University of Cambridge
Faculty of Mathematics
Summer Research Projects

Multi-field Chameleon Models

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Background

In 1998, Saul Perlmutter, Brian Schmidt, and Adam Riess made a startling discovery which won them the Nobel Prize: the Universe is not only expanding, but the speed of expansion is accelerating. One way of explaining this acceleration is to assume that the whole Universe is filled with a previously undetected scalar field whose potential energy is slowly decreasing but has not yet settled down to zero. This idea is not far-fetched: a lot of modern theories, such as supersymmetry or string theory predict hosts of these fields.

One problem with this explanation is that our knowledge of particle physics suggests that the field couples to ordinary matter causing an additional force on visible objects in the universe. Our current theory of gravity, Einstein's theory of *General Relativity*, has been tested to high accuracy in our solar system and galaxy but no hints of such an additional force have been found.

However, all searches for additional forces have been performed in very dense environments and so it is possible that the behaviour of the field depends on the density: it could lead to a strong additional force in vacuum but be hidden completely from our view in dense regions such as our solar system. One candidate is called the *Chameleon* field due to its ability to transform depending on its surrounding.

To date, all fields which can hide sufficiently in the solar system and galaxy failed to have enough energy density to account for the accelerated expansion unless a highly unnatural constant is added to the potential energy. We are trying to generalise previous approaches by introducing multiple fields.

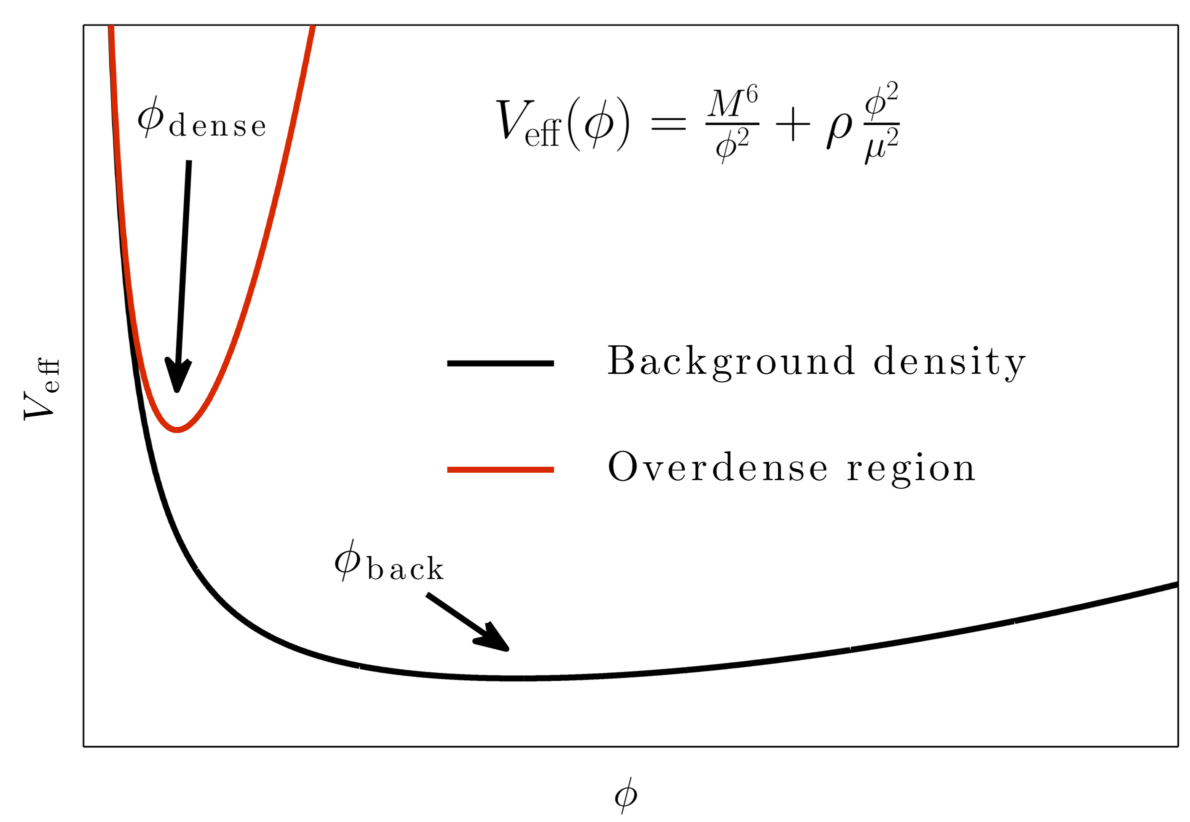

Figure 1 : One example of a Chameleon potential. M and μ are mass scales and ρ is the matter density. In dense regions the field is trapped at the red minimum, in background density it settles down to the black minimum.

