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THE CHALLENGE OF RELATIVISTIC COSMOLOGY TO DESCRIBE THE UNIVERSE

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1. Introduction

The search for a theory capable of describing the origin, the evolution and the structure of the universe is a long-standing issue in astrophysics. Numerous challenges are still open today. Indeed, despite the availability of ever more accurate cosmological observations, a comprehensive theory that suitably frames all our knowledge about the universe has not been entirely developed thus far.

Astrophysical and cosmological phenomena are driven by gravitation. Hence, the final aim of cosmology is to develop a suitable theory of gravitation. The typical spatial, temporal and energetic scales of astrophysics and cosmology span many orders of magnitude. Consider, for instance, the orbital motion of a satellite around the Earth, of a planet around the Sun, of a star around the galactic center, of a galaxy cluster evolving through the expanding universe: in each case we are dealing with gravity-driven phenomena, but they take place at very different scales, that is, they belong to different *gravitational regimes*. The generally adopted approach in cosmological investigations entails to focus on a given gravitational regime, framing it in an optimized (sometimes *ad-hoc*) theoretical framework, imposing more or less tight specific assumptions. Indeed, it should be noted that, independently of the specific theoretical framework, the equations describing the dynamics of complex astrophysical systems cannot be solved analytically in most cases, demanding a numerical and therefore approximated solution. This implies the adoption of a number of assumptions and simplifications of the original problem, in order to facilitate the solution and reduce the computing time. Such a *focused* approach allows to reach a very good agreement between theory and observations at that given gravitational regime, but it is typically problematic to extrapolate the same theoretical framework to other gravitational regimes. Thus, different gravitational regimes are described at best by different – and, as we shall see, even conflicting – theoretical frameworks.

The main challenges of cosmology arise from the inaccessibility of the phenomena and processes under study and from the impossibility to reproduce them in a laboratory, making the extensive use of simulations mandatory. Simulations are a powerful tool to investigate cosmological phenomena. In fact, usually theoretical models[1] can be compared with observations, more precisely, with *data models*,[2] only by means of *computer simulations*.[3] This comparison allows to identify, in principle, whether models are plausible or should be discarded.[4] A typical situation that can arise is the following. Consider the issue of checking the suitability of a model describing the evolution of the primordial universe, that is, a set of processes which cannot be directly accessed by experiment. After selecting a given theoretical model describing the initial phases of the universe, a simulation based on the model allows to compute the observational effects that the model would forecast for the today universe. The simulation output can then be directly compared with the actually observed data as a check for the reliability of the model.

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[1] By theoretical model I mean a non-concrete interpreted structure, characterizing the phenomenon under study in terms of parameters [Weisberg 2013, chap. 3].

[2] Data models, or data sets, are the result of the processing of the so-called *raw data* by means of suitable algorithms. There is a wide philosophical literature on data models and their role in scientific modeling [cf., e.g., Suppes 1962; Leonelli 2019; Bokulich 2020; Bokulich and Parker 2021].

[3] A computational system is said to simulate a theoretical model if it can be characterized in terms of parameters, whose values depend one from the other according to the relations which characterize the theoretical model [Datteri and Schiaffonati 2019, 119-120].

[4] For a detailed analysis of modeling practices in astrophysics and cosmology see, e.g., Castellani & Schettino [2022].

While observations should in principle allow to discriminate between models, it can actually be found that two different, eventually conflicting, theoretical models could both be able to provide a fitting description of the same cosmological phenomenon or process. Such a situation is usually called *under-determination problem*, simply meaning that observations do not allow to clearly discriminate between different theoretical scenarios [cf., e.g., Butterfield 2014; Stanford 2021]. This is a pressing topic in the contemporary debate in philosophy of cosmology. Much of the scientific community is confident that the under-determination problem in cosmology, being an issue related to the present-day experimental and technological limitations, could, at least partially, be solved in the future. A more philosophical perspective raises the question whether, alternatively, the under-determination problem enlightens a more general issue concerning the validity and reliability of the physical principles and methodologies adopted for cosmological investigation.[5]

With the aim of providing a general framework for the present debate in cosmology and its implications in philosophy of cosmology, this paper reviews the cornerstones of relativistic cosmology, pointing out their merit and shortcomings, and describes the main alternative theoretical proposals which should frame our knowledge of the universe. The paper ends with some considerations on how philosophy of cosmology can contribute to the cosmological investigations.

