Reconstructing Dark Energy

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Introduction

It is well known that, despite its successes, there are several problems with the standard model of Cosmology, LCDM.

Some of these problems are:
- -Hubble parameter tension
- -Fine-tuning problem
- -Coincidence problem
- -Nature of both DE and DM
- -Dwarf Galaxies
- -Cuspy Haloes

just to mention a few.

Since these problems have worsen as more data becomes available some alternatives are proposed that could solve one or more of them. These alternatives range from simple extensions or modifications of the standard model to complete reformulations of the theory of Gravity and General Relativity (the latter being generally referred to as "modified gravity"). In particular we are interested in an alternative known as **reconstructions**. They can be either parametric, non-parametric and model-independent. When used in tandem with other models one can obtain really interesting results.

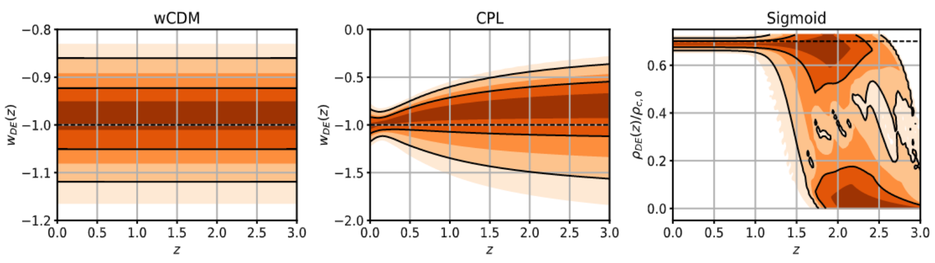
One crucial ingredient to perform reconstructions (and specifically model-selection) is Bayesian Statistics, given its importance in parameter inference.

Parametric Reconstructions

These reconstructions propose a parameterization for a physical quantity with certain physical properties, and its main goal is to explore certain behaviours (i.e. oscillations or exponential growths) when comparing this parameterization with the data.

Some of the most well-known are wCDM and CPL for the equation of state.

$$\text{wCDM:}\quad w(z) = w_c$$
$$\text{CPL:}\quad w(z) = w_0 + w_1\left(\frac{z}{1+z}\right)$$
$$\text{Sigmoid:}\quad \frac{\rho_{DE}}{\rho_{c,0}} = \Omega_{DE,0}\left(k_0 - \frac{1}{1+e^{-10(z-z_{cut})}}\right)$$



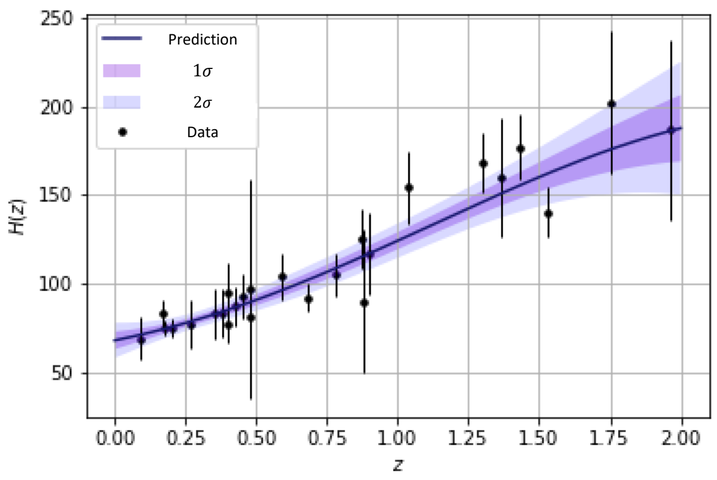
Non-parametric Reconstructions

In a non-parametric reconstruction one does not start with a predefined model or characteristic in mind. This type of reconstruction focuses on statistical methods to directly process the data in a certain way to mine information regarding the physical property to be reconstructed.

A popular example is Regressions. Particularly one known as Gaussian Process (GP) Regression.

With the GP finished one can proceed to make inferences about the data like:
- -Tendencies
- -Preferences for a certain value
- -Tensions with other models

Since this type of reconst. does not have "parameters" and a functional form they cannot be used for model selection.

