Review Article

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Use of scalar fields in physics and cosmology

Abstract

In this paper we discuss briefly the use of scalar fields in Physics and in several research areas, such as Condensed Matter and Cosmology. The versatility of the scalar fields has made them prominent in the contemporary scientific scenario, leading them to be used in the formulation of the Higgs field theory, in the theories of cosmic inflation and of dark energy and in the study of topological defects.

Keywords: Scalar Fields, Condensed Matter, Cosmology, Higgs field, cosmic inflation, Dark Energy.

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MAM Souza

Instituto Federal do Piauí, Brasil

Correspondence: MAM Souza, Instituto Federal do Piauí, 64211-145, Parnaíba, Piauí, Brasil, Email msouz@ifpi.edu.br

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Introduction

In general, we can say that a field is a physical entity that has a real or complex existence, and can have a scalar, vector and tensor nature; it permeates space-time, associating each point with a physical quantity, allowing interaction between particles. The tensor is the generalization of a scalar and a vector, that is, a tensor field (or a tensor itself) associates a scalar and/or a vector with each point in space.). Tensor fields are widely used in general relativity (Riemann curvature tensor) and in the study of stresses and deformations in materials. That's why gauge bosons are the result of the quantization of fundamental fields (quantizing means dividing into discrete parts).

Vector fields associate only one vector with each point in space, such as the electric (**E**), magnetic (**B**) fields and the velocity field in a fluid (**v**). These fields can be obtained using scalar field gradients. In particle physics, bosons with spin 1 are called vector bosons, due to the fact that they originate from vector fields, such as the photon, which mediates the electromagnetic interaction between protons and electrons; the $W^{\pm}$ e Z^0, bosons, which mediate the weak interaction associated with leptons such as neutrinos, electrons and positrons, and the gluon, which mediates the strong force between quarks. Bosons with spin 2 are tensor because they originate from tensor fields, and are widely used in the construction of quantum theories for gravitation, such as the graviton. Bosons with spin 0 are scalars, as they come from scalar fields such as the Higgs boson, see Table 1, where the masses have units in GeV/c^2.

Table 1 Elementary bosons

Name	Symbol	Mass	Spin	Discovery
Photon	γ	0	1	1905
Gluon	g	0	1	1978
Charged bosons	$W^{\pm}$	80	1	1983
Neutral boson	Z^0	91	1	1983
Graviton	G	0	2	-
Higgs boson	H	126	0	2012

Scalar fields can be defined as a function of the position of a point in space, regardless of the adopted coordinate system, whether the coordinates are defined in Euclidean space or in Minkowski space time. They are described as a zero-order tensor, which is why they are relativistic invariant, having the same value when measured by different observers in separate frames of reference. In classical physics, they are commonly used to represent temperature distribution in a medium or the pressure field in a fluid. They are also associated with the potential energy of a field of forces, such as gravitational potential or electrical potential in electrostatics. In high energy physics, scalar fields can still be real or complex. The Higgs field, for example, is represented by a complex scalar field, whereas in Cosmology and Condensed Matter it is more common to use real scalar fields. In field theory, a real scalar field is defined as a real function of the four-vector $\chi^{\mu}=(t,r)$ in Minkowski space time, that is $\phi=\phi(\chi^{\mu})$. Complex scalar fields are also used to represent charged particles that decay through weak interaction, such as mesons. In particle physics, the Higgs field, whose vacuum state is constant with a value equal to 246 GeV, acquires its own mass from the mechanism of spontaneous vacuum symmetry breaking,[1,2] as illustrated in Figure 1, in which we have represented the potential of a scalar field ϕ, where the minimum of the potential represents the vacuum state. In general, we can say that a system is symmetric if it does not change its characteristics and/or properties when faced with changes in the parameters that describe it. In field theory, we say that a theory described by a Lagrangian density $\mathcal{L}(\phi)$, where ϕ represents a scalar field, is symmetric if it becomes invariant to the transformation $\mathcal{L}(\phi)\rightarrow\mathcal{L}(-\phi)$ the vacuum state is degenerate and the possible states transform into one another at the expense of this symmetry. The Lagrangian is the difference between the kinetic and potential energy of a system, and is also called the Lagrange function.

