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Cosmological realism

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ABSTRACT

I discuss the relevance of the current predicament in cosmology to the debate over scientific realism. I argue that the existence of two, empirically successful but ontologically inconsistent cosmological theories presents difficulties for the realist position.

1. Introduction

Richard Boyd (1984, pp. 41–42) summarizes what he calls the “four central theses” of scientific realism:

1. Theoretical terms in scientific theories (i.e., nonobservational terms) should be thought of as putatively referring expressions; that is, scientific theories should be interpreted “realistically".
2. Scientific theories, interpreted realistically, are confirmable and in fact are often confirmed as approximately true by ordinary scientific evidence interpreted in accordance with ordinary methodological standards.
3. The historical progress of mature sciences is largely a matter of successively more accurate approximations to the truth about both observable and unobservable phenomena. Later theories typically build upon the (observational and theoretical) knowledge embodied in previous theories.
4. The reality which scientific theories describe is largely independent of our thoughts or theoretical commitments.

A commitment to scientific realism is often accompanied by a particular set of epistemic commitments, or attitudes, as well (e.g. Smart, 1963; Psillos, 1999; Lipton, 2004; Niiniluoto, 2018):

- The existence of *empirical equivalents* to current scientific theories — theories that differ in important ways from those theories but that make the same, or nearly the same, predictions about observable phenomena — would be difficult to reconcile with theses 1–3, and realists tend toward the view that such equivalents must be contrived or artificial, if they exist at all.
- Bold new conjectures, of the sort that led to the theory of relativity or to quantum mechanics, can (if successful) require abrupt changes in ontology, and in so doing would conflict with all of 1–4. Scientific realists understand “mature” science as progressing according to a gentler, typically *inductivist*, logic of discovery, e.g. ‘abduction’ or ‘inference to the best explanation’ rather than through bold new conjectures.
- Theses 1 and 4 imply that the entities described by current theories actually exist. Since the descriptions of those entities — particularly, of the unobservable (or unobserved) entities — tend to change over time, scientific realists are motivated to search for *referential* or *ontological continuity*: to argue that the *same* entities are being described in spite of changes in the theoretical statements that refer to them.

The current, standard theory of cosmology (the ΛCDM model) qualifies as a mature theory, and it is judged by most cosmologists to be empirically successful as well (Longair, 2006; Peebles, 2020). That theory postulates the existence of dark matter and it claims that most of the matter in the universe is dark. An alternative theory (MOND, for MOdified Newtonian Dynamics) does not postulate the existence of dark matter. It would probably not be correct to say (as discussed in more detail below) that MOND is precisely empirically equivalent to the standard model, at least if empirical equivalence is defined in terms of all *possible* observable consequences. But it has become clear over the last few years that MOND is at least as successful as the standard model at explaining existing observations, including those observations that are believed by many standard-model cosmologists to necessarily imply the existence of dark matter. Furthermore the MONDian explanations often require (far) fewer auxiliary hypotheses than are required under the

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standard model; and in a number of important instances, MOND has *anticipated* the data: that is: it has made successful, novel predictions, some of which were extremely surprising from a standard-model perspective. At least since the addition of the dark matter postulates *c.* 1980, the standard cosmological model has rarely, if ever, managed to do that; its successes have almost always been successes of post-hoc accommodation rather than of prior prediction.

The ΛCDM model is undeniably still the 'standard' cosmological theory: it is the theory that is taught in graduate schools and enshrined in the textbooks. But the existence of an (arguably) more successful and (arguably) less ad hoc alternative theory would seem to provide grist for the anti-realist position that current theories, even mature and successful ones, are at risk of being replaced by new ones, by theories that differ in their ontological commitments but are at least as well confirmed by the evidence as the ones they would replace.

My aim here is to use modern cosmology as a case study for current ideas about scientific realism. In Section 2 I summarize the two cosmological theories and argue that, while the theories come close to satisfying the condition of empirical equivalence, this judgment is complicated by the different ways in which they attain correspondence with the observations, particularly observations on the scale of individual galaxies. Section 3 considers the possibility of identifying referential continuity between the two theories with regard to the entity called 'dark matter' in the standard model. I argue that 'dark matter' is invoked in (at least) two, quite distinct, ways by standard-model cosmologists in explaining data, and that it is reasonable to claim continuity of reference only in the case of one of the two 'dark matters'. In Section 4 I question realists' commitment to abductive reasoning given that the (putatively) abductive explanation of the galaxy rotation-curve anomaly ('dark matter') has been far less fruitful than MOND at generating successful novel predictions. Finally in Section 5 I discuss two arguments that have been made for a realistic interpretation of theories and argue that both arguments support a realistic interpretation of MOND, but in so doing, conflict with the realists' view that mature theories in the physical scientists are likely to be correct.

2. Two cosmological theories

The standard, or ΛCDM, model of cosmology assumes the correctness of Einstein's theory of gravity and motion (or of Newton's, in the appropriate regimes) but it supplements that theory with a raft of auxiliary hypotheses, including postulates about the existence and properties of 'dark matter' and 'dark energy' and about an early epoch of rapid cosmological evolution ('inflation'). The dark matter and dark energy postulates are responses to observations that (in a Popperian sense) falsified the theory as it existed at the time: the discovery in the 1970s that the rotation curves of spiral galaxies do not behave as Newton's laws predict (Bosma, 1981; Rubin et al., 1978) and the discovery in the 1990s that the expansion of the universe does not behave as Einstein's laws predict (Perlmutter et al., 1999; Riess et al., 1998). Both dark matter and dark energy qualify as unobserved (and, possibly, unobservable) entities, and indeed the assumed properties of both have been modified over time in response to new observations, under the continued assumption that Einstein's (or Newton's) theory of gravity is correct. In Lakatosian (1978) terms, those theories of gravity constitute part of the 'hard core' of the standard cosmological research program, and the auxiliary hypotheses relating to dark matter and dark energy have been crafted (and re-crafted) in such a way as to 'shield' the hard core from refutation.

The competing cosmological theory, due in its original form to Mordehai Milgrom (1983a,b,c), does not postulate the existence of dark matter. That theory (variously called 'modified Newtonian dynamics,' 'Milgromian dynamics,' or 'MOND') postulates a different theory of gravity and motion.

One normally associates the science of cosmology with a global theory of the universe: of its large-scale structure and its evolution. But it is appropriate, and useful, to look first at the more local predictions of both theories. Both the postulates of Milgrom, and the standard-model postulates relating to dark matter, were initially targeted toward anomalies that appear on distance scales corresponding to single galaxies or groups of galaxies, regimes in which a non-relativistic theory was believed (and is still believed) to be adequate.

2.1. Prediction vs. accommodation

Newton's laws relate the gravitational acceleration of a test mass (the rate of change of its velocity) to the spatial distribution of matter that produces the gravitational force acting on it. In the case of a disk galaxy, the Newtonian prediction is particularly straightforward to test, because the stars and gas in the disk (like the Sun, in the Milky Way) are observed to move in nearly circular orbits about the disk center; and because the distribution of matter that is responsible for the gravitational force has a nearly planar geometry and so it can be robustly inferred given the observed, two-dimensional distribution of surface brightness (or of gas emission) on the plane of the sky.

Although the fact was not generally appreciated at the time (the late 1970s), observations of spiral galaxy rotation curves were the first tests of Newton's laws in a new regime: the regime of low acceleration. 'Acceleration' can here be taken to mean the centripetal acceleration $a = V^2/R$ of a test body moving (at speed V) in a circular orbit (of radius R); or the gravitational acceleration per unit of mass, expressed as the gradient of the gravitational potential, $\boldsymbol{g}_N = -\nabla\boldsymbol{\Phi}$. Under Newton's laws, these two can be equated:

$$V^2/R = |\nabla\Phi|. \tag{1}$$

Furthermore the gravitational potential follows from the observed distribution of mass via Poission's equation. The resultant expressions for a disk-like distribution of matter are mathematically involved and it is common in elementary treatments (like this one) to approximate the disk as a sphere, for which

$$V^2/R \equiv a = GM(R)/R^2 \equiv g_N \tag{2}$$

with $M(R)$ the mass enclosed within a sphere of radius R. The Newtonian prediction for the rotation curve, $V(R)$, is then something like

$$V(R) \approx \sqrt{[GM(R)/R]}. \tag{3}$$

In many galaxies, the Newtonian prediction for $V(R)$ is found to be reasonably well corroborated near the center. But sufficiently far from the center, the observed values of V always exceed the predicted values, and the discrepancy exhibits two regularities: (i) the large-radius behavior of V is $V(R) \Rightarrow \text{constant} = V_f$, that is, rotation curves are 'asymptotically flat', rather than the asymptotic $V(R) \propto 1/\sqrt{R}$ dependence predicted by Equation (3); and (ii) in a given galaxy, departures from the Newtonian prediction first become noticeable at radii where the acceleration drops below a value $\sim 10^{-10}$ m s^{-2}. The former regularity—the asymptotic flatness of galaxy rotation curves—was recognized, and widely discussed, already by 1980 (e.g. Faber & Gallagher, 1979); the latter became clear only later, during tests of Milgrom's theory.

