The Application of Popperian Methodology to Contemporary Cosmology

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1. Introduction

The scientific methodology developed by Karl Popper has been highly influential not only among philosophers of science but among practicing scientists themselves. Contemporary cosmology is not an exception. As Helge Kragh notes in his contribution to this volume, prominent cosmologists and other physicists have appealed to Popper's falsifiability criterion in an effort to combat what they consider to be unscientific approaches to doing physics.[1] Others have expressed disapproval of the idea that rigid rules devised by philosophers could restrict the activity of a scientific research community.

Ironically, none of the cosmologists appealing to Popper's methodological views have publicly indicated an awareness of the fact that many standard aspects of contemporary cosmology, i.e. not only the more suspect elements such as the multiverse hypothesis or string theory, were explicitly condemned by Popper who, in 1994, described himself "a disgusted opponent" of the Big Bang theory (ibid.).

[1] In addition to the examples listed by Kragh, see Ellis and Silk (2014).

In this chapter, I will examine whether Popper's scathing remarks about the methodology of cosmology could be moderated by the increasingly accepting attitude toward "metaphysical," i.e. non-testable, ideas in science, which appear especially in his later writings. Are there untestable ideas in cosmology that even a Popperian should be able to tolerate and what kind of problems they are meant to solve?

According to Popper (1983: 161), problem-situations in science are usually due to three factors:

Factor 1) "*the discovery of an inconsistency within the ruling theory"*

Factor 2) *"the discovery of an inconsistency between theory and experiment - the experimental falsification of the theory"*

Factor 3) *"the relation between the theory and what may be called the 'metaphysical research programme'"*

I will examine how the problem-situations are exemplified in contemporary cosmology. My discussion will mainly focus on instances of factors 2 and 3. I will deal with these in reverse order, first considering, in section 2, the notion of *metaphysical research programs* (MRPs). In section 3 I will describe the currently untestable ideas in contemporary cosmology and discuss whether at least some of them could be considered to collectively constitute a MRP. In particular, I will focus on the *Cosmological Principle* as a fundamental assumption of the Friedmann–Lemaître–Robertson–Walker family of models.

I will then consider the problem-situation related to the hypothetical *dark matter* both from the perspective of Factor 2 and Factor 3. This is because it is an auxiliary hypothesis[2], designed to save the standard model of cosmology from being refuted, as well as an example of an untestable, "metaphysical" idea that could be seen to partially constitute a MRP for cosmology.

The conclusion I will draw from these considerations is that theories in cosmology, *when conceived of as the study of the whole universe*, remain on the

[2] Properly speaking, though, dark matter is not one hypothesis but at least five, as Merritt (2020: 14, 155) points out. I will here treat these hypotheses as one for simplicity.

untestable side of the demarcation criterion, and Popper is therefore consistent with his own views in not regarding such theories as scientific. Instead, cosmological models thus conceived, *fit the criteria of a MRP* as described by Popper, and could therefore have at least a heuristic importance for physics. However, cosmology *conceived of more modestly as the study of the largest-scale structures in the observable universe*, has produced testable and even well corroborated theories, which conform very well with Popperian methodology.

Finally, I will show that one does not have to be a Popperian in order to draw similar conclusions about the state of cosmology. I will use other methodological tools, namely Voishvillo's (2003) reformulated, generalized *correspondence principle* and Niiniluoto's (1999) *measures of truthlikeness*, to evaluate two different theories, the standard model of cosmology, ΛCDM[3], and Modified Newtonian Dynamics (MOND)[4], as solutions to the mass discrepancy problem with regard to the internal velocities of the satellite galaxies of the Milky Way. These methodological tools, while not strictly Popperian, are either descendants of his ideas (truthlikeness) or are at least motivated by scientific realism (correspondence principle).

2.1 Metaphysical research programmes

Popper is famously known for holding that the demarcation between scientific theories and non-scientific theories, such as metaphysics and pseudo-science, is determined by their testability, but he did not put pseudo-science and metaphysics (at least not all of it) in the same basket. By 1934, in *Logik der Forschung* (p. , he already held the view that "influential metaphysics" had heuristic importance in scientific theorizing (see Lakatos 1968: 178). Popper's views evolved during the subsequent decades, and in the "Metaphysical Epilogue" of Volume 3 of his

[3] The full name of the model is the Lambda Cold Dark Matter model where the "Lambda" refers to the cosmological constant, or dark energy, and "Cold" to the type of non-baryonic dark matter particles postulated by the model.

[4] MOND is often characterized as a theory of modified gravity, but it is perhaps best described as a research program at the heart of which rests Milgrom's law, which can be interpreted either as a modification of the law of gravitation or inertia. For an outline of MOND, see section 4.1.

Postscript to The Logic of Scientific Discovery (published in 1982), he describes science as almost always being "under the sway of metaphysical–that is, untestable–ideas; ideas which not only determine what problems of explanation we shall choose to attack, but also what kinds of answers we shall consider as fitting or satisfactory or acceptable, and as improvements of, or advances on, earlier answers." (ibid., 161) According to Popper, these ideas are organized into *metaphysical research programmes* (MRPs), which contain "general views of the structure of the world," "general views of the problem situation in physical cosmology," and "together with a view of what the most pressing solutions are, a general idea of what a satisfactory solution of these problems would look like." (ibid.).[5]

Popper goes on to list the ten MRPs that he considers to have been the most important in terms of their influence on physics:

(1) the "Block Universe" of Parmenides
(2) the "Atomism" of Leucippus and Democritus
(3) the "Geometrization" of the Pythagoreans, Plato, Eudoxus, Callippus, and Euclid
(4) the "Essentialism and Potentialism" of Aristotle
(5) the "Renaissance" physics of Copernicus, Bruno, Kepler, Galileo, and Descartes
(6) "The Clockwork Theory of the World" of Hobbes, Descartes, and Boyle
(7) the "Dynamism" of Newton, Leibniz, Kant, and Boscovich
(8) the "Fields of Forces" of Faraday and Maxwell
(9) the "Unified Field Theory" of Riemann, Einstein, and Schrödinger
(10) "The Statistical Interpretation of Quantum Theory" of Born (ibid., 162-4).