2. Relativistic cosmology

At present, the best available theory of gravitation is the theory of general relativity, proposed by Albert Einstein in 1916, which imposes a completely different view of gravitation with respect to the past. Newton's theory of gravitation, the theory embraced up to the beginning of XXth century, describes gravity as a force produced by a mass, with a strength decreasing as the inverse of the square distance, affecting the motion of the surrounding bodies and acting instantaneously.

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[5] A general discussion on the issues faced by philosophy of cosmology can be found, e.g., in Smeenk [2013]; Ellis [2017].

This viewpoint is in keeping with our common sense. Fully breaking with tradition, Einstein proposed an original interpretation of gravity: gravitational phenomena are the result of the geometrical properties of a four-dimensional spacetime, that is, gravity should be intended as the geometry of spacetime [Einstein 1916]. In general relativity, the presence of a mass ensures that spacetime, otherwise flat, curves, affecting consequently the trajectories of the surrounding bodies. The change of the spacetime geometry due to the presence of a mass can be seen as its gravitational effect on the other bodies.

The theory of general relativity, apparently conflicting with our common sense, was quickly accepted thanks to an impressive series of experimental confirmations. Already before 1920, Einstein himself computed two renowned predictions of the theory, confirmed by observations shortly afterwards. They are generally referred to as *classical tests of general relativity in the solar system*: (1) the measurement of the deflection of light due to a massive body; (2) the measurement of the advance of the perihelion of Mercury. These two remarkable predictions of the theory are still confirmed nowadays with the advent of increasingly precise astronomical observations. After these initial experimental successes, no further astronomical tests of the theory have been performed between the 1920s and the beginning of the 1960s. This long period of stagnation was mainly due to the limits of the experimental and technological capabilities of that epoch. Later, with the discovery of quasars (1963), pulsars (1967) and cosmic microwave background (1964), the interest in experimental gravitation started to grow again and has recently received a further considerable push by the development of precise cosmology.[6]

The huge success of general relativity in accounting for astrophysical phenomena at *approachable* scales (in particular, at the solar system scale) stimulated a natural trend to extrapolate the theory to less accessible scales, that is, to cosmological (galactic and extra-galactic) scales. These attempts led up to the development of the standard model of cosmology, known as ΛCDM model (see Section 2.2), which accounts for galactic and extra-galactic dynamics on the basis of general relativity at the

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[6] Consider, for example, the recent detection of gravitational waves, already predicted by Einstein's general relativity.

expenses of postulating the existence of the new physics of the so-called *dark sector* (dark matter and dark energy). The challenges of framing our knowledge of the universe and its evolution within the framework of general relativity has fostered the proposal of a number of alternative theories of gravitation. From an experimental point of view, this trend led to an extended attempt to find direct and indirect independent evidences to confirm or confute general relativity and its competing theories.

The reasons leading to bring into question, at least partially, the validity of general relativity arise from two different arguments. In the first instance, the incompleteness of general relativity in its classical formulation is generally recognized. Indeed, this fact is mainly motivated by its inconsistency with the other noteworthy physical theory formulated in the last century, that is, quantum mechanics (for a discussion on this topic see, e.g., Wigner 1997; Padmanabhan 2002). Beside the theoretical problem of the formulation of a unified physical theory capable of accounting for all the fundamental interactions (usually referred as the *theory of everything*), general relativity has to face a more phenomenological challenge, which has become one of the hot topics in astrophysics and particle physics: the universe is assumed to be permeated by a large amount of dark matter and dark energy in order to match theory and observations, but these dark components have not been directly detected yet. As a consequence, a number of alternative theories have been developed, with the purpose of accounting for the available cosmological observations without resorting to a dark sector. In the following, we shall overlook the issues related to quantum gravity, focusing instead on the challenges of general relativity as the theory of gravitation at large and very large scales, where quantum phenomena can be completely neglected.

2.1. Classical tests of relativity in the solar system

In the following, we shall briefly describe the two classical tests of relativity, i.e., the measurements of the deflection of light and of the advance of the perihelion of Mercury. In these cases, we are dealing with two predictions of the theory which have been already confirmed a few years after 1916.

