Research Summary

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1 Introduction

This document briefly summarises my PhD research and outlines some skills that may have not been detailed in CV. Please use this article in conjunction with CV.

2 Brief Summary of PhD research

Central theme of my PhD project is : "Investigating Linear and nonlinear perturbations in scalar field dark energy models". A no. of theoretical models have been proposed to explain accelerated expansion of the Universe. Many of these models are dynamic, in space and time, in contrast to standard ΛCDM model. So an important question to address is how these dynamical models of dark energy can be distinguished observationally. Towards this end, theoretical calculations/simulations in different class of dark energy models are required to investigate the distinguishing features of different theories. In my work I have been looking and comparing linear and nonlinear perturbations of scalar field dark energy cosmologies. One core question that I investigate is that if there are two different Lagrangians for Dark Energy(DE) that are observationally same at level of background cosmology, how efficiently can they be distinguished by perturbations(linear order and beyond).
The project can be roughly divided into following components(each of which summaries one of my articles, published or in preparation):

- To begin with, we started by simulating nonlinear spherically symmetric perturbations in quintessence models of dark energy. It was observed that nonlinear perturbations in matter component (through metric) induce perturbations in dark energy field. Dark energy density and effective equation of state become a function of space and time. Although perturbations induced in DE grow stronger with time, they remain weak compared to dark matter(DM) perturbations. Comparisons were made with non-clustering models of DE and it was found that induced scalar field perturbations do NOT affect dark matter structures in significant manner. For details please see [1].

- In general different DE models might lead to different expansion histories and might be distinguishable by just looking at probes sensitive to background expansion(like type 1a supernovae). But given the great success of ΛCDM, most dark energy alternatives have to be Λ mimicking so as to satisfy expansion constrains from observations. Consequently, often alternative DE models have, by design, some degree of freedom(like parameters of potential of scalar fields) which help the model satisfy the expansion observations. Then different models can have same expansion history. So, then one has to explore next degrees of freedom(like spatio-temporal dynamics): perturbations in DE fields. For example: two different theories of dark energy with scalar fields are: quintessence models and tachyonic models. They are represented by different Lagrangians, but for each of them one can find corresponding potentials that give very similar background expansion. For disentangling the effects coming from different expansion and effects coming from different perturbation dynamics, we need to reconstruct potentials for two scalar fields given a particular background expansion history. This was done in this second part where we worked out the equations, found analytical form for potentials for a very few simple cases. A numerical scheme based on splines was designed to reconstruct the potential. More information can be obtained from our article [2].

- Using techniques developed in first and second part, we simulated nonlinear spherical perturbations for tachyonic models as well. Qualitatively, behaviour was similar to that of dynamics in quintessence counterparts. Perturbations are induced in scalar field, grow with time, but remain weak compared to DM perturbations. However in order to make a systematic comparisons, we simulated both quintessence and tachyon cases with same expansion history. So that any difference that would be observed would be because of different nature of dynamics of perturbations. We found that for backgrounds closer to ΛCDM, the observable effects on metric or matter perturbations are insignificant. These results hold even for expansion cases which are significantly different from $w = -1$ e.g. $w = -0.9$. For background practically disfavoured by observations ($w = -0.5$), the difference between two models can be significant. So, this work suggest that for background models constrained by current observations, distinguishing the two theories(quintessence and tachyonic field) may not be feasible even for nonlinear matter perturbations regime(in spherical symmetry). Please see [3] for details.

- Previous parts, though ventured into nonlinear regime, assumed spherical symmetry. Most of modern cosmology heavily uses linear theory, often in conjunction with semi-analytical nonlinear approximations. In this part we looked at linear perturbations to study if effects like ISW can distinguish the two theories. For this we again compared models from two theories(quintessence & tachyon) with similar background expansions and investigate quantities(e.g. potential(ψ),$\dot{\psi}$,etc.) which contribute to observables, how they evolve. We again get similar reasults as in spherical nonlinear case. For expansion history close to Λ, two cannot be distinguished. We rewrite the linear equations to show how this happens. We also establish a correspondence with equivalent fluid models with corresponding effective speed of sounds for two scalar fields written in terms of effective scalar field perturbations. We then use approx effective c_s^2 and use Planck data to constrain a parameterized form of $c_s^2 = \beta w + \alpha$. ($\beta = 0, \alpha = 1$) corresponds to quintessence while ($\beta = -1, \alpha = 0$) to tachyon. In line with previous works by other people that c_s^2 as a constant is not constrained by current data, we find that α and β are also not constrained. The article for this work is under preparation.