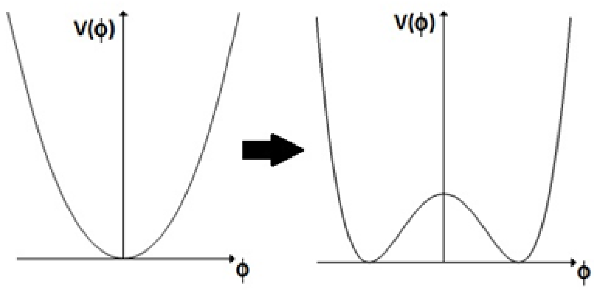

Figure 1 Representation of the spontaneous vacuum symmetry breaking mechanism for a scalar field.

In Physics, the most important application of symmetry is in Noether's theorem,[3] which establishes that for each continuous symmetry in a physical system there is a corresponding conservation law. Thus, it can be shown that the conservation of linear momentum is associated with the translational symmetry or parity of the system. Energy conservation is associated with temporal uniformity and the conservation of electrical charge with gauge symmetry, among others. A system's symmetry is broken when the changes made to it modify its structure, leading to the appearance of distinct phases. In field theory, one of the symmetry breaking mechanisms of great interest is the one that promotes the generation of mass for the field.

In the left graph in Figure 1, we clearly see that the lowest energy state is at the origin; In the second graph, where the symmetry was broken, we have two vacuum states where the field acquires mass, that is, the lowest energy state is no longer null, the existence of a non-zero vacuum state also spontaneously breaks the symmetry of electroweak interaction gauge; This mechanism generates mass for the Z^0, W^+ and W^- gauge bosons, which mediate this interaction.

Next, we will present a brief approach to the use of scalar fields in a limited number of phenomena observed in the 20th century, going through continuous elastic systems in condensed matter, up to the dynamics of the Universe in cosmological theories. These topics were chosen due to their indisputable historical importance and because they are at the forefront of research in the field of Physics. The dynamics of scalar fields is obtained through a non-trivial formalism, where its entire description is associated with the laws of conservation and symmetries and the formalism of quantum field theory, in addition to the fact that many of the proposed theoretical models are structured on a basis experimental and some still have their proof pending.

In section 2 we will discuss how the scalar field can be used to describe the structure of topological defects in Condensed Matter systems, or even in Cosmology; in section 3, we will study the dynamics of scalar fields in the context of the cosmic acceleration of the Universe, and final considerations will be made in section 4.

Topological defects

The symmetry breaking principle for scalar fields has numerous applications. In condensed matter, in continuous elastic media, when the fields that describe the ordering of the structure of materials have their symmetry broken by external agents, topological defects appear.[4,5] A mathematical definition for a defect would be to say that it is a solution, with finite energy, of a non-linear differential equation; from a physical point of view, a topological defect is the transition region between different phases of a system. Symmetry breaking gives rise to a non-trivial set of degenerate states (states with the same energy value), such as magnetic dipoles in the domains of a ferromagnetic material. The study of topological defects earned the 2016 Nobel Prize in Physics for researchers David Thouless, Duncan Haldane and Michael Kosterlitz.

In the low temperature regime, the quantization of magnetic flux in superconductors, such as superfluid helium, generates the appearance of defects, called vortices.[5] Superfluidity is a state of quantum nature where a liquid at low temperatures (≈ 2,2 K for liquid helium) flows without viscosity. The study of liquid helium earned physicist Lev Davidovich Landau (1908-1968) the Nobel Prize in Physics. In the macroscopic world, vortices represent the rotating flow of a fluid in the form of a spiral due to a difference in pressure and can be observed in various natural phenomena, such as tornadoes, the induced drag produced by the tips of an airplane's wings, or when we spin a liquid inside a container, such as a bucket.

At low temperatures, in some materials, the spin vortices couple together to form pairs; at high temperatures, a topological phase transition occurs and the vortices have individual behavior. Topological defects also appear in cosmology, in the form of magnetic monopoles, introduced by Gerardus 't Hooft[6] and Alexander Polyakov, or cosmic strings, proposed by Holger Nielsen and Poul Olesen,[7,8] which are defects associated with the phase transition process of the early Universe, when its temperature decreased to a critical value $T_c = 10^{28}$ K, leading to the spontaneous breaking of symmetry associated with a scalar field and generating these exotic objects , being created up to 10^{-35} s after the Big Bang.