Standard-model cosmologists responded to the rotation-curve anomaly by postulating the existence of dark matter: matter that produces (and responds to) gravitational force but does not interact with photons. The presence of dark matter in, or around, galaxy disks is assumed to generate the additional gravitational force needed to explain the anomalously high rotation speeds. Standard-model cosmologists do not always present the existence of dark matter as a *hypothesis*; for instance, Peter Schneider (2015, p. 77) writes: "The rotation curves of spiral galaxies are flat up to the maximum radius at which they can be measured; *spiral galaxies contain dark matter*" (italics his). However Milgrom (1989, p. 216) has noted, correctly, that standard-model cosmologists routinely (if implicitly) assume the correctness of what he calls the "dark matter hypothesis", or DMH, which "states that dark matter is present in whatever quantities and space distribution is needed to explain away whichever mass discrepancy arises."

Milgrom (1983a) proposed a different explanation of the rotation-curve anomaly: a modification of Newton's laws. He postulated the existence of a new constant of nature, a_0 (‘Milgrom's constant’), with value $a_0 \approx 10^{-10}$ m s^{-2}, and proposed that the relation between centripetal acceleration in galaxy disks, and the gravitational acceleration (force per unit of mass) due to the observed matter, was different from Newton's in regimes where $a \lesssim a_0$. In the low-accleration regime, Milgrom's modified dynamics predict that galaxy rotation curves will be flat; Milgrom has acknowledged (1983a) that he designed his modified dynamics to yield this known result. But the same postulates that imply asymptotic flatness also imply that the gravitational acceleration should be uniquely predictable given the distribution of normal (non-dark) matter, in *all* regimes of acceleration, not just the asymptotic limit. The mathematical form of the relation between source mass and acceleration was left unspecified, except in the asymptotic regime, but Milgrom's prediction of a unique relation has been confirmed in various ways; most strikingly in the form of the so-called ‘radial-acceleration relation’ (RAR) for galaxy disks (McGaugh et al., 2016). Given the RAR, which plots g_N (the Newtonian acceleration based on the observed matter) against the observed centripetal acceleration a, the functional relation between the two quantities can be ‘read off’, thus extending the predictability of Milgrom's postulates to regions of arbitrary acceleration. One finds that the modified dynamics accurately predicts rotation curves at *all* radii in *all* galaxies (e.g. Li et al., 2018). The latter include galaxies which (according to a standard-model cosmologist) are ‘dark matter dominated’, such as dwarf spheroidal galaxies: Milgrom predicted, and the data confirm, that the stars and gas in such galaxies orbit about the center in a manner that is predictable given the observed distribution of normal matter alone, a result that is (to put it mildly) extremely surprising from a standard-model perspective.

One's first reaction on hearing that anomalous data have been explained by modifying the theory of gravity is likely to be, “What an ad hoc solution!” But it should be clear from the preceding discussion that quite the opposite is true. The standard model ‘explains' rotation curves by simply postulating (in Milgrom's words) that “dark matter is present in whatever quantities and space distribution is needed.” Whereas Milgrom's theory *predicts* rotation curves, *even though it was not designed to do so*. There still exists no algorithm, under the standard model, that is capable of making such predictions, successfully or otherwise. Standard-model cosmologists treat rotation-curve data as part of the ‘background knowledge’ and distribute the dark matter as needed to accommodate it.

This discussion suggests why the two theories are approximately, though never exactly, equivalent in their predictions. They are approximately equivalent because both theories assign a gravitational potential (real in the case of dark matter; effective in the case of MOND) to a given galaxy that is consistent with its measured, internal kinematics. The equivalence is only approximate, however, because while MOND assigns a unique, 3d gravitational field to a given galaxy, there are many 3d dark matter distributions that are consistent with a specified rotation curve, or any finite set of measured velocities. A default assumption is to put the dark matter into a spherical ‘halo,’ but if kinematical data for stars or gas outside the disk are found to be inconsistent with the assumption of spherical symmetry, the shape of the halo can be (and often is) adjusted, in such a way that the forces in the disk plane, hence $V(R)$, remain fixed while forces outside the disk plane are modified.

A striking illustration of this difference is the so-called ‘central surface density relation,’ or CSDR, another successful, novel prediction of Milgrom's theory (Brada & Milgrom, 1999; Lelli, McGaugh, Schombert, et al., 2016; Milgrom, 2016). Given the observed distribution of normal matter in a disk galaxy, one can compute the unique, ‘phantom dark matter’ distribution that would yield the same test-particle trajectories, under Newton's laws, as predicted by the modified dynamics. This phantom halo is what a standard-model cosmologist would call ‘dark matter’: its density and shape are what would be inferred by a standard-model theorist given enough kinematical data for the galaxy. Furthermore the phantom dark matter can be shown to obey certain simple regularities: there is a unique, functional, relation between the central surface density of the phantom halo and the surface density of the disk (the CSDR) and there is an approximate upper limit to the surface density of the phantom dark matter associated with any galaxy. No such results are entailed by the standard model. Indeed the first observational corroboration of the upper-limit prediction (Donato et al., 2009) was met with surprise by the standard model cosmologists who undertook the study and who were, apparently, unaware of Milgrom's prediction.

The successful prediction of galaxy rotation curves, and of the CSDR, are two examples of how Milgrom's theory ‘anticipates the data’.[1] Another is the so-called ‘baryonic Tully-Fisher relation’ (BTFR) illustrated in Fig. 1. Already in 1983 Milgrom noted that his postulates imply a unique, that is, a functional, relation between the total mass (normal, not dark) of a disk galaxy and its asymptotic rotation speed:

$$V_{\mathrm{f}} = (GM_{\mathrm{gal}}\, a_0)^{1/4} \propto M_{\mathrm{gal}}{}^{1/4} \tag{4}$$

with M_{gal} the normal (non-dark) mass of a galaxy. The existence of such a relation was not known prior to 1983 nor had its existence been predicted by standard-model cosmologists, who would expect V_{f} to be determined almost entirely by the *dark* mass of a galaxy. It is probably for this reason that the relation was first confirmed observationally by researchers engaged in tests of the Milgromian prediction (Lelli, McGaugh, & Schombert, 2016).

While standard-model cosmologists can not *predict* V_{f} for any observed galaxy, they have invested considerable effort into *simulating* galaxy formation and evolution, and those simulations sometimes have high enough spatial resolution that one can extract information about the rotation curves of the simulated galaxies. The dominant component by mass in such simulations is the dark matter, represented as a dust-like, ‘collisionless' fluid (as would be the case if it consisted of weakly self-interacting particles). The most sophisticated simulations include also a ‘baryonic’ component representing the normal matter (stars, gas); the normal matter reacts to the presence of the dark matter through the latter's gravitational force. Non-gravitational phenomena involving the normal matter—radiative heating and cooling, star formation and evolution, stellar winds, gas turbulence etc.—can be extraordinarily complicated and are often poorly understood, and furthermore their effects are often determined in substantial ways by processes that occur on spatial scales that are far too small to be treated directly in the galaxy formation simulations. Such ‘baryonic’ processes are therefore treated by (sometimes extreme) approximation; for instance, the effects of a supernova blast on the surrounding gas might be represented by a single parameter, the ‘efficiency,’ that determines what fraction of the explosive energy or momentum is transferred to the surrounding gas (e.g. Governato et al., 2010).

It is widely acknowledged, even by standard-model cosmologists, that such simulations are not *predictive*. The goal is rather to explain, in a *retrospective* fashion, known, systematic properties of galaxies: and, hopefully, to do so without the need to select very extreme or unreasonable values for the parameters that specify the baryonic processes. It sometimes happens that years, or even decades, of code refinement are required before the hoped-for results are obtained. The right panel of Fig. 1 illustrates how close (or far) the best current simulations come to reproducing the BTFR that was successfully predicted by Milgrom in 1983.[2]

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[1] Merritt (2020) gives a comprehensive list of successful, novel predictions of Milgrom's theory; see also McGaugh (2020).

[2] Milgromian researchers can carry out such simulations as well, and in so doing may invoke auxiliary hypotheses; for instance, a simulation of the chemical evolution of the interstellar medium might require assumptions about modes of enrichment due to stellar winds. But a simulation under MOND will (almost) always require fewer auxiliary hypotheses than under the standard model since there will be no need to account for the degrees of freedom associated with dark matter. For instance, in the chemical enrichment simulation, a Milgromian will know precisely what the escape speed is from every point in her simulated galaxy, while for the standard-model researcher that quantity depends on the assumed mass and extent of the ‘dark matter halo.’ And for many questions concerning galaxies, MOND yields answers that are completely independent of a galaxy's origin or evolution. That is almost never the case under the standard model.

