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# ON THE NATURE OF DARK MATTER*

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Dark matter in the universe seems to be one of the most important puzzles science has to face in this moment. In this essay, we point out that dark matter could be a spin-0 fundamental interaction of Nature rather than a simple particle. From this hypothesis follows that dark matter behaves just as standard cold dark matter at cosmological level while still in good agreement with observations at galactic scales. This new interaction could be one of the scalar fields predicted by higher-dimensional theories.

*Keywords*: Cosmology; dark matter; braneworld; scalar fields.

For many years, it seemed that our deepest understanding of Nature would come from the study of the tiniest constituents of matter. That feeling changed drastically once the scientific community was able to see the small imperfections of the radiation sea that fills all of the observable universe. If we agree with the most recent cosmological observations, we should instead turn our attention to the largeness in order to complete our knowledge of Nature.

To put it in numbers, there is increasing evidence for the existence of exotic matter which would account for 96% of the total material content of the universe.[1,2] The simplest picture makes the following division. 73% of the cosmic matter is gravitationally repulsive and has been labelled as *dark energy.* On the other hand, 23% of the cosmic matter is gravitationally attractive and has been dubbed *dark*

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*matter*. The adjective *dark* means that they do not emit electromagnetic waves nor do they interact with the particles we know from the Standard Model of Particles (SMP). However, their presence was detected by the important gravitational effects they have imprinted on the evolution history of the cosmos.

Surprisingly, it has been possible to assemble a simple and successful model,[3] the so-called Lambda Cold Dark Matter (LCDM), in which the dark energy is represented by a cosmological constant ($\Lambda$), and the dark matter is *cold*. There is a plethora of specific candidates that can play the role of dark energy and dark matter, the most popular being the particles from the minimal supersymmetric extension of the SMP. The LCDM model is very successful at cosmological level: it accounts for the large scale structure and the accelerated expansion of the universe, for the micro-Kelvin fluctuations of the Cosmic Microwave Background, etc. Moreover, the aforementioned coldness of dark matter predicts well, in accord with cosmological observations, the evolution of small perturbations on a homogeneous and isotropic universe. However, the model fails at galactic level. It predicts cusp density profiles in galaxies, but new high resolution observations indicate that density profiles in the center of galaxies are almost flat.[4–10] In addition, it seems that a new thorn has beed added to the CDM model: old galaxies were assembled at a higher redshift than expected.[11]

As it can be inferred from the last paragraph, the case of dark matter is of particular importance due to its key role in the formation of galaxies, the unit cells of cosmological structure. It is not surprising then that the search for dark matter particles has become one of the most important challenges of science.[12–15]

There are many theoretical proposals that go beyond the SMP; among which the most successful are the superstring theory and the brane models. A common feature of all of these super-theories is the existence of *scalar fields*: the so-called dilatons, radions, etc., which are key elements by themselves. The presence of scalar fields in these models is surprising, to say the least, since no fundamental scalar field has ever been detected, nor even the so-needed Higgs particle of the SMP. To our knowledge, there are only four fundamental interactions in Nature: gravitational, electromagnetic, strong and weak. The first two are of long range, while the other two are of short range, the gravitational one being the weakest of all of them. Gravitation is a spin-2 interaction, and the others are spin-1.

As there is not evidence for the existence of a fundamental scalar field nor of a spin-0 interaction, it seems that our super-theories have to have an internal mechanism to suppress their own scalar fields. But, the evidence is not at all conclusive and we should ask: *did Nature forget the most simple interaction?*

On one hand, we have to face the theoretical existence of fundamental scalar fields; on the other hand, we have to face the problem of the missing matter in the universe. A deal seems possible: could it be possible that Nature did include the spin-0 interaction and made it the dominant one as part of what we called dark energy and dark matter?

Let us construct a model of dark matter using a scalar field, having in mind that, more than a particle, *dark matter could be a new fundamental interaction*; we shall call it the Scalar Field Dark Matter (SFDM) model. With the theoretical and observational evidence we have at hand, let us make the following reasoning.

