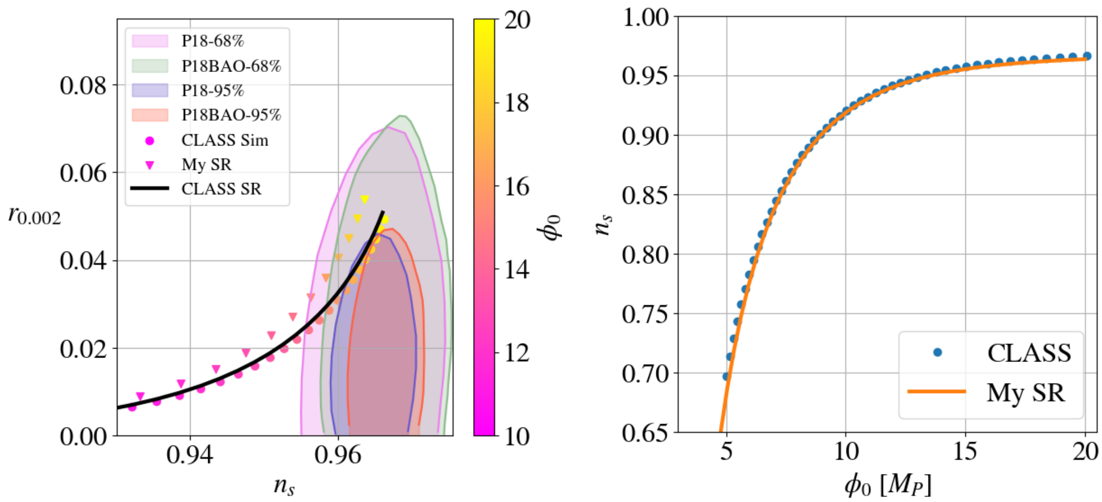

Figure 1: Spectral parameters predicted by the `CLASS` code for the minimally coupled, symmetry broken scalar field; compared with the slow roll approximation based on my temporal evolution. The vacuum expectation value is measured in $M_P = (8\pi G)^{-1/2}$. With shaded regions I have drawn for comparison the results of the 2018 PLANCK [5] survey, with two different confidence levels, as well as with and without taking baryon acoustic oscillations into account.

The `CLASS` code is not directly applicable for the conformally coupled scalar, leaving only the slow roll approximation. With the results of my temporal simulations, as well as literary values for the spectral parameters [2], I calculated the predicted values for n_s. I found that the regime producing viable observables can be mapped to the minimally coupled case, as motivated by the Einstein-Jordan frame transformation [6] between the two:

$$n_s\left(\Phi_0^2\Big|_{\xi=1/6}\right) \Longleftrightarrow n_s\left(\frac{\Phi_0^2}{6+\Phi_0^2}\Bigg|_{\xi=0}\right).$$

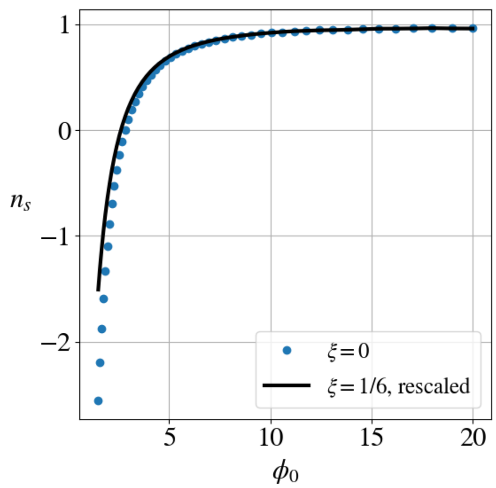

Figure 2: Dependence of the spectral index n_s on the vacuum expectation value for the minimally and conformally coupled cases. For the latter, the above transformation maps it to the minimal one, which can in turn be related to `CLASS` simulations.

For the following semester, I plan to wrap up the single field case for both conformal and minimal couplings. The next step is to approach the dual field model, which requires a more in-depth look into the theory of perturbations.

3 Studies

I took a single course this semester, closely related to my research topic:

- **FIZ/2/132** – Particle Astrophysics

4 Teaching

I supervised the following practice class:

- **elmfiz1af17ga** – Elméleti mechanika A *(gyakorlat)*

This meant 90 minutes of teaching each week. I also wrote lecture notes to share with the students including elaborated solutions for each lesson, totaling in about a hundred pages. It's to be expanded and enhanced, should I return next year.

5 Conferences

I have made my application to this years OTDK, which is to be held in April. As of writing, the work itself has been accepted, but the application forms are awaiting approval. My talk is to be about the methodology of my topic (titled *"Kozmológiai infláció és sötétenergia egyetlen skalárező paramétereinek függvényében"*), and is planned to include 15 minutes of presentation followed by 15 minutes of discussion.

References

[1] Sebastian Bahamonde, Christian G. Böhmer, Sante Carloni, Edmund J. Copeland, Wei Fang, and Nicola Tamanini. Dynamical systems applied to cosmology: Dark energy and modified gravity. *Physics Reports*, 775–777:1–122, November 2018.

[2] Valerio Faraoni. Conformally coupled inflation, 2013.

[3] Zoltán Péli and Zoltán Trócsányi. Vacuum stability and scalar masses in the superweak extension of the standard model. *Physical Review D*, 106(5), September 2022.

[4] Diego Blas, Julien Lesgourgues, and Thomas Tram. The cosmic linear anisotropy solving system (CLASS). Part II: Approximation schemes. *Journal of Cosmology and Astroparticle Physics*, 2011(07):034–034, July 2011.

[5] Y. Planck Collaboration: Akrami and et al. Planck2018 results: X. constraints on inflation. *Astronomy & Astrophysics*, 641:A10, September 2020.

[6] Marieke Postma and Marco Volponi. Equivalence of the Einstein and Jordan frames. *Physical Review D*, 90(10), November 2014.