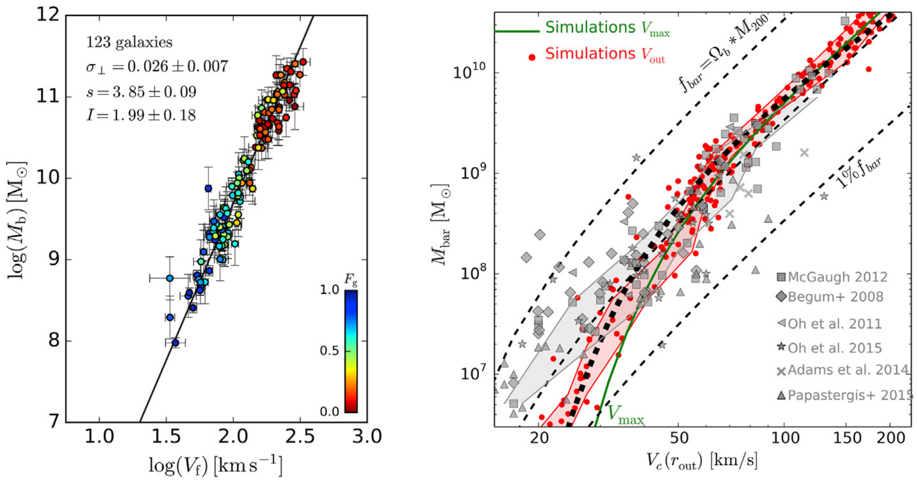

Fig. 1. A confirmed, novel prediction of Milgrom's theory (left) compared with a recent attempt to explain it under the standard cosmological model (right). The left panel plots total ('baryonic', i.e., non-dark) mass versus asymptotic rotation speed for a sample of observed disk galaxies: the 'baryonic Tully-Fisher relation' (BTFR). The best-fit line is indistinguishable from the Milgromian prediction (Eq. (4)). Points are color-coded according to the galaxy's mass fraction in gas, which tends to increase downward (toward lower mass). The right panel plots results from a large-scale simulation of galaxy formation. The standard cosmological model makes no testable prediction about this relation, and simulators are free to define the horizontal axis as they see fit. This plot uses three different measures of the rotation speed: Vc is the circular velocity at twice the 'baryonic' half-mass radius in the simulated galaxy; Vmax is the maximum circular velocity; and Vout is the circular speed at the outermost measured point in the rotation curve. The solid curve labelled "Vmax" shows median values for the entire sample of simulated galaxies as a function of total baryonic mass. The simulated relation differs from the observed/predicted relation in terms of both functional form and scatter, whether expressed in terms of Vmax or Vout. Left panel: figure reprinted with permission from F. Lelli et al., "The baryonic Tully- Fisher relation for different velocity definitions and implications for galaxy angular momentum," Monthly Notices of the Royal Astronomical Society, 484, 2019, p. 3267. Right panel: Figure reprinted with permission from L. V. Sales et al., "The low-mass end of the baryonic Tully–- Fisher relation," Monthly Notices of the Royal Astronomical Society, 464, 2017, p. 2419.

This difference between the way in which Milgromian, and standard-model, theorists explain the observations relating to galaxies—prediction in one case, accommodation in the other—is one reason why it is not really possible to decide whether the two theories are empirically equivalent, even if 'equivalence' is restricted to existing observations. But questions of equivalence aside, there are several arguments that support the claim that the Milgromian explanations of data like those plotted in Fig. 1 are epistemically superior to the standard-model explanations:

- As just noted, while Milgrom's theory makes definite, testable predictions about the behavior of the observable matter in individual galaxies, the standard model can at best make *statistical* statements about the behavior of the matter in *simulated* galaxies.
- Standard-model simulations fail to adequately reproduce many systematic properties of galaxies that are correctly predicted by Milgrom's theory. Fig. 1 shows one example; see Silk and Mamon (2012), Bullock and Boylan-Kolchin (2017) and Tulin and Yu (2018) for others.
- Even if standard-model cosmologists should manage to retrospectively explain facts successfully predicted by Milgrom's theory, one can argue that such explanations are always more ad hoc. There is widespread acknowledgement by philosophers of science that the successful *prediction* of a fact assigns more warrant to a theory than any post-hoc *accommodation* of that fact. For instance, Lipton (2004, p. 170), in a passage that is perfectly apposite here, writes:

> When data need to be accommodated, there is a motive to force a theory and auxiliaries to make the accommodation. The scientist knows the answer she must get, and she does whatever it takes to get it. … In the case of prediction, by contrast, there is no motive for fudging, since the scientist does not know the right answer in advance. She will instead make her prediction on the basis of the most natural and most explanatory theory and auxiliaries she can produce. As a result, if the prediction turns out to have been correct, it provides stronger reason to believe the theory that generated it.

Psillos (1999, p. 107) writes:

> For there is always the possibility that a known fact can be 'forced' into a theory, whereas a theory cannot be forced to yield an hitherto unknown fact. Hence, predicting a new effect — whose existence falls naturally out of a theory — makes the theory more risky and susceptbile to extra experimental scrutiny which may refute it.

And Worrall (1985, p. 313) suggests that "when one theory has accounted for a set of facts by parameter-adjustment, while a rival accounts for the same facts directly and without contrivance, then the rival does, but the first does not, derive support from those facts."

In summary: In explaining observations on the spatial scales that correspond to galaxies, the two theories are empirically equivalent only in the sense that the standard model sometimes manages to accommodate, in an approximate way, facts (e.g. galaxy rotation curves) that are successfully predicted by Milgrom's theory. In effect, standard-model cosmologists use dark matter as a 'MOND emulator': they require dark matter to have whatever macroscopic properties (density, velocity dispersion, spatial distribution) are needed in order to make the behavior of the normal matter in any observed galaxy mimic its behavior under the modified dynamics. And in computer simulations of the formation and evolution of galaxies, where the dark matter is allowed to evolve freely in response to its self-gravity, the description of the *normal* matter is uncertain enough, due to physical processes that occur on 'sub-grid' spatial scales, that the simulator has substantial freedom to adjust its behavior and again obtain (or at least, try to obtain) agreement with the observations.[3]

2.2. Particle dark matter

The standard cosmological model postulates the existence of an entity — dark matter — that does not exist (at least, not necessarily) in Milgrom's theory.

For the moment, I will assume, as standard-model cosmologists almost universally do (e.g. Tanabashi et al., 2018), that the dark matter consists of elementary particles. The standard cosmological model says little about the expected properties of the dark particles: only that (i) their mean mass density should be high enough to constitute approximately 85% of the universe's overall mass budget; and that (ii) the particles should have been moving slowly enough, at early times, that they were able to gravitationally cluster into structures with sizes and masses comparable to those of galaxies and galaxy groups (‘cold dark matter,’ or CDM). A third assumption is often made that (iii) the particles are weakly self-interacting; that is: that they respond to gravitational forces as a collisionless fluid. (The latter assumption is almost always built in to galaxy formation simulations like those described in the previous section.) No particle has yet been identified that fits these requirements and it is generally believed that any such particle must lie outside of the standard model of particle physics.

Nevertheless a number of potentially testable consequences follow from the hypothesis that the dark matter consists of elementary particles. Probably best known is the prediction that dark particles are passing, at every instant, through any terrestrial laboratory[4] and could in principle be detected, using well-established techniques of calorimetry, scintillation or ionization. Experiments designed to detect the particles (so-called ‘direct detection’ experiments) have been carried out since the early 1980s; about a half-dozen such experiments are currently underway (e.g. Kisslinger & Das, 2019). There is intersubjective agreement that no event has yet been observed that can reasonably be interpreted as the signal of a dark particle passing through a laboratory detector (Ko, 2018; Liu et al., 2017; Schumann, 2019).

An independent set of experiments — the ‘indirect detection’ experiments — look for evidence of radiation from particle dark matter beyond the Earth (Funk, 2015; Gaskins, 2016): typical targets are the center of the Milky Way, and the dwarf (‘dark-matter-dominated’) satellite galaxies of the Milky Way. The (additional) assumption here is that the dark particles are either self-annihilating, or decaying, and in the process producing energetic, standard-model particles (e.g. neutrinos) or gamma-ray photons that could be detected from the Earth. Here the major experimental challenge is the difficulty of distinguishing any detected photons or neutrinos from those produced by known astrophysical sources, e.g. pulsars, in the targeted systems (Buckley et al., 2013; Strigari et al., 2018). Although claims have been made from time to time of a detection, more careful modeling of the ‘astrophysical’ (i.e., non-dark-matter) sources in the target object always ends up casting doubt on the dark-matter interpretation. For instance, an apparent excess of gamma rays from the direction of the Galactic center was proposed as a signal of dark matter (Hooper & Goodenough, 2011), but a recent analysis (Abazajian et al., 2020, p. 043012) concludes that “the excess emission in the GC [Galactic center] at GeV energies is dominantly of astrophysical origin“ and not due to dark matter.

Now, one could argue for empirical equivalence here in the following sense: Milgrom's theory *predicts* that direct- and indirect-detection experiments should measure no signal—consistent with all experimental results to date—and the standard cosmological can *accommodate* the lack of detections by adjusting the assumed properties of the putative particles. For instance, the cross-section of interaction of the dark particles with normal matter can be assumed to be very small, making direct detection essentially impossible even if the particles are present in the detector; or, the decay lifetime of the particles can be assumed to be so long that decay products would almost never be observed. Just these explanations for the persistent non-detection are, in fact, often proposed. In much the same way that standard-model cosmologists adjust the assumed, *macroscopic* properties of the dark matter in order to accommodate the observed behavior of stars and gas in galaxies, they can also adjust the assumed *microscopic* properties of the dark particles to accommodate the negative results from the direct- and indirect-detection experiments.