Magnetic monopoles are objects that have a magnetic charge, something similar to the representation of a single pole of a magnet, and are the result of breaking spherical symmetry; they are extremely massive, making them difficult to detect. Cosmic strings are objects represented by one-dimensional lines that extend throughout the Universe, and are linked to the breaking of axial symmetry.

We also have unstable topological defects, called textures, related to a break in non-Abelian global symmetry. A non-Abelian group is formed by non-commutative elements, where the relation $a * b \neq b * a$, is valid, with a and b being elements of a group $G = \{a, b, c, ...\}$. Textures are the result of the phase transition process, during the cosmic expansion of the Universe, in distinct regions of the cosmic fabric that were out of causal contact, which is why they are associated with the fluctuation in temperature, measured today, of the cosmic microwave background radiation (CMB), and which can be observed through light (hot) and dark (cold) spots in the CMB spectrum. In 1961, Tony Skyrme (1922-1987) presented the first three-dimensional topological defect arising from nonlinear field theory, a topological soliton called skyrmion,[8] widely used in spintronics, a technology that uses spintronic quantum bits (qubits), assigning states of spins up (↑) or down (↓) the modulation of information, similar to the 0 and 1 of the conventional binary system.

Skyrmions can be seen as a result of the quantum superposition of baryons and resonance states verified in the study of excitations in elementary particles, whose energy added to the particle's energy states completes the observed spectrum. It is considered a soliton, as it can be studied as a non-linear concentrated wave pulse that propagates without losing its original shape, that is, it has low dispersion. Solitons are used to describe the propagation of light pulses inside optical fibers. The simplest study of topological defects is carried out in (1 + 1) dimension, that is in a temporal dimension and a spatial dimension, and uses the ϕ^4 [9] in the natural system of units given by:

$$V(\phi) = 1/2(1-\phi^2)^2 \tag{1}$$

where ϕ represents a real scalar field. In the natural system of units, measurement units are defined in terms of fundamental physical constants using expressions in which some of these constants are normalized, that is, they have a unit value. We can cite as an example Planck's units, which use $c = 1$, $G = 1$, $k_B = 1$, $e = \sqrt{\alpha}$, $1/4\pi\epsilon_0 = 1$ and $\hbar = 1$, where respectively we have the speed of light in a vacuum, the constant gravity, the Boltzmann constant, the elementary charge as a function of the fine structure constant α, the Coulomb force constant and the reduced Planck constant. If we consider the standard dynamics, described by the Lagrangian density:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi), \tag{2}$$

the equation of motion for the stationary case has the form:

$$\frac{d^2\phi}{dx^2} = \phi(\phi^2 - 1), \tag{3}$$

using the quadrature method to solve the equation of motion we have:

$$\frac{d\phi}{dx}\frac{d^2\phi}{dx^2} = \frac{d\phi}{dx}\frac{dV}{d\phi} \rightarrow \frac{d}{dx}\left(\frac{1}{2}\left(\frac{d\phi}{dx}\right)^2\right) = \frac{d}{dx}V(\phi) \tag{4}$$

Integrating, we obtain:

$$\frac{d\phi}{dx} = \pm\sqrt{2V(\phi) + C}, \tag{5}$$

which are two first order differential equations, where C is a constant of integration. Remembering that as we are working with real scalar fields, V(ϕ) must be positive defined for ϕ to be real. Making the constant C equal to zero, separating the variables and integrating, we obtain the static solutions $\phi = \pm\tanh(x)$. Imposing the constant C to be zero is actually ensuring that the energy of the solutions is finite, since the presence of this constant in the energy density would result in the divergence of the integral used to determine the value of the energy. This type of defect is an accurate representation of the phase transition process, as can be seen in Figure 2.