In the first case, let us consider a photon approaching the Sun from a great distance. General relativity envisages that the presence of the Sun curves the surrounding spacetime in such a way that the path of a passing-by photon is deviated from the straight line (that it would follow otherwise). Writing the relativistic equation of motion of the photon, it is possible to calculate the deflection angle between the actual path of the photon and the straight path. The deflection angle is a function of different quantities and, in particular, it depends on the mass of the Sun and on the impact parameter, that is, the minimal distance between the photon and the Sun.[7] Then, the theoretical prediction for the solar deflection can be checked against the observed deflection, which can be obtained for a given star by comparing its apparent position in proximity of the Sun during an eclipse (epoch of maximum deflection) with the position measured six months earlier, when the apparent position of the star is very far from the Sun and is not affected by any deflection. In 1919 Eddington observed the deflection phenomenon for the first time and, although at that time the measurement precision was limited, he confirmed the theoretical prediction with an accuracy around 30%. The observed deflection could not be explained otherwise by Newtonian theory [cf., e.g., Will 2015]. By means of more recent experiments employing different observational techniques, and, in particular, with the advent of radio interferometry, it has become possible to measure the deflection of light at the level of one part in 10-4.[8]

The second test concerns the estimate of the advance of Mercury's perihelion. In 1882 Newcomb computed a discrepancy of 43 arcseconds per century between the observed precession of the planet and the one computed from Newtonian theory. In general, due to the perturbative effect of the other bodies, the node line of a planet orbiting around the Sun undergoes a precession by an angle $\Delta\omega$ at every revolution, that is, its orbit deviates from a closed ellipse by an angle $\Delta\omega$. This effect occurs for each planet of the solar system, but it is particularly pronounced in the case of Mercury, the nearest planet to the Sun. General relativity

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[7] The mathematical details can be found in most textbooks on general relativity [cf., e.g., Weinberg 1972, 188-194].

[8] Cf., e.g., Will 2014, 42-44, for a review of the results concerning deflection from 1919 to present.

accounts exactly for the observed discrepancy of 43 arcseconds per century. Recent measurements confirm this prediction with an accuracy better than one part in 10^{-4}.[9]

2.2. The ΛCDM model and its challenges

In general relativity, the geometrical properties of spacetime (in particular, its curvature) are linked to the density of matter and energy through the Einstein field equation, a system of ten non-linear coupled equations.[10]

Starting from the field equation, in 1922 Friedman derived for the first time two equations, known as Friedman equations, which govern the evolution of the universe, providing also an estimate of the global expansion rate. In this framework, it turns out that the universe can be only expanding or contracting, while the possibility of a static universe is discarded by the theory. In particular, for a universe dominated by ordinary (that is, baryonic) matter, the equations inexorably forecast a decelerated expansion of the universe. Contrarily, at the end of last century it has been experimentally confirmed that the present universe undergoes a phase of accelerated expansion. Hence, this finding cannot be properly accounted for in a relativistic framework as long as the universe is assumed to be composed totally or mainly of ordinary matter.[11]

Actually, the challenge of cosmology as the science of the universe as a whole is that of providing a consistent portrait of the universe on very large scales (that is, on inaccessible scales) which should at the same time be consistent with all the hints suggested by observations. The best description of all we presently know about the universe is provided by the standard model of cosmology, also known as the ΛCDM

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[9] A review of the main recent results can be found in, e.g., Will 2014, 46-47.

[10] This system can be solved analytically only in very special cases, while it is necessary to resort to numerical methods in the general case, allowing only for approximate solutions.

[11] The main observational confirmation of the accelerated expansion of the present-day universe has been provided at the end of last century by means of the observation and comparison of the luminosity emitted by high redshift type Ia supernovae.

(Λ Cold Dark Matter) model, first proposed by Ostriker and Steindhardt in 1995. The main assumptions of the model are the following [cf., e.g., Perivolaropoulos & Skara 2021, 2-5]:

- gravitational interactions at cosmological scales are described by general relativity;
- the so-called cosmological principle holds: on average the universe is homogeneous and isotropic, as long as large enough scales are considered, that is, scales larger than 100 Mpc;[12]
- the universe is made up of three distinct components: (1) radiation (photons and neutrinos); (2) matter, in the form of ordinary (i.e., baryonic) matter and of non-relativistic (i.e., cold) dark matter; (3) dark energy, an exotic form of energy described by an unusual state equation,[13] which is responsible of the accelerated expansion of the universe and whose behavior can be equivalently described in terms of a cosmological constant, Λ;
- the general spacetime metric is described by the flat Friedman-Robertson-Walker (FRW) metric;
- to explain the present state of the universe, a primordial, very short phase of rapidly accelerated expansion is assumed, known as inflation epoch.

The ΛCDM model accounts, in particular, for two intriguing observational challenges: the issue of the accelerated expansion of the present universe and the so-called «problem of the missing mass». The first issue is figured out by assuming that the main part (about 70%) of the matter-energy density content of the universe is made of dark energy. The second issue concerns the observational fact that the total mass content interacting gravitationally in the universe turns out to be significantly greater than the total content of observed luminous (i.e., ordinary) matter. The ΛCDM model accounts for this issue by assuming that the remaining 30% of matter-energy density content of the universe is made of matter, whereof 25% is in the form of cold dark matter and the remaining 5% in the form of baryonic matter.