2.3. The early universe and large-scale structure

It was noted above that dark matter appears in the standard cosmological model in two distinct ways: (i) its presence is assumed in galaxies whenever the observed, internal motions are inconsistent with the predictions of Newton; (ii) it is postulated that at some early time, before galaxies formed, the universe was filled with a nearly uniform dark-matter ‘fluid’ which subsequently evolved in response to gravitational forces.

In galaxy formation simulations like those described above, the second assumption is used to set the initial conditions of the simulation. The final result of such a simulation may include a set of (simulated) galaxies, each of which consists, typically, of a dark matter ‘halo’ at the center of which sits the normal matter making up the simulated galaxy.

Such simulations say nothing about the dark or luminous matter in any *observed* galaxy. But they do permit a sort of statistical consistency check between postulates (i) and (ii), in the following sense: the simulated galaxies of some specified ‘type’ (e.g. low-mass, gas-rich, rapidly-rotating) should inhabit dark-matter halos that are consistent in their properties (mass, shape, density profile) with the dark matter halos that are required, under postulate (i), to accommodate the *observed* kinematics of the same type of galaxy.

The simulations often fail such consistency tests: the simulators often fail to find any reasonable set of parameters (describing the ‘sub-grid physics') that can accommodate known, systematic, properties of galaxies, including properties correctly predicted by Milgrom's theory (Bullock & Boylan-Kolchin, 2017; Silk & Mamon, 2012; Tulin & Yu, 2018).

But there is another set of tests that relate more directly to postulate (ii), and these are the tests that standard-model cosmologists typically point to when they claim that the evidence for dark matter is irrefutable. The first is the power-spectrum of temperature fluctuations in the so-called cosmic microwave background (CMB): the universe-filling

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[3] Galaxy clusters are gravitationally-bound systems with linear sizes measured in megaparsecs. As in the case of galaxies, MOND has the potential to make testable predictions about the internal kinematics of galaxy clusters, but the situation is complicated by uncertainties about the total (baryonic) mass budget of these systems. It was discovered in the 1980s (quite to everyone's surprise) that ionized, intracluster gas far outweighs the galaxies in the larger clusters, and it is still uncertain whether there might not exist other types of undetected matter in these systems; McGaugh (2015) suggests (based on nucleosynthesis arguments) that there should be additional baryons, Sanders (2007) suggests (based on arguments from particle physics) massive neutrinos, etc. In any event, one finds that MOND correctly predicts the internal kinematics in clusters with small amounts of intracluster gas, while in the larger clusters, the mass implied by Milgromian dynamics can be a factor of two greater than the mass directly observed in stars and gas (Sanders, 2003). A plausible explanation (Milgrom, 2008) is that the gas-rich clusters contain substantial amounts of yet-undetected gas. The expectation that there are undetected mass components in clusters is supported by observation of systems like the so-called “Bullet Cluster,” a pair of interacting clusters that exhibit a lensing signal indicating matter that is displaced with respect to both the galaxies and the observed gas (Bradac et al., 2006), just what a Milgromian cosmologist might expect. It is interesting that galaxy clusters are equally problematic for standard-model cosmologists: their preferred value for the ‘cosmological’ ratio of normal to dark matter over-predicts the observed mass in stars and gas by typical factors of 1.5–2 in galaxy clusters (Vikhlinin et al., 2006).

[4] Or, in the past, through any terrestrial dinosaur (Randall 2017).

radiation that is believed to consist of photons produced during the epoch of recombination, a few hundred thousand years after the Big Bang, when the universe transitioned from an opaque plasma to a transparent neutral gas. The various features in the CMB spectrum are interpreted, by standard-model cosmologists, as imprints in the photon energies due to slight variations in the gravitational potential through which the photons traveled in reaching the earth (among other possible processes). Those variations in the gravitational potential, in turn, are attributed to fluctuations in the density of matter, including both normal and dark matter, about their mean values at early times. The second test is the matter power spectrum (MPS), the Fourier transform of the matter correlation function, a measure of the clumpiness of the galaxy distribution on large spatial scales, hence early times.

By freely adjusting a set of parameters, standard-model cosmologists are able to achieve good fits to the CMB and MPS data (e.g. Weinberg, 2008, chapter 2; Schneider, 2015, chapter 8). When standard-model cosmologists quote a value for the mean density of dark (or normal) matter in the universe, they are almost always citing the so-called 'concordance' values obtained by fitting their model to these data.

But these data can be fit without assuming the existence of dark matter. A relativistic generalization of Milgrom's theory due to Skordis and Złosnik (2020), which they call RMOND, has been shown to reproduce essentially all of the observations that standard-model cosmologists attribute to dark matter, including the CMB spectrum, the matter power spectrum, and observations of gravitational lensing, as well as (in the quasi-Newtonian regime) galaxy-scale phenomena like the BTFR and the CSDR. In addition, RMOND satisfies the other conditions that an acceptable relativistic theory must meet: for instance, that gravitational waves should propogate at the same speed as electromagnetic waves, as recent observations imply.

Neither theory can claim to have successfully *predicted* the CMB or MPS data. In the case of the standard model, it was recognized prior to the observations that in the absence of dark matter, the peaks in the CMB spectrum should have progressively lower amplitudes due to a process called 'baryonic damping'. However no theorist came close to correctly predicting the amplitudes of the second or third peaks before they were measured; indeed the amplitude of the second peak, when first measured in 2002 (de Bernardis et al., 2002), was much lower than expected. In order to accommodate the unexpectedly low amplitude of the second peak, standard-model cosmologists were forced to increase the assumed density of *normal* matter by a factor of two above existing, well-established, estimates, introducing inconsistencies in their model that have persisted until today (Merritt, 2020).

Standard-model cosmologists have often justified their non-acceptance of Milgrom's theory on the grounds of its supposed inability to fit data like the CMB temperature fluctuation spectrum or the matter power spectrum. For instance, Dodelson (2011), in discussing an early relativistic version of MOND, wrote:

> The class of models reducing to MOdified Newtonian Dynamics (MOND) in the weak field limit does an excellent job fitting the rotation curves of galaxies, predicting the relation between baryonic mass and velocity in gas-dominated galaxies, and explaining the properties of the local group … The biggest challenge facing MOND today is the shape of the matter power spectrum … the shape of the predicted spectrum is in violent disagreement with the observed shape.

And standard-model cosmologist Ruth Durrer remarked "A theory must do really well to agree with [the CMB] data. This is the bottleneck."[5]

Skordis & Złosnik's gravitational theory is a generalization of one published in 2004 by Jakob Bekenstein called 'TeVeS'. (This is the theory that Dodelson referred to in the quotation above.) Their RMOND theory contains a term in the gravitational Lagrangian, a vector field (which they call B_μ), that behaves differently in different regimes.[6] On the scale of the expanding universe, the field acts like collisionless dark matter, and the predictions in this regime for the behavior of *observable* matter and photons are essentially indistinguishable from those of the standard model. But on smaller scales where the expansion of the universe can be ignored, the field acts in such a way that the effective gravitational force reproduces Milgrom's modified dynamics.

One expects any version of MOND to contain a scalar term corresponding to Milgrom's constant a_0. In RMOND, that (dimensionless) term is called K_B. One of the notable successes of Skordis and Złosnik's theory is that it naturally explains the several 'cosmic coincidences' first noted by Milgrom: the near-agreement of the magnitude of Milgrom's constant with a number of other quantities that have dimensions of acceleration.

Excellent fits to the CMB spectrum are obtainable using RMOND for a range of parameter values. In other words: the theory can explain those data without 'fine tuning.' Fits obtained under the standard model, by contrast, are well known to be very strongly dependent on the assumed parameter values; indeed the 'precision' with which such values are determinable from the data (under the standard model) is often cited as a primary justification for the (extremely expensive) experiments that are needed to obtain those data (e.g. The Planck Collaboration 2006).

Skordis & Złosnik do not view their theory as necessarily the final word, noting that any theory like RMOND

> should obey the principle of general covariance and the Einstein equivalence principle. These are, however, rather generic and minimal principles that do not provide any guidance as to how RMOND should look … Indeed, many theories obeying these have nothing to do with MOND, and many RMOND theories obeying these same principles are in conflict with observations.

Indeed, even summary discussions of the currently viable alternatives to Einstein's general theory of relativity (most of which were not designed to yield the modified dynamics) can run to hundreds of pages (e.g. Clifton et al., 2012).

It is tempting to infer, from the clearly different forms of the gravitational action in the two theories, that they can not be exactly empirically equivalent. That conclusion is probably correct. For instance, MOND theories generically violate the strong equivalence principle, and indeed a claim has recently been made of an observational confirmation of this prediction (Chae et al., 2020). However a proper comparison of the empirical content of the two theories should take into account that the standard model includes 'dark matter' and 'dark energy,' and that the properties of those theoretical entities are only partially specified. If the two theories should be found to make substantially different predictions in some regime, it is always possible that the properties of dark matter or dark energy could be cleverly engineered so as to maintain empirical equivalence.[7] A similar point can be made about comparison of the two theories in terms of their 'simplicity' or 'elegance': such comparisons must include, on the standard-model side, the (ever-changing) set of postulates that describe the properties of dark matter and dark energy as well as the many auxiliary hypotheses that are invoked to link the two

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[5] Quoted in Wood (2020).