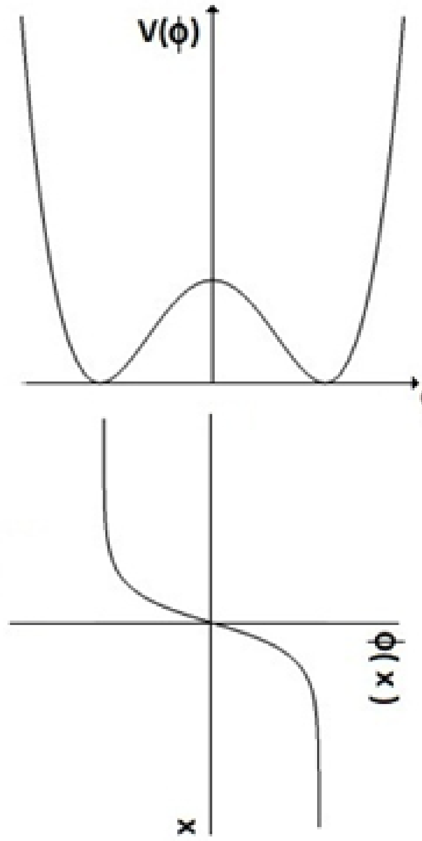

Figure 2 Representation of a kink-type topological defect.

The solution with a positive sign is called kink, while the solution with a negative sign is called antikink. These solutions are topological because they have different asymptotic limits; they connect the different minima of the potential, which are also trivial solutions, $\phi_{\pm} = \pm 1$, with zero energy. More analytically, these solutions will be considered topological if the topological current $j_T^{\mu} = \frac{1}{2}\varepsilon^{\mu\nu}\partial_{\nu}\phi$ generates a topological charge

Q = (1/2)(ϕ (x → ∞) − ϕ (x → −∞)) ≠ 0 , still satisfying the boundary conditions $\lim_{x\to-\infty}\phi(x) = \phi_i$ e $\lim_{x\to-\infty} d\phi/dx = 0$, where ϕ_i are minima of the potential. These limits must be obeyed to ensure that the energy of the system is finite. In fact, we are imposing conditions on the energy density of the model, so that at the extremes of integration the energy density is zero.

The energy of a given field configuration is the result of the integration of energy density throughout space, in 1+1 dimensions we have:

$$E = \int_{-\infty}^{\infty} T^{00} dx = \int_{-\infty}^{\infty} \rho(x) dx = \int_{-\infty}^{\infty} \left[\frac{1}{2}\left(\frac{d\phi}{dx}\right)^2 + V(\phi) \right] dx \quad (6)$$

with T^{00} being the component of the energy-stress tensor given by:

$$T^{\mu\nu} = \frac{\partial \mathcal{L}}{\partial(\partial_{\mu}\phi)}\partial_{\nu}\phi - g_{\mu\nu}\mathcal{L}. \quad (7)$$

When kinks are immersed in two or more dimensions, they are called domain walls and their energies are transformed into energy densities. The energy density of kink is $\rho(x) = sech^4(x)$. An alternative method to investigate the presence of topological defects in scalar field models consists of identifying solutions called BPS (Bogomol'nyi-Prasad-Sommerfield).[10,11] BPS solutions are defined by two minimum energy states and identify the topological sectors of the model. The method was proposed by E. B. Bogomol'nyi in 1976, although in 1975 M. K. Prasad and C. M. Sommerfield had already published a work on the subject. More information can be found at.[12]

Cosmic inflation and dark energy

The standard cosmological model, known as the Big Bang, states that the Universe, at some point, at the beginning of its formation, was in an extreme state of high temperature and density, forming the plasma of quarks and gluons, composed of dissociated elementary particles, as well as free electrons.[13,14] As the Universe expanded rapidly, the temperature decreased and primordial nucleosynthesis began; in this way, the quarks began to interact, forming protons and neutrons, which later linked together, forming simple nuclei (deuterons), with the emission of cosmic microwave background radiation occurring at this stage. When temperatures below the electrons' binding energy were reached, they began to be captured by deuterons, forming a more complex structure, which we know as an atom. As the expansion continued, the first stars were formed and later the formation of galaxies and planets, as illustrated in Figure 3. Today it is known that most of the known chemical elements were synthesized in the interior of stars, where larger nuclei can be formed by the nuclear fusion of hydrogen, under appropriate conditions of temperature and pressure, where the kinetic energy of the reaction nuclei must be large to enable the increased probability of penetration through the Coulomb barrier; this process occurs in very light nuclei, at a temperature of the order of 10^7 K, with the atoms being completely ionized.[15]