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[12] 1 parsec (pc) roughly corresponds to $3.09 \cdot 10^{13}$ km.

[13] For dark energy it holds that $\rho \sim -P$, where ρ and P are dark energy density and pressure, respectively.

One of the main strengths of the ΛCDM account is its relatively simple formulation, since it is the simplest model obeying the Freedman equations beside showing a great predictive power. Indeed, most of the observed properties of the universe at extra-galactic scales are accurately explained by the model, including: the distribution of large scales structures, the spectrum and the statistical properties of the cosmic microwave background, the observed abundances of light nuclei (Hydrogen, Helium, …).[14]

Furthermore, the ΛCDM model sets off at the confluence between astrophysics and particle physics; indeed, it would be the properties of dark matter particles that determine the fundamental properties of the structures in the universe. This fact fostered a strong interest in the searching of direct evidences of dark matter particles, supported by dedicated experiments at particle colliders.[15]

3. Relativity at a crossroad

Although the ΛCDM model has reached an outstanding experimental success, giving at present the best available description of the dynamics at cosmological scales, it exhibits anyway a number of drawbacks, continuously pressing with the advent of increasingly accurate cosmological observations. The drawbacks of ΛCDM are essentially twofold:

- Drawbacks of theoretical nature: the model assumes that the most part of the universe consists, in fact, of a dark sector, made by dark matter and dark energy. These two components are introduced in order to tune theory (that is, general relativity) with observations, while their properties and their direct detection are still under examination.
- Drawbacks of phenomenological nature: while the ΛCDM model accurately reproduces the extra-galactic dynamics, that is,

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[14] For a comprehensive review of the ΛCDM successes see, e.g., Bambi & Dolgov 2016; Ferreira 2019, 24-35; Ishak 2019, 20-38.

[15] A review on the state-of-the-art search for dark matter particles can be found, e.g., in Schumann 2019.

> dynamics at the level of galaxy clusters and beyond, giving a convincing picture of the evolution of the universe, the comparison between theory and observations becomes more problematic at the so-called intermediate scales, that is, when considering the dynamics within a single galaxy.

This situation has made room for intense debates and speculations, resulting in a number of alternative proposals to the ΛCDM model. One of the key points of the debate concerns, in particular, the issue of the legitimacy to extrapolate the theory of general relativity to inaccessible scales and, thus, to adopt it as the theory of the universe as a whole.

As it will be shown shortly, in questioning the adoption of general relativity two different paths can be followed. One possibility is to modify and/or extend the ΛCDM model to account for puzzling observational evidences, still accepting the main ΛCDM assumptions and thus remaining within a relativistic framework. The other possibility is to abandon general relativity in its entirety to formulate a new theory of gravitation, based on different physical principles. The first approach is, thus, aimed at overcoming the phenomenological drawbacks of the ΛCDM model, though accepting its overall description of the universe, in particular the existence of a dark sector. The second approach, instead, seeks to overcome the phenomenological drawbacks as a consequence of a radical review of the theory, that is, with the attempt to overcome its theoretical drawbacks as well.

Independently of the selected approach, an adequate theory of gravitation, being it a revision of general relativity or a totally competing proposal, needs to be compliant with the following conditions [cf., e.g., Capozziello & De Laurentis 2011, 7]:

- it must reproduce the Newtonian dynamics in the low-energy regime;
- it must pass the classical solar system tests, with a level of accuracy at least comparable with general relativity;
- it must account for the observed behavior of galaxies;
- it must be able to reproduce the dynamics of large structures

and the main cosmological observations (as the expansion rate of the universe and the observed abundances of elements).

The main alternative proposals to the ΛCDM model will be briefly reviewed in Sections 3.1 and 3.2. Then, in Section 3.3, we shall consider an illustrative case: how a very well known issue, that of explaining the observed rotation curves of spiral galaxies, can be framed within these different descriptions of gravitation.[16]

3.1. Extensions of relativity

A possible approach to overcome some of the drawbacks of the ΛCDM model is to extend the theory of general relativity, which is at the base of the model. In this case, we deal with what are usually called *extended theories of gravity*. General relativity can be modified in two ways. The first possibility is to explicitly change the structure of the Einstein field equation. An example is the case of teleparallel gravity, where spacetime curvature is replaced by spacetime torsion (inhibited in general relativity) as the mechanism by which geometric deformation produces gravitational interaction [cf., e.g., Bahamonde *et al.* 2021].