[6] Somewhat confusingly, Skordis & Złosnik define two auxiliary fields which they call ν_1 and ν_2 and which appear to contribute to the complexity of their Lagrangian. But these are 'nondynamical' fields that can be expressed in terms of the metric and the field B_μ; they were introduced only to simplify the Lagrangian and they are later 'integrated out'. In Bekenstein's (2004) 'TeVeS' Lagrangian, there is a nondynamical, auxiliary metric and a scalar field (called σ) that can likewise be eliminated in terms of the physical metric and Bekenstein's vector field, as shown in Złosnik, Ferreira, and Starkman (2006), yielding a Lagrangian that belongs to the same general family as that of Skordis & Złosnik.

[7] An example is the effort currently underway to explore 'self-interacting dark matter' models; see e.g. the set of papers in the special issue of *Physics Reports*, "Dark matter self-interactions and small scale structure" (volume 730, February 2018).

'dark sectors' to observable matter, hypotheses that are not necessary under MOND.

In any case: Skordis and Złosnik's work demonstrates that when it comes to explaining data like the CMB spectrum and the matter power spectrum, Milgromian theories that are empirically equivalent to the standard cosmological model can be constructed, and that such theories need be no more contrived or artificial than the standard model.

3. Referential continuity

Scientific realists believe that mature, successful theories in the physical sciences are true or approximately true and that the entities that appear in those theories actually exist. If such a theory should be modified or replaced, the realist expects that the 'same' entities will be present in the new theory, even if the detailed descriptions of those entities, or the detailed manner in which the entities are related to observable phenomena, should change. In the words of Psillos (1999, p. 281):

> If past mature and genuinely successful theories are to be seen as having been truth-like, then it should be the case at least that their central theoretical terms recognisably referred to those entities to which the theoretical terms in their successors also referred (or refer).

In the case under consideration here, the "past theory" is, of course, the standard cosmological model, and the entity in question is dark matter.

It would be difficult to overstate how strongly standard-model cosmologists associate the dark matter in their theory with *elementary particles* — even if they can not specify what *kind* of particles those are. For instance, Bertone & Hooper, in their "History of Dark Matter" (2018, p. 045002-15), write that the phrase 'dark matter'

> is most frequently used as the name, a proper noun, of *whatever particle species accounts for the bulk of our Universe's matter density*. When a modern paper discusses the distribution of dark matter, or the impact of dark matter on structure formation, or the prospects for detecting dark matter with a gamma-ray telescope, one does not have to ask themselves whether the authors might have in mind white dwarfs, neutron stars, or cold clouds of gas—they do not [italics added].

Almost as universal (at least until recently) has been the assumption that the postulated particles are massive and weakly interacting — hence the acronym WIMP, for 'weakly interacting massive particle.'[8]

One indication of the standard-model commitment to *particle* dark matter is the enormous effort that has been expended by experimental (astro-)physicists in attempts to detect the dark particles. Those experiments are typically justified to the funding agencies on the grounds that dark matter is known to exist and that it very likely consists of WIMPs (e.g. Mount et al., 2017).[9]

Had the experiments detected particles with the necessary properties, there would be no motivation to consider alternate theories of cosmology that lack dark matter. An 'entity realist' like Hacking (1983) or Cartwright (1999) could have argued that the dark particles are real, since we can manipulate them in our laboratories and intervene in their activities,[10] and the more pressing question for scientific realists would have become: does the confirmed existence of the particles constitute a sufficient warrant for belief in the theory that invokes them (e.g. Clarke, 2008)?

But the direct-detection experiments have not been successful (Kislinger & Das, 2019; Ko, 2018; Liu et al., 2017). Dark matter remains an unobserved, and possibly unobservable, entity: a *theoretical* entity. And so the primary question for the realist becomes: Given that an *alternate* theory successfully explains the same data as the standard model, without invoking dark matter, is there some sense in which the 'same' entity is being described by the two theories?

To the extent that standard-model cosmologists equate 'dark matter' with some (yet undiscovered) elementary particle, one could reasonably argue that ontological continuity simply can not obtain between the standard model and Milgrom's theory, since the latter does not postulate any such particle. But I propose to take a more liberal view here. Even standard-model cosmologists sometimes speculate about forms of dark matter that do not consist of WIMPs: for instance, axions, or black holes, or hydrogen snowballs. What is common to all these suggestions is the requirement that the postulated entities are able to explain the observations just as successfully as WIMPs have been shown to do.

What this suggests, of course, is a causal (rather than a descriptivist) theory of reference.[11] Stanford (2006, p. 147) writes that "on causal theories of reference, a theoretical term refers to whatever entities in the world actually cause the observable phenomena or events that led past theorists to introduce the term into their theories in the first place." Thus, for instance, a causal definition of reference would imply that the 'luminiferous aether' of 19th-century physics is what we now call the electromagnetic field (Hardin & Rosenberg, 1982).

An objection to making reference purely causal is that "continuity and sameness in reference becomes very easily satisfiable" (Psillos, 1999, p. 290): there will always be *something* that is the cause of whatever phenomenon the theoretical term was introduced to explain, and so any entity introduced to explain that phenomenon will necessarily refer, even if the theory that contains the entity should turn out to be completely false.

Kitcher (1993) argues that a causal definition of reference can be sharpened by distinguishing between what he calls "working posits" and "presuppositional posits." The first refer to postulates that are implicated in the theory's empirical content, its "problem-solving schemata"; the latter to metaphysical concepts. Thus, he argues, the 'aether' was a presuppostional posit: its existence was not assumed in making or testing predictions (at least until the Michelson-Morley experiments); the successes of Maxwell's theory were due entirely to the mathematical description of wave propagation, even if Maxwell himself professed a belief in the real existence of the aether. Thus, Kitcher argues, there is

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[8] 'Massive' here means of order 10^2 GeV/c^2; in the same units, the mass of the proton is 0.938. 'Weakly interacting' means that the particles interact with other particles via a force that is as weak or weaker than the so-called 'weak nuclear force' (in addition to interacting via gravitational forces).

[9] A measure of the standard-model community's commitment to particle dark matter is the amount of money earmarked by the funding agencies, year after year, for the detection experiments. The most elaborate experiment currently under development is called DARWIN: "The detector, estimated to cost between €100-million and €150 million, is being developed by the international XENON collaboration, which runs one of the 3 experiments starting up this year — a 6-tonne detector called XENONnT at the Gran Sasso National Laboratory near Rome. DARWIN would contain almost ten times this volume of xenon" (Gibney, 2020).

[10] Hacking, in 1989, wrote that his argument for entity realism "is evidently inapplicable to extragalactic astrophysics" (p. 555) then went on to discuss the case of gravitational lensing. It is curious that he did not mention particle dark matter, in this paper or in any subsequent paper. Even before 1989, the possibility of detecting the dark particles experimentally had been widely discussed (e.g. Goodman & Witten, 1985; Wasserman, 1986) and the results from a number of ongoing experiments had been published (e.g. Ahlen et al., 1987; Caldwell et al., 1988).

[11] Cosmologists sometimes explicitly invoke a causal definition of dark matter. 'Dark Matter Day' is an annual event first scheduled on 31 October 2017. The UKRI-based web page for that year's event (https://stfc.ukri.org/news/dark-matter-day-2017/) stated "Finding out what dark matter is made of is a pressing pursuit in physics. We don't yet know if it's composed of undiscovered particles or whether it requires some other change in our understanding of the universe's laws of physics." This example notwithstanding, standard-model cosmologists rarely apply the term 'dark matter' to alternate theories of gravity.

referential continuity between aether theories and theories of electromagnetic waves, even though the term ‘aether’ is no longer believed to refer.

Following Psillos and Kitcher, we should ask in what manner the theoretical entity ‘dark matter’ relates causally to the observations that it is invoked to explain. And here it is necessary first to expand on a point that was discussed in passing in the previous section:

A standard-model cosmologist who carries out computer simulations of galaxy formation sets her initial conditions by assuming that the universe was smoothly filled with dark matter at some early time. The end result of her calculation is a set of simulated galaxies each of which sits inside a ‘dark matter halo’ that formed from that same dark matter. At least conceptually, such simulations suggest a link between dark matter in the early universe and dark matter around nearby galaxies.[12] But if the same cosmologist is asked why she *believes* in the existence of dark matter, she is unlikely to point to her simulations. She will refer instead to a particular set of observations—galaxy rotation curves, the CMB fluctuation spectrum—and cite the standard-model explanations of those data that invoke dark matter.

Those data, and their associated explanations in terms of dark matter, fall into two distinct sets, which might be called ‘local’ vs ‘global,’ or ‘small scale’ vs ‘large scale.’ Small-scale observations include the rotation curves of individual, nearby galaxies; such data are explained by postulating whatever amount and distribution of dark matter are needed to reconcile the observed motions with Newton's laws (this is what Milgrom called the ‘dark matter hypothesis', or DMH). Large-scale observations, like the CMB fluctuation spectrum and the matter power spectrum, are explained by postulating a universe-filling sea of dark matter at early times.