He makes the claim that, although the central ideas of these programmes were not (and some are even currently not) testable, they were *criticizable*, as is evidenced by the fact that there was a progression of ideas criticized on theoretical grounds, and replaced by new ideas (ibid., 172). The last two programs (9 and 10) contain ideas that contradict each other and give rise to what Popper calls a "schism in physics":

[5] There are obvious comparisons to be made with Popper's notion of a MRP with Lakatos' *scientific research programmes*. Indeed, Lakatos was greatly indebted to the work of Popper, Agassi and Watkins in this regard (Lakatos 1968: 177-8). Although I cannot pursue that connection here, see section 3.3 for a discussion of some parallel ideas.

“Instead of a problem situation within a research programme, or relative to a research programme” there is “a clash between two research programmes, neither of which seems to be doing its job.” (ibid., 173) Specifically, the schism concerns the *interpretation* of classical physics and of quantum theory. Whereas MRP 9 describes all matter as disturbances or vibrations of geometrized fields, MRP 10 takes an instrumentalist view of those fields, which now represent purely statistical probabilities of finding a particle in a certain state and location (ibid., 164). While classical physics was often interpreted in a determinist, objectivist way, in quantum theory this leads to highly counterintuitive consequences, which have led many to abandon the objective interpretation, or worse, lose interest in interpreting physical theories altogether.

It is safe to say that since the publication of *The Postscript*, this schism has not been resolved. If cosmology is simply understood as a branch of physics, this would seem to preclude the examination of cosmology’s problem-situation in relation to a MRP. However, cosmology, at least when conceived of as the study of the entire universe, differs from other areas of physics in notable ways, due to the uniqueness of its object of study, as well as inherent difficulties in obtaining knowledge about regions of the universe to which we lack observational access. However the schism between MRP 9 and MRP 10 will be resolved, if it is resolved, the cosmological project, as it has been conceived by most of the research community, has required the adoption of several untestable assumptions that guide cosmological research. It is in this sense that cosmology has its own problem-situation in relation to a MRP.

2.2 Popper’s use of the term “metaphysical”

Before further examination of contemporary cosmology in light of the notion of a MRP, some remarks are in order about Popper’s equation of “untestable” with “metaphysical,” which contemporary cosmologists understandably might not welcome as a characterization of their research. Firstly, as Popper himself (1956: 74), notes, this is a technical term in his use[6]. Furthermore, as a scholar of the history of philosophy, Popper was obviously aware of different definitions of metaphysics, and was opposed to essentialist definitions at any rate, since he did not think science and philosophy should be in the business of answering "What is?" type of questions, but instead ought to focus on solving problems (see Ribeiro 2014: 209).

Nevertheless, many philosophers have objected to Popper's conception of metaphysics, recent examples being Akrami (2009) and Ribeiro (2014). Ribeiro argues, over Popper's conception, for what Popper himself calls the traditional way of defining metaphysics as "general theories about the nature of the world." By Popper's definition, theories as different as the germ theory of disease on the one hand, and Plato's Theory of Forms on the other, are all examples of metaphysical or formerly metaphysical theories. In contrast, Ribeiro proposes non-testability as a necessary but not sufficient criterion for a criticizable theory to be considered metaphysical. Metaphysical theories must also be sufficiently *general*. In fact, according to Ribeiro, the non-testability of metaphysical theories *follows* from their high level of generality.[7] Instead, non-general and untestable theories ought to be considered *speculative or proto-science* if they are criticizable, or *pseudo-science* if they are not criticizable.

Ribeiro claims, perhaps plausibly, that Popper was more interested in demarcating science from pseudo-science, and not in demarcating either science or pseudo-science from metaphysics, and thus overlooked the criterion of generality. She points to Popper's own wavering between describing MRPs in physics as being constituted by metaphysical ideas on the hand, and "speculative physics" on the other (Popper 1984: 161-2), as "telling" of the fact that there is a conflation of two types of ideas in Popper's use of the term "metaphysical."

Ribeiro concludes that equating "metaphysical" with "untestable" is simply too confusing. For her, there is no reason, apart from being able to maintain the Popperian demarcation criterion, why we should not prefer the traditional definition

[6] See also Lakatos (1968: 168, n 58)

[7] Although I cannot discuss the point here, it is an interesting question whether this claim is defensible. Certainly, it is not obvious that a highly general theory, such as materialism, *must be* untestable.

of metaphysics, if as Popper himself claims, the boundary between science and metaphysics is blurry anyway.

The terminological disagreement between Popper and Ribeiro need not be resolved here. Firstly, both seem to think there are almost always untestable ideas, of varying levels of generality, in the background of scientific theories, which would make the boundaries between science and proto-science, as well as between science and metaphysics, blurry. Secondly, both seem to think there is progress from the untestable ideas, both general (e.g. atomism) and non-general (e.g. germ theory of disease), to scientific theories. Thirdly, it is not clear to me that the untestable ideas present in contemporary cosmological theories that I am concerned with here are of a sufficiently high level of generality to be metaphysical in the traditional sense. Certainly none of them are sufficiently general, such that their non-testability somehow follows from their generality. I only wish to highlight the possibility of choosing different terminology for those to whom the term "metaphysical" in "metaphysical research programmes" would be upsetting in the context of contemporary cosmology, or for those who object to Popper's conception of metaphysics for other reasons. Although in what follows, I will stick to Popper's terminology, in my view one could equally well switch terminology and call MRPs speculative or proto-scientific research programmes.