Another possibility is to preserve the formal structure of the Einstein field equation, i.e., that of the Friedman equations, and rather modify:

a) the content of the right-hand side of the field equation, in order to embed further contributions to the matter-energy density tensor;
b) or the content of the metric tensor at the left-hand side of the field equation, including additional scalar or tensor fields other than the metric itself.

Examples are scalar-tensor theories, where the metric tensor is reformulated in order to include the effects of an additional scalar field as well [cf., e.g., Fujii & Maeda 2003], and vector-tensor theories, where

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[16] Note that, from a historical perspective, the systematic observations of the rotation curves of galaxies have been one of the main evidences that led to the formulation of dark matter.

the additional dynamical field is a time-like quadrivector. The most known formulation of scalar-tensor theories is the Brans-Dicke theory, proposed in 1961 [Brans & Dicke 1961]. An example of vector-tensor theories is the Einstein-Aether theory [cf., e.g., Jacobson 2008].

Independently of the adopted approach, each extended theory aims at reproducing at the same level of accuracy the processes that the ΛCDM model already adequately explains and at improving the performances of the model for the aspects where ΛCDM is inadequate.

3.2. Alternative theories of gravitation

To overcome the theoretical and phenomenological drawbacks of the ΛCDM model, a different approach can be followed by rejecting relativistic cosmology in favor of an alternative theory of gravitation capable of explaining the structure and evolution of the universe resorting to different physical principles. Of course, due to the outstanding experimental success of relativistic cosmology, only a limited part of the scientific community has faced with this approach. A suitable alternative theory of gravitation, capable of achieving the same predictive success of relativity at different scales, has not been formulated yet. Indeed, a comprehensive theory of gravitation needs to account simultaneously for the observable present-day universe but also to provide a convincing picture of its origin and evolution over time. Most of the attempts proposed up to now are mainly focused on reproducing phenomenologically the observations that relativistic cosmology struggles to frame properly.

The most successful alternative to general relativity is represented by MOND (MOdified Newtonian Dynamics) theory, first introduced by Milgrom in 1983 to account for the phenomenology of galaxies [Milgrom 1983]. In general, within a single galaxy, the motion of stars around the galactic bulk is slow and the weak-field quasi-static limit can be adopted.[17] By applying Newtonian mechanics, it can be deduced that

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[17] This means that it is not necessary to resort to a relativistic description of the dynamics, since the velocities coming into play are significantly lower than the speed of light and the spacetime can be considered locally flat.

the total mass content of a galaxy, obeying to the Newton's universal law of gravity, cannot be limited to the observed ordinary matter alone (otherwise theory's predictions would disagree with observations). The ΛCDM model and its extensions solve this issue by assuming that a significant dark matter content should be added, with a distribution extending well beyond the visible boundaries of individual galaxies (see also next section).

The basic idea of MOND theory is that the apparent discrepancy between visible matter and gravitational matter can be explained, in fact, as the result of the break of Newton's gravitational law at the level of galaxies rather than by postulating a new kind of matter. By introducing a new universal constant, the scale-acceleration $a_0=10^{-8}$ cm/s^2, MOND theory predicts that for accelerations much greater than a_0 Newton's law holds, that is, the true gravitational acceleration g equals the Newtonian one, g_N, while in the opposite case (called MOND regime) the gravitational law is suitably modified, the true gravitational acceleration being $g = (g_N\, a_0)^{½}$. This behavior is summarized by the empirical Milgrom's law [cf., e.g., Milgrom 1983]. Within the MOND framework, different models can be formulated, depending on the kind of modification adopted for the gravitational law: examples are the Bekenstein-Milgrom MOND [Bekenstein & Milgrom 1984] or the QUMOND theory [Milgrom 2010].

Although these theories provide very accurate predictions of galactic dynamics, they are based on a physical law (i.e., Milgrom's law) which is purely heuristic, that is, it cannot be derived by any universal principle. As a consequence, these proposals are basically toy models.[18] Although typical accelerations in the solar system can be significantly higher than a_0, MOND should produce detectable effects also at the solar system level. Hence, it could be possible, in principle, to test MOND-based theories also by means of solar system observations. There have been made some attempts in this sense, with the aim of identifying possible observational evidences in favor of the MOND approach [cf., e.g., Magueijo & Bekenstein 1983; Iorio 2008; Blanchet & Novak 2011].