A particle physicist who wishes to estimate the density of dark matter in his laboratory does not need to assume anything about the early universe; he simply refers to the Milky Way's measured rotation curve and invokes the DMH. And a cosmologist who calculates the CMB spectrum does not care about dark matter in the Milky Way, or any other observed galaxy; his calculation does not invoke the DMH in any way.[13] The two dark-matter postulates are independent in their entailments; predictions derived from them belong to two, non-overlapping sets — even though a standard-model researcher is likely to assume that both sorts of prediction, if confirmed, provide corroboration for a *single* entity, ‘dark matter.’

For a Milgromian researcher, who does not assume the existence of dark matter, there is no compelling reason to make this conceptual connection. So, for instance, he can consider explanations for the large-scale data that are independent of his explanation of the local data. An example is the demonstration by Angus (2009) that the CMB spectrum can be explained, even in a Milgromian cosmology, by postulating ‘sterile neutrino’ dark matter. The rms velocity of such particles would be too high for them to cluster into structures with the sizes and masses of single galaxies, hence they would not be implicated in the explanation of galaxy rotation curves—leaving open the possibility of explaining *those* data via the modified dynamics rather than via the DMH.

The relevance of this discussion to the question of referential continuity should be clear. The two different explanatory roles that standard-model cosmologists assign, if only implicitly, to dark matter are likely to appear *explicitly* distinct in alternative theories like Angus's. Those alternate theories demonstrate what could have been clear already to standard-model cosmologists: that the explanations of the small-scale and large-scale phenomena are, or at least can be, disconnected, even if one imagines that the same entity (‘dark matter’) is responsible for both. And so it is entirely possible (for instance) that continuity of reference between the standard model and an alternate theory could be satisfied for the entity that is deemed responsible for one set of phenomena, but not for the other.

With this in mind, we can now return to the question of how dark matter is causally invoked by standard-model cosmologists in their explanations. Consider first the case of the large-scale data. When cosmologists write computer programs for computing the CMB or matter power spectra, ‘dark matter’ appears as a (numerically-specified) function $\rho(\boldsymbol{x},\boldsymbol{v},t)$ where ρ represents the mass density of the dark matter in phase space, $(\boldsymbol{x},\boldsymbol{v})$ are phase-space coordinates and t is time. The function ρ is programmed to evolve as the dependent variable in the collisionless Boltzmann, or ‘Vlasov’, equation. That is: the dark-matter density evolves *as if* it were composed of a collection of particles that move in response to gravitational forces (from themselves and from other particles), without any additional inter-particle or radiative forces.

The preceding sentence might be taken as defining the ‘core-causal’ description (Psillos, 1999, chapter 12) of dark matter: it contains all the elements that would need to be true in order for the entity to play the causal role that the theory requires of it.

One can also identify properties that are *not* essential in order for ‘dark matter’ to play this causal role. The dark matter need not be particulate: indeed the Vlasov equation contains no term corresponding to ‘particle mass' or number of particles. Such computer codes *do* often contain a variable that stands for the mass, m, of a dark particle, but that mass is used only in specifying the initial velocity field $\boldsymbol{v}(\boldsymbol{x})$ of the dark matter, under the assumption that the initial velocities are ‘thermal’ and hence m-dependent. But in computing the CMB spectrum the initial velocity field is almost irrelevant; this is why, for instance, Angus (2009) could correctly predict those data using particles (neutrinos) of much lower mass than is normally assumed for WIMPs.

Now, Skordis and Złosnik (2020), when motivating the mathematical form of their proposed gravitational action, state as a desirable feature that there be a “significant amount of energy density scaling precisely as a^{-3}”, with a the cosmological scale factor, and note that “Within the DM [dark matter] paradigm such a law is a natural consequence of the energy density of particles obeying the collisionless Boltzmann equation.“ They go on to demonstrate that on the largest physical scales, their action contains a term that precisely mimics collisionless dark matter; and that by virtue of this behavior they are able to correctly accommodate the CMB data and other large-scale observations.

I propose, therefore, that it would be reasonable to claim referential continuity between the two theories with respect to the theoretical entity ‘dark matter,’ insofar as that entity is invoked to explain the large-scale data. This claim is based on the fact that the relevant field in the Skordis & Złosnik gravitational action reproduces (by construction) the core-causal properties of ‘dark matter’ in the standard model.

What about dark matter as it is invoked to explain the galactic-scale data? By assumption, this dark matter generates whatever gravitational field would be necessary under Newtonian dynamics to explain the kinematics of normal matter in observed galaxies. As near as anyone can determine, those observed kinematics are always correctly predicted by Milgromian dynamics (McGaugh, 2014). Thus, in respect to explanations of phenomena like galactic rotation curves, it would be appropriate to find core-causal continuity between ‘dark matter’ and the new description of gravity in Milgrom's theory as well.

But there is more to be said here. Standard-model cosmologists routinely postulate properties for the galaxy-scale dark matter that go beyond its ability to generate gravitational fields. One example, discussed in detail above, is the assumption that the dark matter consists of elementary particles and the prediction that those particles are interacting with normal matter on the Earth. No one engaged in direct-detection experiments would argue that the sought-after interactions would be expected if the particles do not exist. And standard-model

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[12] One might hope to connect the two hypotheses in some manner that does not depend on the details of the galaxy formation simulations. For instance, the assumed, mean density of dark matter at early times ought to be related in a computable way to the mean density of dark matter in the local universe. But the latter is difficult to infer from data, since most of the postulated dark matter would be far from the centers of galaxies and so would have little effect on the observable matter.

[13] It may have been confusion on this point that led Niiniluto to his misstatements in the passage quoted below.

cosmologists routinely assume that, on scales corresponding to galaxies (as on larger scales), the dark matter both generates, *and responds to*, gravitational forces, in the same manner as a collisionless fluid of particles. The response of galaxy-scale dark matter to gravitational fields — generated both by the dark matter itself, and by the normal matter — is a necessary element of standard-model descriptions of a range of phenomena, including mergers between galaxies that are (assumed to be) embedded in dark-matter halos, decay of the orbits of satellite galaxies in the (postulated) dark halo of the Milky Way, etc.

Now, what matters for the causal continuity argument is whether dark matter is invoked in *solving problems* or in *explaining observations*. But it is debatable whether any of the physical processes mentioned in the previous paragraph actually take place. This is obvious in the case of the particle-detection experiments,[14] and it is uncertain as well whether one can identify any signatures of past orbital decay or mergers that require dark matter for their explanation (e.g. Kroupa, 2012, 2015). Thus: while standard-model cosmologists often *assume* that the dark matter, on galactic scales, responds to gravity like a collisionless ensemble of particles, it is not clear that such behavior is implicated in the *explanation* of any observed phenomenon or in the *solution* of any problem.[15]

The fact that the dark particles behave (at least in terms of experiments and observations to date) like *unobservable* entities suggests that we consider an alternate criterion for referential continuity. So-called 'structural realism' posits that what is preserved in theory change is the *relation between* entities — as reflected in the theory's mathematical structure, for instance — and that the real nature of those entities is either unknowable ('epistemic structural realism') or that the relations are all there is ('ontic structural realism') (Ladyman, 1998). On this view, objects like dark-matter particles play only "a heuristic role allowing for the introduction of the structures which then carry the ontological weight" (French, 1999, p. 204), and demonstrating continuity under theory change would amount to demonstrating that the postulated relations — the "structure" — remains unchanged, without regard to the entities whose behavior is assumed to reflect that structure.

Consider, then, the mathematical relations that standard-model cosmologists postulate for galactic-scale dark matter in its dynamical interactions with normal matter. When a massive body moves through an ensemble of particles, its gravitational force causes the trajectories of the particles to curve around behind it, leading to an overdensity that trails the massive body. That overdensity, in turn, exerts its own gravitational force back on the body and causes it to decelerate — a second order effect of the particles' gravitation. This so-called 'dynamical friction' force exists both in collisionless and collisional fluids (like gases or liquids) and its mathematical description is quite similar in the two cases. That description has the form $d\boldsymbol{V}/dt \propto -M\rho F(\boldsymbol{V})$, where $d\boldsymbol{V}/dt$ is the rate of deceleration due to the friction, M is the mass of the body (e.g. satellite galaxy) undergoing deceleration, ρ is the mass density of the background fluid (e.g. dark matter), and $F(\boldsymbol{V})$ is a calculable function that describes the degree of background polarization due to passage of the massive body. A structural realist would want to emphasize that this equation contains nothing that refers to the mass, m, or number density, n, of the postulated particles — a consequence of the assumption that m is so small that the response of the particle 'fluid' to perturbations depends only on the product $m \times n = \rho$. (Recall that the same was true in the case of the large-scale dark matter.) And so a structural realist would want to know whether the new field in RMOND implies a mathematically similar relation. The answer is "no". On the scale of single galaxies, the new degrees of freedom in RMOND have an energy density that is negligible compared with that of the normal matter and their only influence on the normal matter is to modify its mutual interactions, yielding Milgromian dynamics. Hence there is nothing in RMOND that corresponds to the dynamical friction force due to dark matter in the standard model.[16]

On the basis of these arguments, I conclude that continuity is lacking when it comes to the elements of the two theories that are invoked to explain the anomalous kinematics of galaxies.