Screening mechanisms

It can be shown that the introduction of a new scalar field, ϕ, leads to an additional force of strength

$$|F_\phi| \propto |\nabla\phi| \,.$$

This shows that one way of hiding the additional force is to ensure that ϕ is approximately constant in dense regions so that $|\nabla\phi|$ is small. This is the so called *Chameleon Mechanism*. It is achieved by giving the effective potential energy of the field a very sharp minimum in overdense regions, for example with the potential in figure 1. A sharp minimum means little variation in the field and, thus, a negligible additional force. In low density regions the minimum is flatter, leading to larger variations (see figure 2) and a larger force.

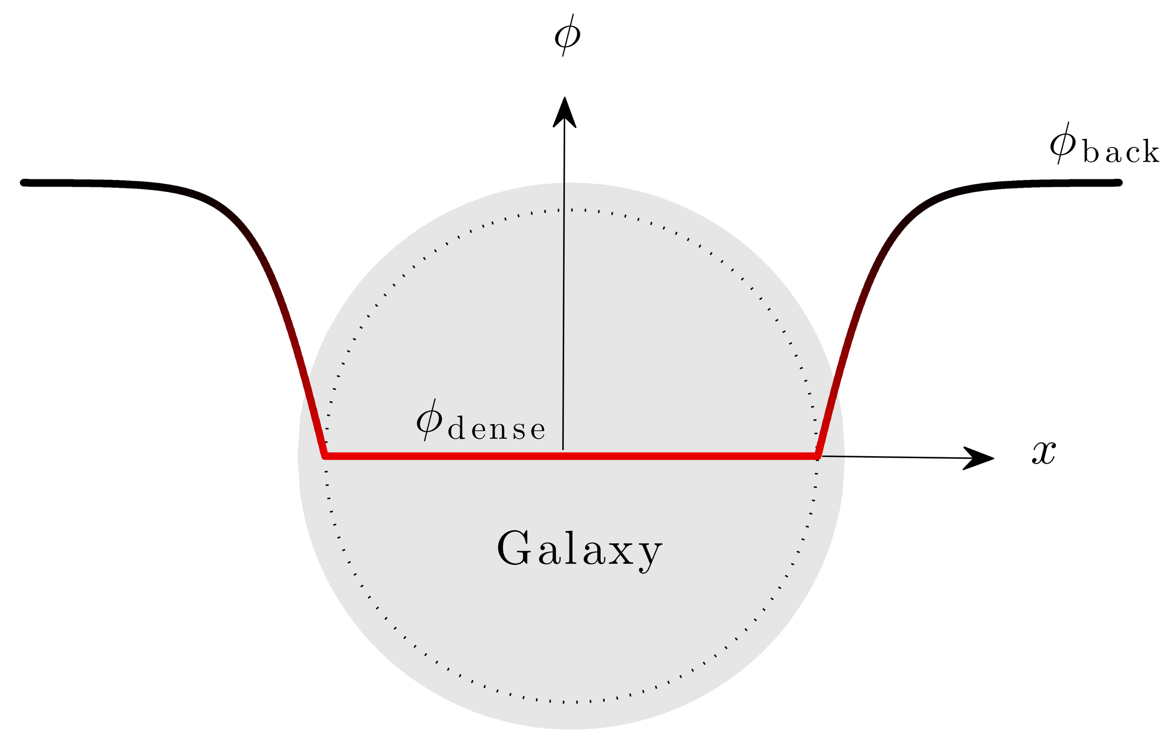

Figure 2 : Field profile for a Chameleon field in a galaxy. The field is almost constant in the galaxy and only starts to vary very close to the edge, outside the so called *screening radius* (dotted circle).

Multi-field models

Since no single field model has managed to explain the accelerated expansion while hiding unwanted forces we considered multi-field models. In particular, we investigated models where the radial component of the field hides the extra force and accelerated expansion is produced by the angular components. The hope is that experiments only constrain the potential in radial direction so that the potential in angular direction can be tweaked so as to produce accelerated expansion.

One simple such potential is shown in figure 3. It is a rotated version of the Chameleon potential shown above with a small term breaking the rotational symmetry and producing a gradient in angular direction.