- **Currently working on:** N-body simulation with scalar field dark energy. I am working on two versions of N-body code: one treats scalar field using equations from linear theory, other version allows fully relativistic nonlinear equations for scalar field. One of the main purposes of this project is to check if partially non-linear contributions coming from scalar field can cause any deviation from linear theory version. A minimalistic code, responsible for basic dynamics, is in working/testing condition.

- **Other project working on:** Minimally coupled dark energy models are hard to constrain/distinguish because of very small amount of dark energy presence at early times(e.g. at last scattering). But the theories in which coupling of DE to DM is allowed, there are stronger effects coming from dynamics of perturbations which make them interesting to study. Even for models which have background exactly same as ΛCDM, perturbations lead to different dynamics for Λ and for different coupling strengths. We did spherical collapse studies with such models, using formalism developed in above mentioned projects. But, unfortunately similar results were published by other group, who have been working on similar problems for longer time, hence, we could not write an article on this. But I am still interested in this problem from an N-body perspective. There has been work by Marco Baldi on coupled dark energy N-body simulations CoDECS. In my future works, I would like to explore these simulations from a more relativistic approach.

3 Skills used frequently in PhD research

- For above mentioned projects, I have to solve differential equations numerically. This includes ordinary as well as partial differential equations. I have experience in different type of numerical methods for solving differential equations, e.g. RK class of algorithms, Kick-Drift-Kick, various second/higher order methods like Adams-Bashforth,etc. While dealing scalar fields in general relativity, one is often confronted with numerical instability coming from CFL conditions(this is very crucial for N-body simulation). This has to be dealt with partially implicit methods assisted by FFTs.

- Numerical implementation of interpolation/extrapolation schemes.
- Symbolic coding in Mathematica to obtain dynamics equations from Lagrangians.
- Numerical differentiation techniques based on finite difference schemes, interpolation methods and using FFT.
- Parallel Computing: Regularly use OpenMP. Familiar with MPI, but has not used it for my codes yet, intend to use it for N-body code once basic dynamics code is tested.
- CMB code: Have used CLASS and made minor modifications to implement parametric form of c_s^2. I intend to modify it further for explicitly implementing tachyonic scalar field models.
- Optimization methods like- Newton-Raphson, Gradient descent, simulated annealing, etc.
- Have used and am familiar with MCMC sampling for probability distributions: Gibbs sampling, Metropolis-Hastings etc.

4 Other skills

- Bayesian Statistics: Familiar with basic bayesian statistics, its practical implementation using Markov chains. Also, I am interested in and have studied about bayesian latent variable models.
- Neural Networks(NNs): Has been learning about it and is now familiar with basic concepts of NNs and its practical implementation using Keras level API on top of Tensorflow and using PyTorch.
- Machine Learning/Data skills: Familiar with and have introductory hands-on experience with basic concepts of machine learning: Various techniques-linear regression, general additive models with R, Neural Nets, SVMs, Gaussian Processes, etc. Essential ideas of training, optimization, test set, validation, cross-validation, data augmentation, etc. One thing that I am interested in and has been learning about is model selection using validation based approaches and Bayesian evidence based methods.

5 Teaching

I am keen on teaching numerical/computational methods to beginning undergrads and even high school students. I have been TA in many courses during my PhD(listed below). I have written an educational article with my PhD guide and a summer intern, which was published in Resonance[4]. I would be interested in further teaching opportunities, particularly in numerical methods.

- Teaching Assistant for Classical Mechanics lab(PHY111), Fall Sem(2016 & 2017)
- Teaching Assistant for Modern Physics lab(PHY212), Spring Sem(2017)
- Teaching Assistant for Computational Methods in Physics(using C), Spring Sem(2018)
- Teaching Assistant for Introduction to Computers(intro to Scientific computing using Python), Fall Sem (2018)
- Teaching Assistant for Computational Methods in Physics, Spring Sem (2020)

References

[1] M. P. Rajvanshi and J. S. Bagla, JCAP **06** (2018), 018 [erratum: JCAP **03** (2020), E01] doi:10.1088/1475-7516/2018/06/018 [arXiv:1802.05840 [astro-ph.CO]].

[2] M. P. Rajvanshi and J. S. Bagla, J. Astrophys. Astron. **40** (2019) no.6, 44 doi:10.1007/s12036-019-9613-2 [arXiv:1905.01103 [astro-ph.CO]].

[3] Rajvanshi et al 2020 Class. Quantum Grav "Non-linear spherical collapse in tachyon models, and a comparison of collapse in tachyon and quintessence models of dark energy," [arXiv:2003.07647 [astro-ph.CO]]. doi:https://doi.org/10.1088/1361-6382/abbb63

[4] M. P. Rajvanshi, T. Chakraborty and J. S. Bagla, [arXiv:1803.04267 [physics.pop-ph]].