3.1 Metaphysical ideas in contemporary cosmology

We are now in a position to examine contemporary cosmology through the prism of Popper's notion of MRPs. Are there untestable principles or ideas in cosmology that "determine what problems of explanation we shall choose to attack, but also what kinds of answers we shall consider as fitting or satisfactory or acceptable, and as improvements of, or advances on, earlier answers"? To ask this is to probe at the foundations of cosmology.

One has to begin from the fact that, at astronomical scales, gravity is the dominant interaction, so a theory of gravity is the starting point of a cosmological model. The field equations of Einstein's general theory of relativity are considered the default choice in this regard.[8] In a classical case of underdetermination, these equations allow for a wide range of possible cosmological models, so assumptions must be added and observational evidence taken into account to restrict the range of possibilities. Perhaps the most important of these assumptions is known as the Cosmological Principle (CP), which, following Jung and Beisbart (2006), I shall define here as the claim that, at any time, the universe is homogeneous[9] at sufficiently large scales.[10]

While Popper was dismissive of the CP (Kragh, this volume, section 2.2), I will propose here that the CP is in fact the main component of what in a Popperian sense constitutes a MRP for cosmology. To clarify this point, I must now provide two contrasting outlines of cosmology as a field of study. Ellis (2006: 1183) defines cosmology as "the study of the large-scale structure of the Universe, where 'the Universe' means all that exists in a physical sense," whereas observational cosmology "aims to determine the large-scale geometry of the observable universe and the distribution of matter in it from observations of radiation emitted by distant objects." Ellis sees observational cosmology as a subdiscipline of cosmology, whereas Beisbart (2009) highlights the possibility of looking at these as two alternative conceptions of the discipline. Cosmology as the study of the universe as a whole is an ambitious project, whereas studying the large-scale structures of the observable universe is a more modest one.

[8] In sections 3.3, 4.1, 4.2 and 4.3 I will look at MOND as an alternative to assuming the universal correctness of general relativity, but only in a limited sense, as it applies to the dark matter hypothesis. The foundations of a Milgromian cosmology would be deserving of a much thorough treatment than I could provide here.

[9] Roughly, homogeneity is uniformity with respect to location. The CP is often thought to include the claim that the universe is isotropic (isotropy is, roughly, uniformity with respect to direction), but the isotropy of the observable universe is testable (and therefore no principle has to be assumed for the claim), and global isotropy follows analytically from global homogeneity and the isotropy of the observable universe (Jung and Beisbart 2006: 252). See Butterfield (2014: 61) for different approaches to defining "sufficiently large scales."

[10] It is common to confuse the CP for another principle, known as the Copernican Principle, according to which our position in the universe is not "privileged" or "special." Jung and Beisbart (ibid.) remark that while isotropy and homogeneity are mathematically defined concepts, "privileged" and "special" have no such unambiguous meaning. They have also shown the logical gap between two principles: the Cosmological Principle implies the Copernican Principle, but not vice versa.

Assuming the CP in the respective contexts of these two projects, i.e. for the observable universe and for the entire universe are two very different things. With regard to the observable universe it is in principle observationally refutable *and* verifiable (since it is not a universal principle), and there is at least considerable evidence in its favor (see for example Lahav 2001, Beisbart 2009, Sarkar et al. 2009, Yang and Saslaw 2011, Maartens 2016). For the entire universe, Popper's skeptical attitude toward the testability of the CP finds representation among contemporary philosophers of cosmology, such as Beisbart (2009) and Butterfield (2014), but this does not contradict my suggestion that it partially constitutes a MRP. To elaborate on this suggestion, I must now look at the motivation for the adoption of the CP and its theoretical and interpretive roles in cosmology.

3.2 The Cosmological Principle as a constituent of a MRP

Since my primary aim here is not to offer a historical account, I will mention only some key developments.[11] In 1917, Einstein adopted the idea of a homogeneous universe for his first cosmological model to satisfy Mach's principle (Torretti 2000: 171), as well as for mathematical convenience.[12] Since then, several other considerations have entered the picture. In the 1920s Alexander Friedmann demonstrated that one can use the CP to build a coordinate system in order to solve Einstein's equations for a dynamical model of an expanding universe. (Ntelis 2018: 2) With evidence of the expansion of the universe taken into account, a class of models known as the Friedmann–Lemaître–Robertson–Walker (FLRW) models became the mathematical basis for realistically describing the observable universe. Butterfield (2014: 61) observes how radical the notion of allowing the geometry and material contents of the universe to change over time was initially, but is now considered one of the main motivations for accepting the CP. Butterfield (ibid.)

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[11] See Kragh (1996) for a historical account.

[12] Convenience undoubtedly still motivates the adoption of the CP, but as Jung and Beisbart (2006: 251) ask, "Why should Nature facilitate our calculations?"

considers the CP a "lucky break" for avoiding underdetermination in cosmology due to its mathematically elegant consequences for the spacetime metric, its mathematical relation to other principles, and the aforementioned fact that there is considerable evidence that it holds with regard to the observable universe.