4. The best explanation

Realists typically assume that there exists a 'logic of discovery' followed by scientists. Since roughly the 1980s,[17] that logic has often been taken to be some variety of inductivism: 'abduction' or 'inference to the best explanation' (IBE). For instance, Psillos (2009, p. 5) writes: "It's an implicit part of the realist thesis that the ampliative–abductive methods employed by scientists to arrive at their theoretical beliefs are reliable: they tend to generate approximately true beliefs and theories."[18]

Some writers make a distinction between abduction and IBE; I will ignore that distinction in what follows. But a distinction should be made between abductive inferences that are 'local' vs. 'global,' or 'horizontal' vs. 'vertical' (e.g. Hintikka, 1968). An example of a local/horizontal inference might be "I observe footprints; I infer that someone has walked past." An example of a global/vertical inference might be "I observe precession of Mercury's orbital periapsis; I infer the general theory of relativity." The latter inference is far more ampliative—it goes much farther beyond the facts to be explained—than the former. It is fair to say that Milgrom's proposed solution to the rotation-curve anomaly—which argues from the observed, asymptotic flatness of galaxy rotation curves to a wholesale rejection of the current theory of gravity—is closer to the latter case.

What makes either sort of explanation 'best'? Usually, the 'best' explanation is expected to be the *most likely* among the set of explanations that are deemed otherwise acceptable. Likelihood, in turn, is to be evaluated on the basis of background knowledge or assumptions. For instance, Niiniluoto (2005, p. 261) defines the principle of "high posterior probability" as: "Given evidence *E*, accept the explanation *H* of *E* such that *H* has the maximal posterior probability *P(H/E&B)* on *E*" with *B* the background knowledge. The latter includes both known facts and accepted theories. Psillos (2009, p. 184) writes (italics added):

> To say that a certain hypothesis H is the best explanation of the evidence is to say, at least in part, that the causal-nomological story that

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[14] No one would interpret a successful detection as anything other than a confirmation of the dark matter hypothesis, and as a refutation of theories like Milgrom's. What is less often considered is how to interpret the absence of any detection. Experimental physicists hardly ever refer to MOND, even though that theory provides the most natural explanation of their results. For instance, Abe et al. (2019), describing the latest results from the XMASS-1 liquid xenon experiment, begin their paper with "The existence of dark matter (DM) in the universe is inferred from many cosmological and astrophysical observations" and conclude by stating that they have succeeded in placing upper limits on the cross-section of interaction of the dark particles with nucleons; there is no suggestion that the lack of a detected signal might be due to the non-existence of the dark particles. This attitude is typical.

[15] The lack of any clear evidence for these phenomena can, of course, be explained by assuming that dark matter does not exist, and Kroupa argues just this way in his (2012, 2015).

[16] This is similar to the cosmological behavior of the electromagnetic field. In the early, radiation-dominated era, the energy density of the electromagnetic field was a dominant influence on the cosmological expansion, but today that field's only signficant influence on the (normal) matter takes the form of Coulomb or radiative interactions.

[17] As recently as 1974, Lakatos wrote (p. 161): "at least among philosophers of science, Baconian method [i.e. inductivist logic of discovery] is now only taken seriously by the most provincial and illiterate." This view—closely associated with Popper's critical rationalism—was commonly accepted throughout much of the 20th century and is still the preferred epistemology of many scientists and philosophers (e.g. Jarvie et al., 1995; Parusniková & Agassi, 2020; Sassower et al., 2019), although it seems to have fallen out of favor with scientific realists.

[18] Note Psillos's implicit *assumption* that scientists follow "ampliative-inductive methods." That assumption is very common in the realist literature; e.g. Chakravartty (2017, p. 20): "Inference to the best explanation … seems ubiquitous in scientific practice." Chakravartty gives no justification for his sweeping statement.

> H tells tallies best with background knowledge. This knowledge must contain all relevant information about, say, the types of causes that, typically, bring about certain effects, or the laws that govern certain phenomena etc. *At least in non-revolutionary applications of IBE*, the relevant background knowledge can have the resources to discriminate between better and worse potential explanations of the evidence.

Note the qualification. Here, as in much of the realist literature, 'background knowledge' includes the existing, standard, theoretical framework ("the laws that govern certain phenomena"), and the 'best' explanation, at least in "non-revolutionary applications," will be one that *leaves that framework intact.* Psillos reiterates:

> Suppose there are two potentially explanatory hypotheses H_1 and H_2 but the relevant background knowledge favours H_1 over H_2. *Unless there are specific reasons to challenge the background knowledge*, H_1 should be accepted as the best explanation (italics added).

According to Psillos, the 'best' explanation is one that targets the anomaly and explains it in a manner that does not require changes in accepted theory(ies). As Day and Kincaid (1994, p. 277) express it, this amounts to "evaluating any particular belief in terms of its fit with what else one believes."

Just such an attitude is apparent in Niiniluoto's (2018, p. 147) discussion of the rotation-curve anomaly. Niiniluoto presents the dark-matter hypothesis as an exemplar of (what Psillos might call) 'non-revolutionary' IBE:

> Already in 1933 Fritz Zwicky estimated that there is not enough ordinary matter to hold galactic clusters together, and postulated that there must additional "dark matter". Further evidence was given in 1980 by Vera Rubin, who noted that the rotation curves for the velocities of stars and gas clouds are flat instead of decreasing with distance from the galactic center. Here theory T is Newton's mechanics, and the initial condition I states the amount of ordinary baryonic matter in the universe. Anomalous evidence E, including observations about the expanding universe and the anisotropies in the cosmic microwave background radiation, has led to the explanatory hypothesis that the universe consists only about 5% of ordinary matter and the rest is dark matter and dark energy. Here *theory T is kept constant*, but the initial condition I is revised into a hypothesis I*E about the amount of dark matter, so that T and I*E entail E. *The majority of physicists accept this abductive inference to the best explanation* … The alternative strategy is to accept the initial condition I about ordinary matter, but to revise Newton's theory T*E, so that T*E and I entail E. Such revisions of the standard cosmological Lambda-GMD [sic] model have been proposed by modifying the Newtonian dynamics (Mordechai Milgrom's MOND in 1983).

Based on this passage, Niiniluoto seems to have misunderstood how ordinary ('baryonic') matter enters into the two competing explanations.[19] Nevertheless it is clear what Niiniluoto is arguing: that the 'best' explanation is, *ipso facto*, the one in which the current theory of gravity "is kept constant." And (Niiniluoto implies) because that explanation is 'best,' it is the one that has been adopted by the "majority of physicists".[20]

The definition of 'best' advocated by Psillos, Niiniluoto and others is reasonable from the point of view of a realist who believes that successful, 'mature,' theories are essentially correct. Of course, if scientists in the past had been constrained to reason in this way, we would have been deprived of many of those current theories! But the realist's attitude is, apparently, "That was then, this is now": fundamental changes in our 'mature' theories are no longer to be expected (even though such changes were necessary to get us where we are today), and so an explanation of an observational anomaly that postulates such changes is *ipso facto* not 'best.'

But there is a more important point to be made here. Niiniluoto ignores the fact that the Milgromian explanation is *predictive* of rotation curve data, while the standard-model explanation is only *accommodating* of those data. Recall from the previous discussion how this came about: Milgrom initially crafted his postulates to yield the known, asymptotic flatness of rotation curves, but the same postulates imply that a galaxy's kinematics should be *fully predictable* based on the observed ('baryonic') mass alone, and this bold prediction has been shown again and again to be correct—as near as anyone can tell, Milgrom's theory correctly predicts the rotation curve of every observed galaxy. The standard-model explanation of the rotation-curve anomaly—which simply instructs the scientist to assume whatever amount and distribution of dark matter are required to explain whatever discrepancy arises, galaxy by galaxy—can boast no such predictive success.

Now, advocates of IBE as a model for scientific discovery often acknowledge that the 'best' explanation, *in addition to being the most likely*, should also have this extra property: it should successfully predict novel facts. For instance, Niiniluto, in the same volume from which the passage above was taken, writes (p. 117):

> A hypothesis that explains our initial data, and is thereby confirmed by it to some extent, may still be ad hoc. To remove this doubt, the hypothesis should be independently testable, i.e. it should either explain some old evidence or be successful in serious new tests. … one may argue that IBE as an acceptance rule should contain an additional condition stating that the "best" hypothesis is one with both explanatory and predictive power.

Psillos (1999, pp. 105 and 173) concurs:

> we should not accept a hypothesis merely on the basis that it entails the evidence, if that hypothesis is the product of an ad hoc manoeuvre
>
> … The notion of empirical success that realists are happy with is such that it includes the generation of novel predictions which are in principle testable.

But there is an obvious inconsistency here. The requirement that a theoretical explanation be fruitful—that it successfully predict new facts, in addition to the anomaly that it targets—conflicts with the requirement that it be a *likely* explanation of that anomaly. As Salmon (2001, p. 121) puts it:

> In general, the bolder a hypothesis is, the smaller its probability will be on any given body of evidence. … Scientists often choose bolder hypotheses because of their informational value, even if this means opting for less probable hypotheses.