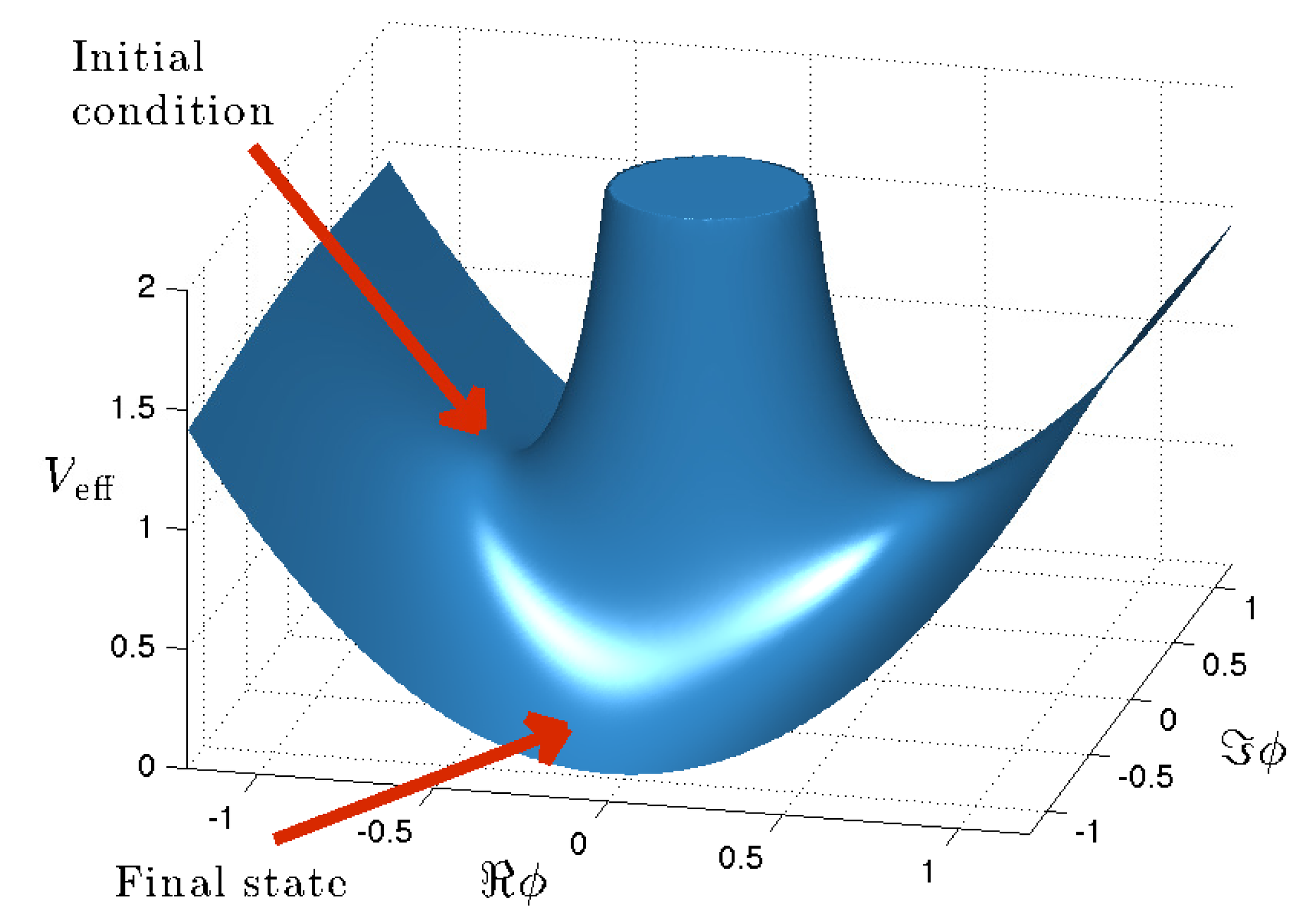

Figure 3 : Example of a multi-field potential. $V_{\rm eff}$ is rescaled by the background density $H_0^2 M_{\rm pl}^2$ and ϕ by a typical field value. The field starts rolling slowly close to the maximum and will eventually roll down to zero potential energy.

No-go theorem

To explain the observed accelerated expansion the model has to satisfy:

- Additional forces need to be hidden sufficiently to have evaded all experiments to date.
- The field must not roll too quickly and cannot have settled down to its minimum.
- The energy density must be $V_{\rm eff} \approx H_0^2 M_{\rm pl}^2$, where H_0 is the current Hubble parameter and $M_{\rm pl}$ is the Planck mass.

We showed that for any number of fields these conditions cannot be satisfied simultaneously. The proof is rather technical. Hence, it is not possible to construct a multi-field model in which the radial field hides the extra force and the angular fields produce accelerated expansion.

Summary

- The accelerated expansion of the universe could be explained by a previously undetected field which fills the entire universe.
- For this field to be undetected, the force arising from its interaction with visible matter has to be hidden in dense environments.
- To date, no satisfactory model has been found which can explain accelerated expansion and hide the extra force sufficiently.
- We showed that it is not possible to devise a multi-field model in which the radial field is responsible for hiding the extra force and the angular fields produce the accelerated expansion.