Returning to the two alternative conceptions of cosmology, we may now say that Popper's harsh criticism of cosmology does not seem to apply to the more modest project of describing the largest observable structures of the universe, at least as far the claims about homogeneity and isotropy go.[13] The difficulties with the CP begin when claims are made about the universe as a whole, since there is no straightforward observational evidence we could appeal to. Here astronomers, cosmologists and philosophers have traditionally relied on some type of "fair sample" hypothesis, according to which the universe as a whole exhibits the same properties as the regions we are able observe. But why should we think this is the case?

Beisbart (2009: 189-201) examines several strategies for justifying this assumption:

One strategy is to argue that it is more likely than not that initial conditions compatible with the observable universe would lead to a universe that obeys the CP globally, but this has not been established, and would be difficult to establish due to there being "no natural measure for initial conditions from which probabilities can be obtained." (Ibid., 193)

A second type of strategy is to argue that models that conform to the CP have greater explanatory power than those that do not. In particular, inflationary cosmology is thought to provide such a model, but this line of thought meets the following difficulties:

1) there are inflationary models that result in a universe in which the observable universe obeys the CP but other regions do not;

2) the purely hypothetical object known as the inflation field is an ad hoc maneuver to prevent the refutation of the standard model, and therefore methodologically suspect (see also Merritt 2020: 39);

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[13] This does not preclude the possibility of criticizing other aspects of cosmology, such as its reliance on the untestable auxiliary hypotheses of inflation, dark matter and dark energy. This is discussed further in section 3.3.

3) too much hangs on the "style" of explanation preferred (Beisbart 2009: 196).

A third strategy is to attempt to generalize from the assumed invariance of physical laws within the universe, to the invariance between physical magnitudes within the universe. It suffices to say that this is a logical leap that would require further argumentation.

A fourth strategy rests on an induction made from the observable universe to regions beyond it, but it is not clear what kind of inductive approach could work here. For example, in a Bayesian approach, there is no way to fix the prior probability of the universe being homogeneous (ibid., 200). While he concludes that no attempt is successful at the moment, he emphasizes that this may change depending on future observations.

From a Popperian standpoint we might ask: why not merely assume as a working hypothesis that the CP holds globally, and attempt to formulate testable consequences of this hypothesis? Jung and Beisbart (2006: 246-7) suggest that the best we can hope for is to check for consistency with other well established theories. However, there are cosmological models that violate the global CP but describe the observable universe realistically (for a review, see Sundell 2016), so this only brings us back to the problem of underdetermination.

I must come to the conclusion that there is no compelling evidence for assuming the CP for the entire universe, and assuming it for the entire universe does not result in unique predictions for the observable universe. However, it has guided cosmology for the past 90 years (Beisbart 2009: 176), provides constraints for initial conditions (ibid., 201) and affects the way light propagation is studied (Jung and Beisbart 2006: 246) (just to mention a few consequences for modeling). An independent result that *would* confirm or refute the CP would, thus, be a significant step forward in cosmology. Taking the assumption of a homogeneous universe to be a constituent of a MRP for cosmology, this is precisely what one would expect:

"By raising the problems of explanation which the theory is designed to solve, the metaphysical research programme makes it possible to judge the success of the theory as an explanation." (Popper 1982: 161)

3.3 The standard model of cosmology (ΛCDM) as a metaphysical research program

I am now in a position to suggest that there is a MRP in cosmology and that the CP is a part of it. But what exactly is that MRP? I have only looked at the CP so far, but other claims about the universe as a whole generally face the same challenges as the CP does, and can hence be characterized as metaphysical in the Popperian sense. Therefore, I tentatively propose that any sufficiently developed and stable[14] cosmological model, when *cosmology is conceived of as the study of the whole universe,* could be considered a MRP. This formulation is vague (what counts as "sufficiently developed and stable"?), but then, Popper does not provide any strict criteria for a MRP, and essentialist definitions are not Popperian in spirit, anyway.

I also say "could be considered," since whether we *should* examine anything through the notion of a MRP depends on whether this is fruitful for understanding the phenomenon in question. I certainly think it *is* useful in the case of some of the untestable features of the standard model of cosmology, ΛCDM, since they are instrumental in defining the problem situation that any theory has in relation to it.

Exactly which features one would include in the MRP depends on how strict the requirement for stability is. Although it is not my primary purpose here to compare Popper's notion of MRPs to Lakatos' (1968) notion of scientific research programs (SRPs), it is worth noting a parallel: Lakatos states that the "hard core" of a SRP can develop slowly in some case, "by a long, preliminary process of trial and error" (Lakatos 1970: 48, note 4; as cited by Merritt 2020: 30). Merritt (ibid., note 10) mentions the hypothetical dark matter in this parallel context: it has been a feature of the standard model for about 40 years and most cosmologists present its existence as a known fact (despite no independent evidence of its existence), so it could be reasonably included in the MRP.

[14] By this I mean stable over time in terms of the ideas it contains. Popper's examples of MRPs contain ideas that in some cases were held for centuries, in some cases less.

The fact that MOND, the main rival of the dark matter hypothesis, is not considered by standard model cosmologists to be an acceptable answer to the so-called problem of missing mass despite its numerous successes also speaks in favor of including dark matter in the MRP, since this points to clear criteria for "what kinds of answers we shall consider as fitting or satisfactory or acceptable, and as improvements of, or advances on, earlier answers." (Popper 1983: 161)[15]

There are several important differences between the CP and the dark matter hypothesis as parts of the MRP. One of these concerns the scope of their (un)testability. The CP is untestable for the entire universe, whereas the dark matter hypothesis is untestable simpliciter. It is perhaps tempting to assume the CP for the whole universe, since it has been confirmed to correctly describe the observable regions. But what makes dark matter so appealing? The typical answer would be that there is no serious alternative, reflecting its aforementioned role in defining the problem situation. Contra this, Merritt (2020) has provided serious considerations in favor of an alternative, known as MOND, from a Popperian-Lakatosian perspective.