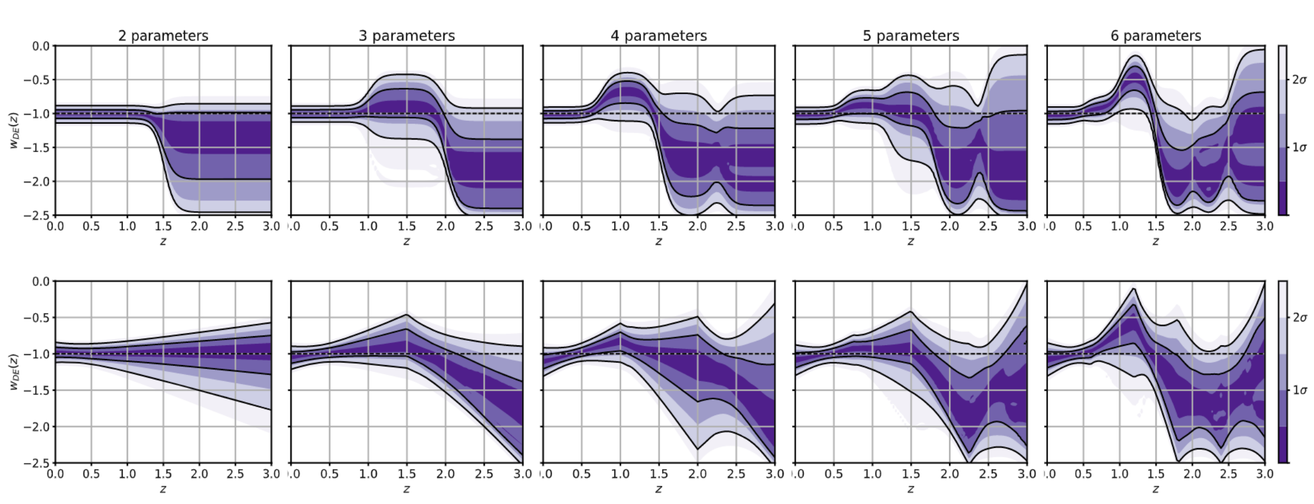


Model-independent Reconstructions

This approach to reconstructions has something in common with both parametric and non-parametric approaches since they often have some parameters to infer but they lack a well-defined functional form. They can be a sum of terms like a Taylor or Fourier series, a Padé approximant, etc. They have parameters that need to be inferred with data.

An advantage they possess over a non-parametric reconst. is their availability for model selection (by using Bayesian statistics) with other models. Here we show 2 of them: a binning scheme (or sum of step functions); and a linear interpolation.

$$f(z) = f_1 + \sum_{i=1}^{N-1} \frac{f_{i+1}-f_i}{2}\left(1+\tanh\left(\frac{z-z_i}{\xi}\right)\right) \qquad f(z) = f_i + \frac{f_{i+1}-f_i}{z_{i+1}-z_i}(z-z_i),\quad z\in[z_i, z_{i+1}]$$



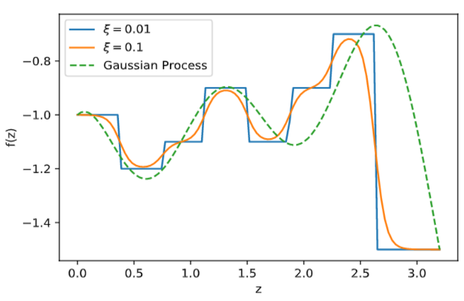
Applications with an Interacting Dark Sector

(in collaboration with Özgür Akarsu and Eleonora Di Valentino)

As mentioned in the introduction, these approaches to reconstruction can be combined with alternatives of LCDM, and in this case we focus on an Interacting Dark Energy (IDE). This interaction occurs between DE and DM and represents an exchange of energy.

$$\dot{\rho}_{\rm DM} + 3H\rho_{\rm DM} = Q,$$
$$\dot{\rho}_{\rm DE} + 3H\rho_{\rm DE}(1+w_{\rm DE}) = -Q$$

The method for reconstruction to be used is a Gaussian Process but as an interpolation. This allows us to perform model selection and to compare it with other parameterizations such as wCDM or CPL. Unfortunately, given that we use a model-independent approach, the interaction remains phenomenological in nature.



Our results reveal that the data prefers an interaction that oscillates and allows the DE's effective equation of state to have an asymptote. This characteristic is essential for DE models with a sign switch. That is: a DE energy density which is negative at early-times and positive in late-times.