Note that the MOND framework and the ΛCDM framework reach

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[18] A general discussion on this topic can be found, e.g., in Famaey & McGaugh 2012, 42-43.

their most predictive success at different gravitational regimes, at galactic scales and at extra-galactic scales, respectively. This fact has driven the development of hybrid models to frame the best of the two theories in a common theoretical scenario. These attempts are generally referred to as *relativistic MOND*: MOND, thus, becomes an extension of relativistic cosmology and its approximation in the weak-field limit [cf., e.g., Famaey & McGaugh 2012, 87-99]. Some examples are the scalar-tensor k-essence theories [cf., e.g., Armendariz-Picon *et al.* 2001] and the TeVeS (Tensor-Vector-Scalar) theory [Bekenstein 2004].

3.3. An example: interpreting the rotation curve of spiral galaxies

The observational fact that there is a discrepancy between luminous (i.e., observable) and dynamical (i.e., gravitational) mass of cosmological objects is known since the 1930s, with the observations made by Zwicky, Oort and Babcok.[19] The main observational evidence of the discrepancy was obtained later on, starting from the 1970s, by the systematic study of the rotation curves of spiral galaxies [Freeman 1970]. The rotation curve measures the rotational velocity of the matter content of a galaxy as a function of the distance from the galactic bulk and it is typically deduced from radio spectroscopical observations.[20]

From the virial theorem a simple expression for the rotational velocity as a function of the change of the distance r from the galactic bulk can be derived as

$$v_{rot} = \sqrt{\frac{GM(r)}{r}},$$

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[19] An historical perspective on the discovery of dark matter can be found in van der Bergh 1999.

[20] Rotation curves are mainly deduced by the analysis of the profile of the 21-cm line of neutral Hydrogen (HI – 21 cm). In fact, the Doppler shift of the central wavelength of the line emitted by this element depends on the relative velocity of the emitting cloud with respect to the observer. Due to the abundance of Hydrogen in the universe, the Doppler shift of the HI – 21 cm emission line can be easily observed in the regions surrounding the edges of a visible galaxy. This is the most effective method to derive the rotational velocity of matter.

where $M(r)$ is the matter content within a disk of radius r and G is the gravitational constant. It follows that the rotational velocity should initially increase with the distance, as the matter content increases, and then it should decrease with the inverse of the squared distance, for values of r beyond the visible edges of the galaxy. What actually happens is that the rotational velocity, instead of decreasing, remains flat well beyond the visible edges of the galaxy and this is a common feature of spiral galaxies.[21]

There are two, not mutually exclusive, ways to account for the observed discrepancy: either there is a significant quantity of matter that is not luminous but gravitationally interacting, or the gravitational law needs to be revised when considering the slow motion of bodies within a single galaxy. The ΛCDM model and its extensions embrace the first option. The equation for the rotational velocity shows that a constant, or flat, rotational velocity implies that the mass content within r, that is, $M(r)$, is proportional to r itself. Accordingly, each galaxy is surrounded by dark matter, with mass density proportional to r^{-2}.[22] In principle, dark matter can arrange in different ways inside and/or around galaxies [cf., e.g., Van Albada & Sancisi 1986]. The ΛCDM model assumes that dark matter arranges along a halo extending far beyond the visible edge of galaxies: dark matter is located in an extended spherical shell, well separated by the internal bulge of baryonic matter. Other possible models can assume different distributions of matter: for example, ordinary and dark matter can coexist within a common disk of matter, which becomes progressively darker as drifting apart the galactic bulge. Anyway, a common drawback of any attempt to model dark matter distribution lies in some level of inconsistency with observations, frequently resulting in the addition of *ad-hoc* constraints [cf., e.g., Sanders 1990].

Alternatively, we have seen that the observed mass discrepancy in

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[21] Systematic observations of rotation curves have been made on extended sets of galaxies, both spiral and not, and such behavior has been observed routinely [cf., e.g., Bergström 2000; Sofue 2017].