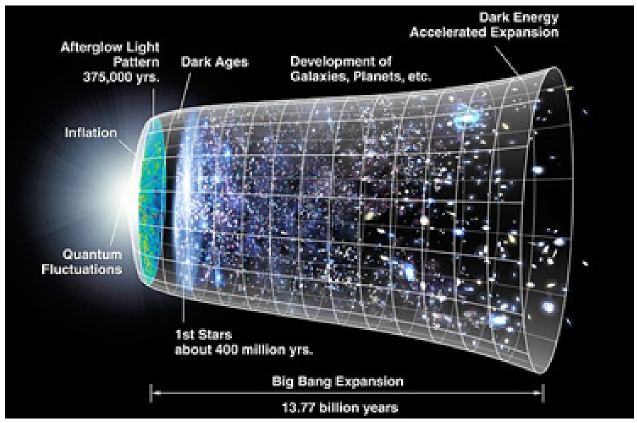

Figure 3 Evolution process of the Universe.

Some of the most modern aspects of cosmology use the scalar field to explain the accelerated expansion of the Universe in its initial phase,[16-18] or even in quintessence models,[19-22] which describes dark energy through the dynamics of scalar fields to elucidate the current phase of expansion. The standard cosmological model successfully explains some of the main observed properties of our Universe, but unfortunately it still leaves many problems unsolved, such as the process of formation of large-scale structures, that is, the formation of stars, planets, galaxies, etc, magnetic monopoles, in addition to the anisotropies observed by the WMAP satellite (Wilkinson Microwave Anisotropy Probe) in the cosmic microwave background radiation (CMB).

CMB is electromagnetic radiation in the microwave range originating from the primordial Universe, when the first ionized nuclei were formed. Its accidental discovery in 1965, by Arno Penzias and Robert Wilson, was one of the greatest pieces of evidence in favor of the Big-Bang theory.[23] It is currently estimated that its average temperature is 2,725 K, its frequency is 160,4 GHz and that its spectrum is identical to that of a black body. The most viable solution to solving these problems is presented in the context of the theory of cosmic inflation, proposed by Alan Guth, in which a scalar field, called an inflation, would be responsible for the evolution of the primordial Universe in a very short period of intense accelerated expansion.[16] Therefore, considering a phase of accelerated expansion governed by a scalar field also guarantees the existence of in homogeneities in the Universe, which would explain the formation of structures, causing the Universe to begin to slow down at a given moment, therefore leading to a phase of evolution dominated by non-relativistic matter. In quantitative terms, considering a flat Universe, for an inflationary regime governed by the dynamics of a scalar field ϕ , where $V = V(\phi)$ is the potential associated with the inflation field, we have the Einstein-Hilbert Action for gravitation in the form:

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}R+\mathcal{L}(\phi,X)\right) \tag{8}$$

where R is the curvature scalar, $\mathcal{L}(\phi,X)$ is the Lagrangian of the model and $X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$ the kinetic term. For a flat Universe we have the Friedmann-Robertson-Walker metric given by:

$$ds^2 = dt^2 - a^2(t)\left(dx^2+dy^2+dz^2\right), \tag{9}$$

where t is time, x, y and z are spatial coordinates and a(t) is the scale factor. Using equations (8) and (9) we obtain the equations of motion:

$$H^2 = \frac{2}{3}\rho, \tag{10}$$

$$\frac{\ddot{a}}{a} = -\frac{1}{3}(\rho+3p) \tag{11}$$

we have that $H = \dot{a}/a$, with H being the Hubble parameter and $\dot{a}$ the derivative of the scale factor in relation to time t. If we consider the standard dynamics, described by the Lagrangian density:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) \tag{12}$$

the continuity equation can be written as:

$$\ddot{\phi}+3H\dot{\phi}+V_\phi = 0 \ , \tag{13}$$

where $V_\phi = dV/d\phi$. Using the Noether's theorem one can prove that the energy-stress tensor of scalar field can be computed as:

$$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - V(\phi)\right), \tag{14}$$

Considering the field only as a function of time and using the equation (14), the energy density and pressure responsible for acceleration are given by:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V \ , \quad p = \frac{1}{2}\dot{\phi}^2 - V \tag{15}$$

Where we have the sum of a kinetic term and a potential term. The kinetic term $\dot{\phi} = d\phi/dt$ represents the temporal rate of variation of the field. Interesting results appear when we consider that the scalar field varies very slowly, that is, inflation occurs when the scalar field is "slowly rolling" over its potential, as illustrated in Figure 4, in a regime called slow-roll, so that with a good approximation the kinetic term is supplanted by the potential and we obtain $\rho \approx V$ and $p \approx -V$, resulting in $\rho \approx -p$, that is, the energy density of the scalar field generates a negative pressure, causing a rapid expansion of the primordial Universe.