Additionally, Merritt (2017) has shown that standard model cosmology has features of what Popper calls conventionalism, i.e. ad hoc stratagems are used to avoid the refutation of the standard model. Over-reliance on these is an indication of a degenerating program, although Merritt refrains from stating whether the program has degenerated beyond hope.

Is the use of ad hoc stratagems problematic, if elements of the standard model are viewed as a MRP? After all, there is no requirement of refutability in metaphysics. I wish to re-state here that Popper's conception of metaphysics does not coincide with his conception of pseudo-science. Although the metaphysical ideas included in the MRP are untestable, Popper sees them as "speculative physics, or perhaps as speculative anticipations of testable physical theories" (Popper 1982: 161). They must therefore be criticizable unlike pseudo-scientific theories, which according

[15] This is not an endorsement of the current situation. While some aspects of Popper's methodology of science, such as the demarcation criterion, are prescriptive, I take his claims about the significance of the MRP to be largely descriptive, and this is how my claims about the MRP in cosmology should also be read.

to their proponents, are constantly verified no matter what.[16] Whether auxiliary hypotheses such as dark matter are genuinely criticizable depends not only on the nature of the hypothesis but the attitudes of the research community. As a worrying example, Merritt (2017: 47) reports how no graduate level cosmology textbooks even mentions the empirical mass discrepancy–acceleration relation (which is commonly thought to hint at the breakdown of Newtonian gravity at low accelerations rather than the presence of undetectable dark matter).

As Kragh (this volume) has documented, not all standard model cosmologists have received the criticism of their colleagues with gratitude, let alone when it is seen to originate from the prescriptions of philosophers such as Popper. As an additional example, de Swart, Bertone and van Dongen (2017: 6) complain that Popperian critiques of standard model cosmology do not capture the rational motivation for accepting the dark matter hypothesis as practically confirmed. Instead their roughly sketched argument amounts to suggesting that we need to better understand the "actual practice and methods of physics, astronomy and cosmology" (ibid.). But this is hardly a good response to someone who is criticizing the *actual practice and methods* of standard model cosmologists, especially when these critics include astrophysicists and cosmologists who understand these practices and methods very well.[17] One day, if their program has already yielded genuine discoveries[18], standard model cosmologists might be in the right to complain about methodological prescriptions - not before.

[16] As an example of what the fruitful interplay of metaphysics and physics can look like, Popper (1982: 165-173) describes how, during the 17th, 18th and 19th centuries, there was genuine progress from MRP 6 ("The Clockwork Theory of the World") to MRP 7 ("Dynamism") and then to MRP 8 ("Fields of Forces") largely on theoretical grounds.

[17] In addition to Merritt's work, see Kroupa (2012) for an astrophysicist's analysis of the repeated falsifications of the standard model.

[18] In the present case, an example of a genuine discovery would be the independent detection of a (class of) dark matter particle(s), and a successful study of its/their properties that would explain the observed Milgromian dynamics at the edges of galaxies.

4. Beyond Popper

In the previous sections, my focus has been on applying Popper's methodology to contemporary cosmology. The considerations in the following sections are not radical departures from Popper's ideas, but are motivated by ideas that are either directly descended from Popper's thought, or at least motivated by a similar critical realist approach to methodology. The motivation behind this is to show that one does not have to be a Popperian to be critical of ΛCDM and take MOND to be a serious rival to it. In order to illustrate this, I will use the methodological tools of *principle of correspondence* and *measures of truthlikeness* to examine these two rivals. 4.1 examines MOND only, whereas 4.2 compares MOND and ΛCDM directly.

4.1 A brief outline of MOND

"In science, problem situations are the result, as a rule, of three factors. One is the discovery of an inconsistency within the ruling theory. ***A second is the discovery of an inconsistency between theory and experiment - the experimental falsification of the theory.*** *The third, and perhaps the most important one, is the relation between the theory and what may be called the 'metaphysical research programme'."*

(Popper 1983: 161; emphasis added)

The Newtonian predictions for the rotational velocities of objects at the edges of galaxies do not match our observations. The two main options for correcting this discrepancy could be the introduction of a hypothetical object or modifying the Newtonian laws.[19] I have already discussed the dark matter hypothesis as an example of a hypothetical object and will now briefly discuss MOND as an alternative solution.

Developed by Mordehai Milgrom in 1983, MOND describes the difference in the dynamics of objects that depends on whether the objects are situated in high-acceleration regimes, such as objects orbiting the Sun in our Solar System, or

[19] See Lazutkina (2017) to see how MOND and dark matter can be compared to other cases in the history of astronomy and physics.

low-acceleration regimes, such as objects at the edge of our galactic disk orbiting the center of our galaxy (Milgrom 1983a, 1983b, 1983c).

High-acceleration regimes are also known as Newtonian regimes, because they were the only ones observed in detail before the work of Zwicky, Rubin, and others that lead to the observations that contradict the prediction, which follows from the conjunction of Newton's second law and Newton's law of gravitation.[20]

By noticing that the contradiction follows from the conjunction of these two laws, Milgrom (2014) suggests that a modification of either is possible. Therefore, the core of MOND, known as Milgrom's law, is not strictly speaking a theory of modified gravity nor modified inertia, but rather accounts for the empirical dependence between acceleration and dynamical behavior in a way that can be interpreted as a modification of either. Milgrom's law thus implies the disjunction of modified gravity and modified inertia, although it is silent on how to construct a full theory of either type.