[22] If the mass content within a distance r, $M(r)$, is proportional to r, i.e., $M(r) \propto r$, since the mass density ρ is defined as $\rho = M / V$ (with V the volume), it follows that for a spherical shell with radius r (such that $V = 4/3\pi r^3$) it holds that $\rho(r) \propto r^{-2}$.

galaxies could be explained by assuming that the physics at galactic scales undergoes a modification, as in the MOND framework. In this case, the Milgrom's law holds, entailing that in the MOND regime (that is, for accelerations much smaller than a_0, as within a single galaxy) the rotational velocity remains constant with increasing distance.[23] Furthermore, the MOND framework provides a natural and simple account (differently from the ΛCDM model) for other phenomenological facts as the baryonic Tully-Fisher relation and the relation between mass discrepancy and radial velocity in galaxies (known with the acronym MDAR).[24]

As already noted, although MOND is extremely powerful in describing galactic dynamics, it is difficult to extrapolate the theory to extra-galactic scales, where the reliability of the ΛCDM model is remarkable. This fact supports the prospect of a relativistic MOND theory. An interesting proposal in this direction has been suggested by Berehziani and Khoury with a theory of dark matter superfluidity, assuming that dark matter particles behave, at low temperatures, as a superfluid instead of a system of individual non-collisional particles [Berehziani & Koury 2015].[25]

4. Final remarks

What has been said so far shows that, as of today, the phenomena that occur around the universe can be accounted for by means of different, even conflicting, theoretical scenarios, which turn out to be, anyway, equally plausible if compared with the observations. Of course, two

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[23] This fact follows immediately from the definition of the true gravitational acceleration.

[24] From a philosophical perspective, a detailed discussion on how these observational facts can be framed within MOND and ΛCDM has been recently proposed by M. Massimi [Massimi 2018].

[25] Superfluidity can be defined as the ability of a fluid to flow without apparent friction, that is, the special property of having null viscosity. As a consequence, a superfluid flows without loss of kinetic energy. Superfluidity has been directly observed in Helium isotopes and in ultra-cold atomic gases and it is conjectured to occur in astrophysical systems, as neutron stars.

mutually exclusive theoretical descriptions cannot be true at the same time; nevertheless, cosmology is permeated, likely by its very nature, by a strong interpretative ambiguity. In general, observational cosmology faces with two peculiar limitations [Ellis 2014, 23-24]:

- the uniqueness of the universe, making unfeasible the comparison with similar objects;
- the fact that we observe an extremely extended universe from a single possible point of view in space and time, that is, the Earth as of today.

As a consequence, the intensive use of simulations has become mandatory in cosmology, as they are an unavoidable tool for the cosmological inquiry. In many cases it is really impossible to get observational or experimental data. Consider, for example, the study of the origin of the universe, usually depicted as the «Big Bang epoch»: information on past epochs can only be extrapolated by observing the present-day universe, but no direct access is allowed. In such situations, simulations become the only tool of inquiry. This fact sets, however, some questioning concerning the trustworthiness of the inferences deduced from simulations and also concerning the relationship between simulations and experiments.[26]

Over the history of modern science, each proposed theory has been acknowledged as an adequate description only when providing an agreement, to some extent, with experimental data, and this requirement has also stimulated the development of new, more fitting, theories. In this respect, experimental cosmology has directed a great deal of effort in designing and assembling increasingly innovative instrumentation, to provide increasingly accurate observations capable of finally discriminating between competing theoretical scenarios. A

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[26] Bayesan inference approach can help, in some cases, in discriminating between competing models. This approach consists in computing the posterior probability of a given model as a conditional probability given the available observations. By means of the posterior probabilities, different models can be, in principle, quantitatively compared. The main *caveat* of such an approach lies in assigning the prior probabilities, based on a set of assumptions.

necessary condition for a scientific theory to be defined as such is to provide quantitative predictions that can be tested and confirmed later on. Being the future cosmological observations capable of solving the present theoretical ambiguity or not, the point is that, at present, the cosmological inquiry is no doubt limited by the lack of conclusive data. Therefore, the adoption of simulations becomes mandatory. Consider as another example the issue of formation of structures (galaxies, galaxy clusters) in the universe. The ΛCDM model provides a description for the evolution of structures, where dark matter and dark energy play a fundamental role. A *direct* test of the model in such respect is unfeasible, since we can only access the universe from our viewpoint (the Earth) at the present epoch, while the evolution of structures takes place over cosmological times. On the other hand, we expect that past events act causally on the present ones, that is, the distribution of structures in the present-day universe needs to be the result of the past dynamics. Hence, a possibility is to simulate the evolution of structures in the universe as depicted by the ΛCDM model in order to establish the distribution that they would take if observed today from the Earth. The *simulated observations* of the distribution of today structures, according to the ΛCDM model, can be directly compared later on with the *actual observations* of the distribution of structures collected with astronomical instrumentation. In this way simulations can act as a link between theory and observations which could not be otherwise directly compared.