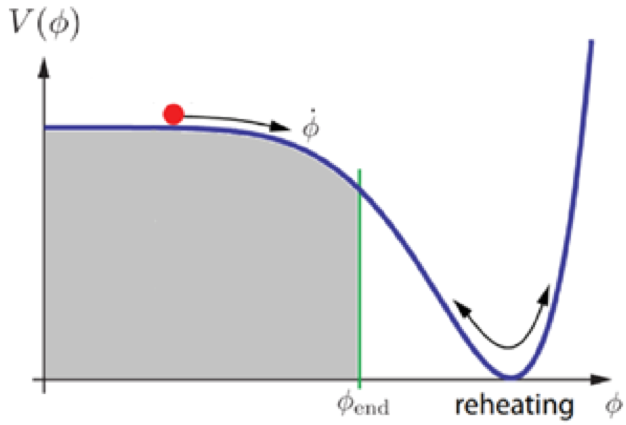

Figure 4 Slow-roll regime. The shaded region is where inflation occurs, the field "rolls" slowly towards the minimum potential, ϕ_{end} is the value of the field at the end of inflation.

Using equations (15) we can still rewrite equations (10) and (11) and obtain the results as a function of the inflation field:

$$H^2 = \frac{1}{3}\dot{\phi}^2 + \frac{2}{3}V, \tag{16}$$

$$\dot{H} = -\dot{\phi}^2 \tag{17}$$

In fact, in this approximation, the inflation field does not vary very quickly and we can neglect the kinetic term to obtain the first order equations:

$$H^2 = \frac{2}{3}V(\phi), \tag{18}$$

$$3H\dot{\phi}+V_\phi = 0 \ . \tag{19}$$

These equations show us that the choice of potential allows us to apply limits to inflationary parameters. The number N of e-folds is written as $N = \ln(a_{end}\backslash a)$, where a_{end} is the scale factor at the end of inflation and can be obtained through the expression:

$$a = a_0 exp\left(\int_{t_i}^{t_f}\left(\frac{2}{3}V(\phi)\right)^{1/2}dt\right), \tag{20}$$

or equivalently:

$$N = \int_{t}^{t_{end}} Hdt \tag{21}$$

The behavior of the scale factor in the inflationary regime can be seen in Figure 5. The e-fold number is used to quantify how long the inflationary period must be in order to solve the Hot Big-Bang problems (usually N □ 40 − 70). Furthermore, the parameters of the slow-roll regime can be found in,[24,25] and are given by:

$$\grave{o} = \frac{1}{4}\left(\frac{V_\phi}{V}\right)^2 \ e \quad \eta = \frac{1}{2}\frac{V_{\phi\phi}}{V} \tag{22}$$

To establish the flatness condition, the expressions above must obey the restriction $|\grave{o}| << 1$ and $|\eta| << 1$. Therefore, we can see that all parameters are sensitive to the choice of potential. In one of the best-known inflation models, the field dynamics are governed by a quadratic potential of the type $V(\phi) = V_0\phi^2$, some applications can be found in.[26]

As the field ϕ "rolls" towards the minimum potential $V(\phi)$, inflation ends, and it is natural to assume that at the end of inflation $\epsilon = 1$.[27] This period can be seen in Fig. 4, where the inflation begins to gain kinetic energy and the potential energy term $V(\phi)$ ceases to be dominant. If the potential has a local minimum, the field will stop rolling and will begin to oscillate around this minimum, with this oscillation being gradually ceased by the friction term $3H\phi$ in the equation of motion (13).[28] At a given moment, this field will be stationary at the minimum of the potential, but if this minimum value is $V_{min} > 0$ then the potential returns to dominate the kinetic energy and inflation occurs indefinitely. However, if $V_{min} = 0$ cosmological inflation will no longer exist and the dynamics of the Universe will be dictated by other existing fields.