First of all, because of the success of the LCDM model, we should impose the condition that the scalar field should mimic the behavior of the CDM model at cosmological scales. Second, SFDM should provide us with a new perspective with respect to the formation and the structure of galaxies, that could make the theoretical expectation compatible with actual observations.

Third, from theoretical reasoning, the scalar field must be stabilized in some manner. One possibility is to endow the scalar field to a scalar potential with a minimum. Fourth, the SFDM models should not alter the successful early universe of the LCDM model, like for instance, the epoch of nucleosynthesis. If possible, the scalar field should be subdominant at those epochs.

One of the simplest scalar potentials that would fulfill the above requirements is a cosh potential.[16,17] Therefore, we propose the following effective Lagrangian for a L-SFDM model,

$$\begin{aligned} \mathcal{L}_{\text{L-SFDM}} &= \mathcal{L}_{\text{GR}} + \mathcal{L}_{\text{B}} + \mathcal{L}_{\Lambda} - \sqrt{-g}\,[\Phi^{,\mu}\Phi_{,\mu} + 2V(\Phi)]\,, \\ V(\Phi) &= \frac{m_\Phi^2}{8\pi G\lambda^2}\left[\cosh\left(\sqrt{8\pi G}\lambda\Phi\right) - 1\right] \end{aligned} \tag{1}$$

where $\lambda$ and $m_\Phi$ are the free parameters of the model; the latter is recognized as the mass of the scalar field. The values of $\lambda$ and $m_\Phi$ can be fixed by imposing that the SFDM model should reproduce the success of CDM at cosmological scales,[17,18] and then

$$\lambda \sim 20\,, \qquad m_\Phi \sim 10^{-23}\ \text{eV}\,. \tag{2}$$

A brief description of the cosmological model that arises from Eq. (1) is as follows. After inflation, the universe is dominated by the radiation component, and the scalar potential is exponential (the scalar field is far from the minimum). The large value of $\lambda$ makes the scalar matter subdominant and behave as part of the radiation fluid. It is in this epoch too that the field approaches the minimum of the potential, ceases to follow the radiation fluid, and begins to behave as a dust fluid. From this time on, the evolution of the homogeneous and isotropic universe proceeds exactly as in the LCDM model.

The latter is also true for the development of scalar fluctuations, which grow as in the CDM case, except that all structure on scales smaller than $\lambda_\Phi = m_\Phi^{-1} \sim 10$ pc is suppressed. This eventually prevents, once a scalar fluctuation collapses and forms a gravitationally bound object, the formation of density profile with a central cusp. This is confirmed by the numerical simulations for the collapse of a single scalar fluctuation, which ends as a self-gravitating scalar object called *oscillaton*.[19–22] The energy density profile of oscillatons is regular everywhere.

Oscillatons are stable scalar configurations if their mass is below the critical value[21]

$$M_{\rm crit} \sim 0.6 \frac{m_{\rm Pl}^2}{m_\Phi} \,. \tag{3}$$

For the scalar mass value (2), we get $M_{\rm crit} \sim 10^{12} M_\odot$, which is roughly the mass content of a typical galaxy. Also, numerical studies within the weak-gravity regime have shown that a galaxy scalar fluctuation rapidly virializes,[23] which seems to be in accord with observations of the oldest galaxies in the universe.[11]

In this essay, we have made a resumé of a promising SFDM scenario, which offers the same results as the concordance LCDM model at large scales, and also new vistas for galaxy formation that seem to be in accord with actual observations. If realistic, this model would give more than a simple answer to a major puzzle of current Cosmology. It would make us think of a largely predicted (by our super-theories) simple spin-0, long range interaction of prime influence in the evolution of the universe.

Last but not least, there may be a connection between the dark matter scalar field and the inflaton field. Such a connection was explored in Ref. 24 within the braneworld scenario for the second Randall–Sundrum model. Though the predicted inflationary quantities (spectral index, the amplitude of primordial gravitational waves) are at variance with observations, the idea is compelling: could a dark matter scalar field be the only responsible for the *whole* process of structure formation in the universe, from primordial perturbations to galaxies? The answer could be yes.

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