What, then, counts as a low-acceleration regime (also known as a deep-MOND regime), where the modified dynamics have to be applied for conserving consistency with the observed behavior? Milgrom's law introduces a new constant, critical acceleration – a_0 – ($a_0 \approx 1.2 \times 10^{-10}$ m / s^{-2}). When the acceleration of an object is well above this threshold, it obeys Newtonian dynamics, and when it is well below it, its behavior conforms to the modified dynamics (ibid.). The transition from the Newtonian regime to the deep-MOND regime is described by an interpolating function, μ, which is currently unspecified, yet thought to be quite steep (Famaey and Zhao 2006).

Although MOND requires a relativistic extension as the basis of a realistic cosmological model, it is a research program that has steadily produced unique, novel predictions that have been corroborated or confirmed, as will be exemplified in section 4.3 (see also Merritt 2020: 194 for a summary of MOND's successes). It also passes the methodological test of conforming to the principle of correspondence, as seen in section 4.1. MOND has its problems of course, but they are not necessarily

[20] Strictly speaking one should already speak of modified versions of Newton's laws, because the scope of their application is already constrained by the conditions given by the general theory of relativity, whereas the unmodified, falsified Newtonian laws have no such restrictions.

insurmountable. Recently, the development of a relativistic extension of MOND known as RelMOND was able to solve a long-standing problem for MOND, namely to reproduce the observed Cosmic Microwave Background (CMB) and matter power spectra (Skordis and Złosnik 2020). Achieving empirical adequacy in this regard is especially important for MOND because, so far, only the standard model has been able to do so, and this has been considered a significant advantage of the standard model over MOND.

4.2 The Correspondence Principle and MOND

When the prediction of a theory turns out to be false, and the ad hoc conventionalist stratagems mentioned previously are avoided, the theory is thereby refuted. Whatever new theory is proposed to take the place of the old theory must either agree with the empirically successful parts of the old theory, or if the old theory is completely discarded, there must be an explanation – founded on the new theory – for why the old theory had the limited empirical success it did.

This idea has its origin in a 1913 paper by Niels Bohr, although the term "correspondence principle" (*Korrespondenzprizip*) did not appear in his writings until 1920 (van der Waerden 1967: 7-8).[21] In a more general form, a philosophical formulation of it was given, among others, by I. V. Kuznetsov (1948: 56, translation mine): "Theories whose validity is experimentally established for a particular field of physical phenomena, are not eliminated as something false with the emergence of new more general theories, but retain their significance for the former field of phenomena, as the limiting form and special case of the new theories."

However, as shown by E. K. Voishvillo (2003), there are inaccuracies in this formulation. The old theory is not a special case of the new one, since it turns out to be false (in light of the refuting observation). Instead, a *modified* version of the old theory is a special case of the new theory. The statements of the old theory are

[21] While philosophically opposed to Bohr's other famous principle, i.e. the principle of complementarity, Popper (1963: 101) considered the correspondence principle "extremely fruitful" for scientific research.

reformulated by adding new conditions (in the light of the new one), thereby narrowing the scope of its application, and deleting the implied false part from it. In the relevant fields of theoretical knowledge, the implementation of this procedure is a formal way of testing whether a new proposed theory fits the current scientific picture. Its failure to do so is a formal reason to discard it (ibid.).

I also follow Aliabadi (1996: 9-10, 45-55), who holds that the old theory should merely be a good approximation of the new one in limited cases.

Here, Voishvillo's approach will be applied to MOND in order to demonstrate that the modification of Newton's second law is a special case of the law of the general theory of relativity and at the same time a special case of one of the interpretations of the modification of this law by Milgrom $F = m\mu(a/a_0)a$

As mentioned, Milgrom introduces a new constant, critical acceleration – a_0 – ($a_0 \approx 1{,}2 \text{ x } 10^{-10}$ m / c^2)

. When the acceleration of an object significantly exceeds this threshold, it obeys Newtonian dynamics, and when it is much lower than it, its behavior is accurately described to the MOND. The transition from the Newtonian regime to the MOND mode is described by the interpolating function μ. Thus, the dependence μ(a/a0) is introduced. For large accelerations, the value of this term is 1, i.e. Newton's laws (F = ma) are preserved. For small accelerations, where a is less than a0, we obtain GM / r2 = $\mu(a/a_o)a$. Thus, Newtonian dynamics, with the addition of the condition μ (a / a_o) ≈ 1), becomes a special case of MOND.

According to Newton's second law:

F = d (mv)/dt, i.e. $\forall x \forall v \forall m \forall t \forall f((V(v,x,t) \;\&\; M(m,x) \;\&\; F(f, x, t)) \rightarrow f = d(mv)/dt$

Where *x* is a body, and *f*, *m*, *v*, and *t* are real numbers –the possible values of force, mass, velocity, and time. V (v, x, t) means - the number v is the value of the speed of the body t at the time t, M(m,x) means - m is mass of x, F(f,x,t) means - f is force that acts on body x at moment t.