The fact that the scalar field is coupled to other fields causes the inflaton to decay into pairs of elementary particles during the oscillatory phase, in a process called *reheating*.[29] As a consequence, the energy of the scalar field would be transferred to the particles and these particles, through mutual interaction, would occasionally decay, giving rise to ordinary matter and radiation in thermal equilibrium, promoting the initial conditions necessary for the evolution of the Universe in accordance with the standard cosmological model. In the current context of the dynamics of the Universe, observational data from Astronomy, obtained through the study of type Ia supernovae, led a group of scientists to announce that the Universe had gone through not one, but two phases of cosmic acceleration; the second, by the way, would be happening right now. A supernova is a collapsed star, that is, it may be one of the final stages of a star that has already consumed all its nuclear fuel and can no longer win its fight against gravitational contraction. As a result, we have a huge explosion, which ejects a significant amount of energy into the interstellar medium.

Type Ia supernovae come from the explosions of white dwarfs with a mass lower than the Chandrasekhar limit, which is necessary for an explosion: around 1.38 solar masses. However, in binary systems a unique phenomenon can occur, where a white dwarf merges with its companion, increasing its mass and collapsing, ending in a supernova explosion. A white dwarf is the final stage of a star with up to 10 solar masses. In their evolutionary process, such stars will transform into red giants, ejecting their outer layers and becoming planetary nebulae, with a dense core made up of carbon and oxygen, remaining in balance with gravity through the forces of degeneracy between electrons originated by the Pauli Exclusion Principle.

The cosmological constant (Λ) is an element that opposes gravitational attraction, analogous to the energy density of the vacuum, having been initially used by Albert Einstein (1879-1955) to describe a stationary Universe in 1917. In 1929, with the discovery the separation of galaxies by astronomer Edwin Hubble (1889-1953) and the emergence of the Big-Bang theory by George Gamow (1904-1968) in 1948, its use was abandoned. However, with the evidence of the new phase of cosmic acceleration of the Universe, some theories once again used the cosmological constant, so that it began to play the role of a repulsive term responsible for the acceleration.

In addition to the use of type Ia Supernovas, there are three more techniques used by astronomers to study dark energy, they are:

1) Baryon acoustic oscillations (BAOs): based on the emission of mechanical waves, such as a sound wave, due to the difference between the forces of gravitational attraction and the radiation pressure in the inhomogeneous primordial Universe, producing oscillations in the fluid formed by photons and baryons. As dark matter only interacts gravitationally, it practically does not propagate. The acoustic horizon, which is the distance traveled by this acoustic wave until the baryons stop (decoupling of matter and radiation), is printed in the CMB as a primary anisotropy, and also appears as a small excess density in the distribution of baryons in a scale that can be observed in the correlation functions of galaxies, Ly-α, forest, among others.[31]

2) Weak lensing: gravitational lensing is a phenomenon that occurs due to a distortion in space-time caused by the presence of an extremely massive body between an object and an observer, causing deviations in the paths of the observed light rays. They are evidence in favor of dark matter, since some lenses are created by celestial bodies that apparently do not emit electromagnetic radiation. These deviations can be measured statistically by mapping the positions of objects such as galaxies, which have a tendency to align with the lens, in an effect known as *shear*. Because it depends on the mass of both baryons and dark matter, *shear* is a very promising experimental astronomy tool for the study of dark energy, using gravitational lens tomography for this purpose.[32]

In an attempt to explain this new phase of accelerated expansion, the existence of a new form of energy that does not interact with light, called dark energy, was proposed, which would encompass just under three-quarters of the contents of the Universe, as shown in Figure 6. Some theories use the dynamics of a scalar field to describe dark energy; this field would be spread homogeneously and isotropically throughout the Universe, with a non-stationary energy density and would exert a negative pressure, that is, it would act contrary to the gravitational attraction of the matter content of the Universe, according to Eqs. (15). It is an alternative to the Λ - CDM (Cold Dark Matter) model, which places the cosmological constant as a candidate for dark energy.[22,30]