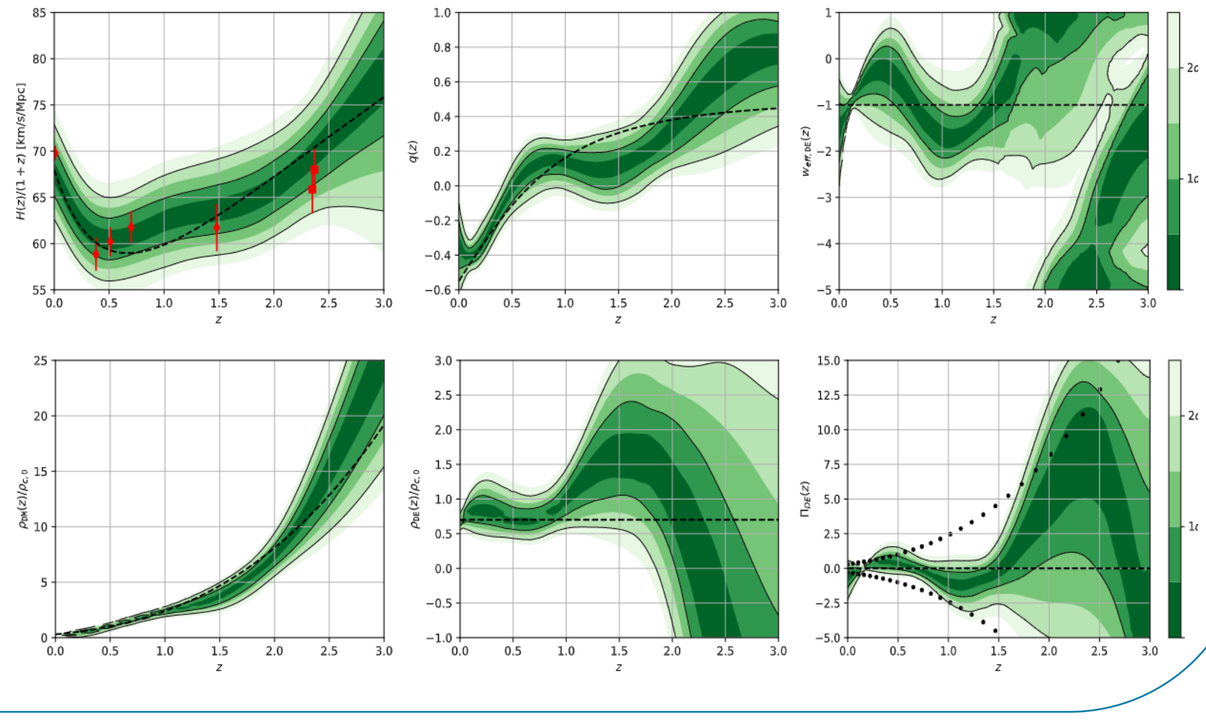
Important eqs. for the IDE model

$$\frac{H^2(z)}{H_0^2} = \Omega_{b,0}(1+z)^3 + \frac{\rho_{\rm DM}(z)}{\rho_{\rm c,0}} + \frac{\rho_{\rm DE}(z)}{\rho_{\rm c,0}}$$

$$\dot{\rho}_{\rm DM} + 3H(1+w_{\rm eff,DM})\rho_{\rm DM} = 0$$
$$\dot{\rho}_{\rm DE} + 3H(1+w_{\rm eff,DE})\rho_{\rm DE} = 0$$

$$w_{\rm eff,DM} = \frac{-Q}{3H\rho_{\rm DM}}, \qquad w_{\rm eff,DE} = w_{\rm DE} + \frac{Q}{3H\rho_{\rm DE}}$$

$$\Pi_{\rm DM} = \frac{-Q}{3H\rho_{\rm c,0}} = -\Pi_{\rm DE}$$



Conclusion

Since the nature of both DE and DM is still unknown, and even their existence is up for debate, the reconstructions are a good way of studying certain characteristics. They can give an insight for new models and show where the problems or tensions might be alleviated. All of this, of course, by making the assumption that the problem is the underlying theory and not the data.

For further reading please refer to:
https://arxiv.org/abs/2111.10457
https://arxiv.org/abs/1903.11127
https://arxiv.org/abs/2305.16290

The software used to make the reconstructions can be found in:
https://github.com/ja-vazquez/SimpleMC