In MOND: F = $m\mu(a/a_0)a$,[22]

The logical form of the law can be given thus:

$\forall x \forall v \forall m \forall t \forall f((V(v,x,t) \,\&\, M(m,x) \,\&\, F(f, x, t)) \rightarrow F = m\mu(a/ao)a)$

Add the condition D: $\mu\ (a\ /\ a_0) \approx 1$ to consider Newtonian dynamics as a particular case of MOND. From Milgrom's law an expression logically follows with the condition D introduced into the antecedent. Thus, this expression is a special case of Milgrom's law:

$\forall x \forall v \forall m \forall t \forall f((V(v,x,t) \,\&\, M(m,x) \,\&\, F(f, x, t) \,\&\, D) \rightarrow F = m\mu(a/a_0)a)$

This is equivalent to:

$\forall x \forall v \forall m \forall t \forall f((V(v,x,t) \,\&\, M(m,x) \,\&\, F(f, x, t) \,\&\, D) \rightarrow (F = m\mu(a/a_0)a \,\&\, D))$

Since the condition D means $\mu\ (a\ /\ a_0) \approx 1$, we obtain F = d (mv) / dt as the consequent

Thus, we have:

$\forall x \forall v \forall m \forall t \forall f((V(v,x,t) \,\&\, M(m,x) \,\&\, F(f, x, t) \,\&\, D) \rightarrow F = d\,(mv)/dt)$

This demonstrates that Newton's second law is a special case of MOND when condition D is taken into account, that is, when working with standard accelerations.

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[22] For simplicity, here and later, a is used instead of dv / dt for Milgrom's law.

This result proves that MOND satisfies the formal requirement posed to a theory that aims to succeed an old theory that is empirically successful within constraints. Namely, the modified version of Newtonian dynamics is true within the constraints given by conditions *B*, *D* and *S*. Thus, a modified version of Newtonian dynamics becomes a special case of MOND.

4.3 Truthlikeness: ΛCDM versus MOND

The notion of *verisimilitude* was introduced to contemporary philosophy of science by Popper. A part of his falsificationism, and a consequence of his critique of inductionism, is the claim we are never justified in claiming that a theory is true or even probably true. Yet, Popper was a scientific realist and, accepting the Tarskian notion of truth, claimed that scientific progress can be understood as more *truthlike* theories replacing less truthlike theories.

According to Popper's definition of truthlikeness, known as the *content approach*, theory A is more truthlike than theory B if A has more truth content than B without implying more falsity content than B, where the content of a theory is understood as the set of claims it makes. Popper's approach works when A is true (has no falsity content), but in 1974 David Miller and Pavel Tichý both independently proved that when a theory has some falsity content, its truth content cannot be increased without increasing its falsity content. A consequence of this is that, following Popper's approach, we cannot say that A is more truthlike than B, when A has some falsity content, and therefore cannot make sense of scientific progress (Oddie 2016).

Despite the problems with Popper's approach, the notion of truthlikeness has become an important part of scientific realism. Most agree that a good way to make sense of scientific progress is to say that, for example, general relativity is more truthlike than Newtonian dynamics. The concept of truthlikeness can also be used as part of a realist reply to the pessimistic meta-induction (in both its semantical and epistemological forms) and the problem of meaning variance.

Despite the intuitive appeal of truthlikeness, the question of specifying the notion in a coherent way remains. There are various competing approaches, and it would be impossible to provide a comprehensive survey of them here. Instead, one particularly promising approach will be selected for closer examination, namely the *likeness approach*. Niiniluoto (1999: 68) summarizes this approach in the following way: truthlikeness = truth + similarity. According to this approach, the measuring of truthlikeness is relative to what he calls *cognitive problems*, which are represented by either finite or infinite sets of statements, expressed in an interpreted and semantically determinate language, whose elements are mutually exclusive and jointly exhaustive possible answers to the problem. A single element represents a *complete* potential answer to the cognitive problem, whereas a disjunction of several elements represents a *partial* potential answer (ibid).

Although the measure of truthlikeness must be specified for each specific, concrete cognitive problem, Niiniluoto provides measures for some "canonical" cognitive problems. The simplest type of cognitive problem is a yes/no question. From the point of view of applying truthlikeness to astrophysics, the more interesting types of cognitive problems concern the magnitude of some physical quantity (e.g. the mass of a star), or the functional relation of some physical quantities (e.g. the dependence between the distance of a star from the galactic center and its rotational velocity) (ibid., 69). The latter kind of measure is of special interest to us, since the theories discussed in the previous chapters are motivated by the discrepancy between functional dependencies derived from empirical data and theoretical predictions. Theories in astrophysics imply statements regarding functional dependencies between observable physical quantities. Typically, these statements are only approximately accurate at best, and so strictly speaking each of them is false, assuming that our measurements of the quantities correspond to their true values. This is why the measure of truthlikeness, which is suitable for cognitive problems relevant to astrophysics, cannot be expressed by a measure of the true and false sentences implied by astrophysical theories (ibid., 73).

Rather, the measure of truthlikeness provided by Niiniluoto to cognitive problems concerning point values and functional dependencies is founded on abstractions of the properties of the Euclidean plane, known as *the metric space*. For a measure of truthlikeness to count as a metric in this sense, it must satisfy strict formal conditions. However, so-called *distance functions* are able to preserve the relevant features of metrics, if we are not interested in the numerical value of the metric but the results it gives for comparative purposes (Niiniluto 1987: 1-4).

It is precisely these comparative results that are valuable in the present context. With the assumption that our measurements of the relevant physical quantities are accurate, it is possible to compare the truthlikeness of different theories implying functional dependencies between the quantities, by employing a metric known as the *Minkowski distance* (Niiniluoto 1999: 69).

To calculate the distance between the two points values, Niiniluoto (ibid.) provides the following equation:

$$d(x, y) = | x-y |$$

To calculate the distance between two functions, the equation is as follows:

$$d(f, g) = \int | f(x) - g(x) | dx$$

Since the measuring of truthlikeness is relative to a concrete cognitive problem, we will here consider the internal velocities of specific dwarf galaxies. One reason to choose this concrete cognitive problem is that postulating the dark matter hypothesis was originally motivated by the shape of galactic rotation curves, i.e. the velocities are much higher than what is predicted by Newtonian dynamics. This discrepancy can be formulated in terms of truthlikeness.