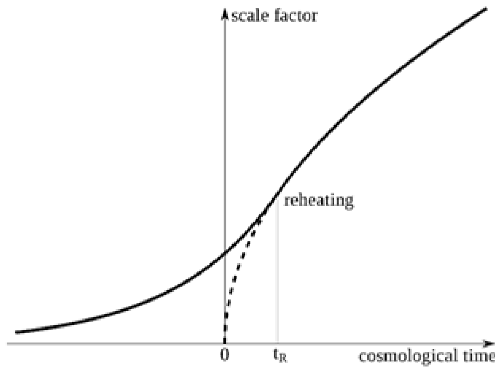

Figure 5 Graph of the FRWL scale factor during inflation ($a \sim e^t$) and radiation -dominated expansion ($a \sim t^{1/2}$). The dotted line shows the beginning of the expansion in a traditional non-inflationary Big-Bang model.

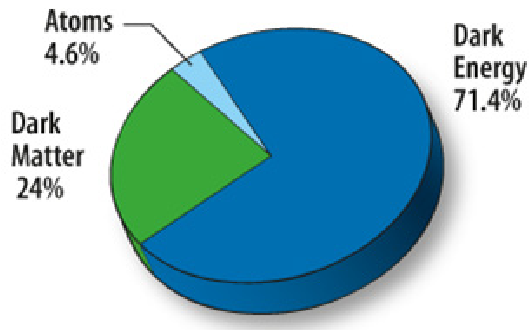

Figure 6 Composition of the observable Universe.

3) Cluster counting: It is based on the mass function, which allows us to know the growth rate, distribution and quantity of matter in the Universe. This function is obtained by cataloging groups and clusters of galaxies, which have their masses estimated by indirect experimental techniques such as, for example, measuring the temperature of the intracluster gas through X-ray measurements. The method is subject to many statistical variables and to study dark energy, a count of order 10^5 clusters is necessary.

Since mid-2009, there have been several observational Cosmology Projects with high financial investment, which aim to study Dark Energy, highlighting the instruments: BOSS (Baryon Oscillation Spectroscopic Survey), DES (Dark Energy Survey), J-PAS (Javalambre Physics of the Accelerating Universe Survey), WFMOS (Wide-Field Multi-Object Spectrograph), DESI (Dark Energy Spectroscopic Instrument), LSST(Large Synoptic Survey Telescope) and Euclid/JDEM (Joint Dark Energy Mission), the latter, a project by the European Space Operations Center (ESOC), can be seen in the Figure 7.

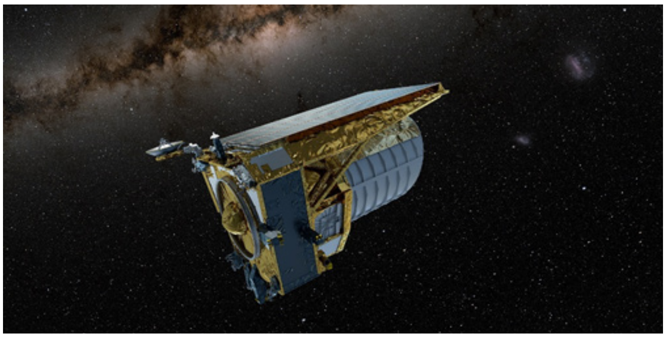

Figure 7 Artistic conception of the Space telescope Euclid. The objective of the Euclid mission is to better understand dark energy and dark matter by accurately measuring the accelerating expansion of the universe. The mission launched on July 1, 2023.

Final considerations

It is peculiar to observe that such complex aspects of nature can be explained by the dynamics of the simplest field we know, the scalar field. In the study of topological defects in condensed matter systems, scalar fields are already well established, providing accurate results proven directly by experimental methods, and having wide acceptance in the scientific community. On the other hand, although scalar fields have produced results in agreement with astronomical observational data, they have never been observed experimentally, not even through indirect measurement and quantification techniques. In the search for understanding the Universe, many phenomena remain open to explanation; only with time, the improvement of instruments and the development of new space exploration technologies will we be able to confirm whether our conjectures regarding the dynamics and constitution of the Cosmos are true or false.

Acknowledgment

None

Conflicts of Interests

None

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