The issue of the epistemic and inferential role of simulations is a hot topic in philosophy of science. Different theses have been proposed concerning the kind of evidence provided by simulations, their epistemic role in supporting scientific activity and their connection with experiments.[27] Many authors argued in favor of the inferential and epistemic power of simulations to various extents [cf., e.g., Beisbart 2012, 2018; Lusk 2016; Boge 2020; Parker 2020], suggesting as well that simulations could be viewed themselves as experiments [cf., e.g., Barberousse *et al.* 2009; Morrison 2009; Parker 2009]. Within this intriguing debate, cosmology finds a totally peculiar place, precisely

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[27] A general discussion on the use of simulations in science can be found in the textbook by E. Winsberg [Winsberg 2010].

because in many cases direct observation or direct comparison with the data turns out to be unfeasible, leaving simulations as the only tool to infer information. Part of the contemporary debate in philosophy of cosmology is, thus, devoted to the exploration of the role of simulations in this peculiar context. For example, M. Jacquart argues in favor of the epistemic role of simulations in astrophysics, underlining how simulations can account for three key roles in astrophysical reasoning: testing hypotheses, exploring the space of possibilities and amplifying observations [Jacquart 2020]. In this sense, simulations can provide genuinely new knowledge. Furthermore, M. Gueguen points out that simulations are an essential tool for the specific issue of matter distribution within galaxies and, hence, a powerful tool to investigate the properties of dark matter [Gueguen 2020].

Given the crucial role of simulations in evaluating cosmological models, it is necessary to establish proper reliability criteria. The usual criterion for trustworthiness in science is robustness:[28] the basic idea is that a simulation is said to be robust if the outcome does not change for small variations of a set of key assumptions [cf., e.g., Woodward 2006; Weisberg 2013, chap. 9].[29] In cosmology this kind of analysis is typically performed as an analysis of convergence, that is, by varying systematically some key parameters of the model within a given range, carrying on a statistical analysis of the convergence of simulations. The question is if robustness, or convergence, alone is a sufficient criterion to evaluate the reliability of a set of simulations. M. Gueguen argues that robustness itself is not a sufficient criterion, since in cosmological simulations it happens that numerical artifacts induce convergence, leading to a misrepresented outcome [Gueguen 2020]. Similar conclusion, that is, that the criterion of convergence is necessary but not sufficient for the reliability of a simulation, is argued by G. Smeenk and S.C. Gallagher, who propose some additional criteria of trustworthiness [Smeenk & Gallagher 2020].[30]

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[28] This criterion is extensively adopted, for example, in biology and in climate science.

[29] The phrasing *robustness analysis* is adopted through the philosophical literature with slightly different meanings depending on the context as extensively discussed in Lisciandra 2017.

[30] The introduction of additional criteria of trustworthiness could help in evaluating

In conclusion, contemporary cosmological inquiry turns out to be a very peculiar discipline. Indeed, cosmology aims at studying phenomena and processes which are often inaccessible, resulting in the lack of a direct comparison with observations and conclusions need to be drawn by extrapolating our knowledge to unexplorable spatial, temporal and energy scales. Consequently, simulation, rather than experiment, becomes the fundamental tool of inquiry. Indeed, the hypothesized theoretical scenarios can be compared with the available observations only through simulations. Given a theoretical model for the evolution of the universe, simulations allow to extrapolate the predictions of that scenario for the part of the universe that we can observe today, enabling in such a way the comparison between theory and observations. Within the present-day debate on experimental cosmology, philosophy of cosmology can provide a relevant contribution to the discussion concerning, in particular, the investigation on the kind of inferences that simulations can supply.

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the reliability of numerical simulations in the possible case that the model itself is not robust with respect to small parameter changes (e.g., highly non-linear models with chaotic behavior), no matter how reliable the simulation methods might be.

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Keywords

relativistic cosmology; general relativity; alternative theories of gravitation; philosophy of cosmology

Abstract

The search for a theory capable of describing the origin, the evolution and the structure of the universe is a long-standing issue. Recently, experimental cosmology has reached an astonishing accuracy. Nevertheless, a comprehensive theory of the universe has not been entirely formulated and developed thus far.

Cosmology as an experimental science has to face unique challenges, due to the inaccessibility of the phenomena and processes under study and to the impossibility to reproduce them in a laboratory. These limits entail an extensive use of computer simulations, which become a fundamental tool of investigation, allowing to confront theoretical models and observations. This background arouses an intriguing philosophical debate concerning the inferential power of simulations in cosmology and their epistemic role.

This paper reviews the cornerstones of relativistic cosmology and of the main alternative proposals to relativity and proposes some considerations on the contribution that philosophy of cosmology can provide to the contemporary debate in cosmology.

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