While Popper and Niiniluoto are interested in explaining the growth of scientific knowledge, I will here repurpose the formal apparatus of Niiniluoto's approach and use it as a heuristic methodological tool. The empirical data is assumed to be accurate (the truth), and the ways to get closer to the truth is to either introduce a hypothetical object or modify the theoretical predictions i.e. the theory of gravity.

The goal, no matter which option is chosen (e.g. ΛCDM or MOND) is to try to minimize the distance between the predicted values and observational data, and thus to get closer to the truth.

The internal velocities of dwarf galaxies provide an excellent test for MOND and ΛCDM, because they have a low surface brightness (indicating low stellar mass) and high rotational speeds (indicating a high dynamical mass or the breakdown of Newtonian dynamics) (Strigari et al. 2008) Relevant data concerning their internal dynamics is available for nine dwarf spheroidal galaxies, which orbit the Milky Way galaxy. These are: Draco, Sculptor, Sextans, Fornax, Leo I, Leo II, Canes Venatici I, Carina, and Ursa Minor.

Based on the distribution of the visible matter of these galaxies, MOND predicts the rotational velocity of these galaxies. With ΛCDM, the story is more complicated: since it involves free parameters, ΛCDM makes no unique prediction regarding their internal dynamics. Instead, the hope of physicists working in this paradigm is to one day provide a theory of galaxy formation involving the gravitational interaction of baryonic matter and non-baryonic dark matter, which will explain the observed dynamics. The best that ΛCDM can provide at the moment is a post hoc simulation of the dynamics of these galaxies, and it is the truthlikeness of this that we can measure relative to our observations.

The results show that in 6 of 8 cases, MOND produces predictions (Alexander et al. 2017) closer to the truth than ΛCDM post hoc simulations (Fattahi et al. 2016), without requiring nearly as many free parameters:

Galaxy	Observed velocities	Predictions MOND	Post hoc sim. ΛCDM	Truthlikeness MOND	Truthlikeness ΛCDM
Fornax	20.1	20.8	25.5	0.59	0.16
Carina	11.3	9.9	13.8	0.42	0.29

Leo I	15.8	15.9	16.2	0.9	0.71
Leo II	11.3	11.6	12.8	0.77	0.4
Sculptor	15.8	14.9	15.7	0.53	0.9
Draco	15.6	15.1	14.7	0.67	0.53
Sextans	13.5	11.8	18.2	0.37	0.18
Ursa Minor	16.3	15.4	16.6	0.53	0.77

As the result of the measurement of truthlikeness is relative to concrete individual internal velocities of dwarf galaxies, we cannot say anything about the general success of these theories in terms of truthlikeness with regard to their ability to conform to observational data of these circular velocities in general. It is only possible to offer truthlikeness of the concrete predictions for concrete galaxies.

Nevertheless, this is but the first step taken in the application of the notion of truthlikeness to astrophysical theories. Further work must be done in order to compare the truthlikeness of these theories more generally.[23]

5. Conclusions

I have now analyzed some problem-situations in cosmology through the prism of Popper's notion of MRPs and identified the CP as one of its main constituents. Dark

[23] To see how the calculations are fully worked out, as well as truthlikeness measures for MOND predictions regarding the rotation curves of other galaxies, see Lazutkina(unpublished).

matter also seems like a plausible candidate for inclusion in the MRP. Overall, theories of cosmology, when it is understood as the study of the whole universe, seem more like MRPs than scientific theories, if Popperian standards are applied, whereas theories of cosmology, when it is understood to be the study of the largest-scale structures of the observable universe, can be scientific in principle. But even metaphysical ideas must be criticizable according to Popper. The criticizability of the MRP that informs the standard model does not depend only on how the hypotheses are formulated at any one time, but what the response to reasonable criticism is.

The response to criticism of the currently favored model depends, of course, on whether there exist viable alternative theories. In the present case, MOND has been shown to be not only a viable alternative by conforming to the correspondence principle, but superior in some respects. Not only does MOND adhere to Popper's methodological prescriptions unlike ΛCDM, but it is also more truthlike with regard to the concrete cognitive problems presented here.

The dark matter controversy is only one piece of the puzzle. The more fundamental issue is that, like ancient Greek atomists, contemporary cosmologists are far away from being able to test their theses about the universe as a whole. One might even say that we are currently much further away from the testability of these claims than the ancient Greeks were in relation to modern atomic theory. Then again, how conceivable would modern scientific instruments and experimental techniques have been to the atomists 2500 years ago? MacIntyre (1981/2007: 93) attributes to Popper the idea that radical future innovations are impossible to predict, because the prediction involves the conception of the innovation itself. Hence, we are not in a position to conclusively predict whether the CP, for instance, might one day become testable.

This is not to say that Popper's harsh words against contemporary Big Bang cosmology are not understandable in light of his methodological views. Many features of the standard model are presented as proven fact.[24] Some cosmologists and philosophers of cosmology seem to acknowledge the methodological limitations of cosmology, and the tentativeness of the current favored model on the one hand,

[24] For a notable and egregious example concerning the status of dark matter, see Clowe et al. (2006).

but immediately after speak of the “successes” and “discoveries” of the discipline, as if these were settled matters.[25]

Instead of hanging on to a degenerating program, a cosmologist adhering to Popperian norms would take a step back, acknowledge the problems of Big Bang cosmology for what they are instead of hailing them as “discoveries,” and take an attitude of epistemic humility together with the freedom of making bold conjectures from which he might one day hope to derive testable consequences.[26]

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[25] As a concrete example, see the nominally Popperian cosmologist Ellis (2006).

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