Here Salmon is, of course, echoing Popper; as when Popper (1983, p. 256) challenged the inductivist to explain

> why scientists invariably prefer a highly testable theory whose content goes far beyond all observed evidence to an ad hoc hypothesis, designed to explain just this evidence, and little beyond it, even though the latter must always be more probable than the former on any given evidence. How is the demand for a high informative content of a theory—for knowledge—to be combined with the demand for a high probability, which means lack of content, and lack of knowledge?

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[19] When explaining the rotation curve of a spiral galaxy, both the standard-model cosmologist, and the Milgromian cosmologist, infer the distribution of *ordinary* matter using the same, well-established techniques. Those techniques require the application of auxiliary hypotheses (both observational and theoretical) but (barring personal ideosyncracies) the same set of hypotheses will be adopted by both researchers. The spatially-averaged, or cosmological, density of baryons, the quantity that Niiniluoto seems to be referring to in the quoted passage, does not enter into the problem for either researcher. See also footnote 13.

[20] Niiniluoto's choice of words admits of a different intended meaning: that we should judge the dark matter explanation to be 'best' *because* it is the explanation that has been adopted by the majority of physicists.

Charles Peirce (1878/1998, paragraph 120) came close to expressing the same idea:

> For after all, what is a likely hypothesis? It is one which falls in with our preconceived ideas. But these may be wrong. Their errors are just what the scientific man is out gunning for more particularly. … The best hypothesis, in the sense of the one most recommending itself to the inquirer, is the one which can be the most readily refuted if it is false.[21]

Peirce's view aligns with Popper's if we identify (as Popper did) the “most readily refuted” hypothesis with the boldest one: the one that entails the highest number of testable propositions.

The inconsistency between these two requirements for a ‘best’ explanation—that it have a high probability based on background assumptions, and that it successfully make predictions that go beyond those assumptions—is well illustrated by the two competing explanations of the rotation-curve anomaly. Milgrom's bold hypothesis can hardly be called ‘probable’, yet a great deal of its novel content has been experimentally confirmed; while the standard-model explanation of rotation curves, while (arguably) more probable given the background knowledge *c.* 1980, entails fewer testable propositions and has had a dismal record of anticipating new discoveries.

This situation invites the questions: Can these two requirements be reconciled? If not: which is more fundamental? And which should we respect when deciding on the ‘best’ explanation of the rotation curve anomaly?

It is interesting to examine the astrophysical literature. Milgrom (1983a,b,c), when introducing his three postulates, nowhere suggests that those postulates are ‘probable’ or ‘best’. He gives two motivations for his proposed modification of Newton's laws: (i) that the dark matter hypothesis is ad hoc; and (ii) that the discrepancies that are explained by postulating dark matter occur in regimes of very low acceleration, where there are no, independent tests of the validity of Newton's (or Einstein's) theory, hence it is not unreasonable to consider modifying that theory. Furthermore Milgrom stated clearly that his novel predictions could be, and should be, experimentally tested and he noted that for many of them, the tests would be “straightforward.”

Without taking too much license, we can summarize Milgrom's justificatory arguments from 1983 as follows:

1. The first tests, *c.* 1975, of Newton's laws in the regime of low acceleration failed: galaxy rotation curves were predicted to decline at large radii, but were found to be asymptotically flat.
2. Explanations of the anomaly that postulate the existence of dark matter are ad hoc, since they instruct the scientist simply to assume whatever distribution of dark matter is needed to accommodate the discrepancy.
3. One can explain the anomaly in a different way, by postulating a modification of Newton's laws.
4. That hypothesis entails a number of novel, testable predictions, as follows: …

So stated, Milgrom's argument would seem a poor example of IBE, or indeed of ‘inference’ of any kind. Milgrom took a shot in the dark, so to speak, with no obvious expectation of success, and *he assigned the entire warrant for acceptance of his conjecture to future confirmation of its novel predictions*.

Perhaps this is unsurprising given Psillos's restriction of IBE to “non-revolutionary applications.” Milgrom's proposal is nothing if not revolutionary. But it is striking how well Milgrom's methodology aligns with a different epistemological school: the critical rationalism of Karl Popper. Popper, of course, did not believe in a logic of *discovery*: only of *justification*. As opposed to the inductivists, he found no intrinsic merit in a hypothesis being likely:

> My theory of preference has nothing to do with a preference for the ‘more probable’ hypothesis. … the ‘better’ or ‘preferable’ hypothesis will, more often than not, be the *more improbable one* (1972, p. 17).

What mattered to Popper was that a new hypothesis have more content—that it entail more (testable) predictions—than the hypothesis it replaces:

> the new theory should be *independently testable*. That is to say, apart from explaining all the *explicanda* which the new theory was designed to explain, it must have new and testable consequences (preferably consequences of a *new kind*); it must lead to the prediction of phenomena which have not so far been observed (1963, p. 241)

and furthermore that at least some of the novel content be experimentally confirmed; that is, that the modified theory pass some new, and severe, tests:

> if the progress of science is to continue, and its rationality not to decline, we need not only successful refutations, but also positive successes. We must, that is, manage reasonably often to produce theories that entail new predictions, especially predictions of new effects, new testable consequences, suggested by the new theory and never thought of before (ibid, p. 243).

Popper, like Milgrom in his papers from 1983, pinned the entire warrant for acceptability of an explanatory hypothesis on its (future) success: on how well it stands up to tests: to attempted refutations. No additional merit accrues to a hypothesis on the grounds that it is ‘best’ in the sense of ‘a priori most probable.’ In Popper's (1972, p. 18) words, “Of course, one may *call* the preferable theory the more ‘probable’ one: *words do not matter*, as long as one is not misled by them.”

Paul Feyerabend was famously averse to methodological strictures, but there is one methodological rule that he argued for, again and again (1963; 1964a,b; 1965; 1970; 1978): When faced with an experimental anomaly whose refuting character can not be definitely established, he said, prefer the hypothesis that explains the results without contrivance and which links that explanation to other observable phenomena. Feyerabend coined the term “effective refutation” to describe situations like this:

> The reason why a refutation through alternatives is stronger is easily seen. The direct case is “open,” in the sense that a different explanation of the apparent failure of the theory (of the inconsistency between the theory and certain singular statements) might seem to be possible. The presence of an alternative makes this attitude much more difficult, if not impossible, for we possess now not only the *appearance* of failure (viz., the inconsistency) but also an explanation, on the basis of a successful theory, of why failure *actually occurred* (1965, pp. 249–250).

Feyerabend illustrated his proposed methodological rule using the (historical) example of Brownian motion, but his rule would seem to apply perfectly to several of the experimental results described here. For instance: the non-detection of dark particles constitutes a (non-refuting) anomaly for the standard cosmological model, but it is naturally explained by Milgrom's theory, and Milgrom's explanation also entails a number of other successful predictions, e.g. the full rotation curve of the Galaxy, which are not matched by the standard model. As in the case of Popper's theory of corroboration, Feyerabend's rule for theory choice makes no reference to the ‘best’ explanation except insofar as the ‘best’ explanation is the one that is empirically most successful.

Given these examples, one wonders what is to be gained by calling an inference ‘best,’ so long as it satisfies the other condition that Psillos and Niiniluoto (and Popper and Feyerabend) identify as essential—success at making novel predictions. Perhaps the methodological rule, “Accept a

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[21] Nyrup (2015) proposes what he calls a “Peircean view of IBE”: that IBH “first and foremost justifies pursuing hypotheses rather than accepting them as true.”

new hypothesis only if it passes new tests" is unpalatable to realists, since it effectively removes the 'inference' from 'inference to the best explanation.' As Lakatos (1968, p. 388) noted, "It is up to us to devise bold theories; it is up to Nature whether to corroborate or to refute them."

5. Two arguments for realism

5.1. *Novelty = truth*

Many philosophers have based arguments for scientific realism on the empirical success of theories (Barnes, 2008; Hitchcock & Sober, 2004; Lipton, 1990; Musgrave, 1988; Putnam, 1975; White, 2003). In Roger White's (2003, p. 654) words, "one central argument for scientific realism claims that the predictive success of scientific theories in general is significant evidence for their truth."

Perhaps no one has argued more strongly for the special epistemic status of successful, *novel* predictions than Jared Leplin (1997). Leplin's thesis is neatly captured by the title of his book: *A Novel Defense of Scientific Realism.* He writes (p. 100; italics added):

> One way that a theory displays explanatory power is by successfully predicting a result from which its provenance is free. If no other theories predict even qualitative generalizations of the result, then there is an explanatory challenge that the theory uniquely meets. In this situation, if we are not to credit the theory with some measure of truth, then we have *no* way to understand how the theory is able to meet this challenge. … Novel success is the exception to the antirealist strategy of proliferating explanations of success; *it cannot be explained without crediting the theory that achieves it with some measure of truth.*

As this passage suggests, Leplin sets two conditions (which he views as sufficient, if not necessary) for a predicted experimental result to be considered novel. First, following Elie Zahar (1973) and Lakatos and Zahar (1976), Leplin proposes an "independence condition": that the theory explaining the result should not depend on knowledge of the result for its content or development. (In Zahar's words, the theory was not "cleverly engineered to yield the known facts"; in Leplin's formulation, the novel result is "one whose antecedent availability a theory need not depend on" (p. 49).) The success of a theory in explaining a result that *was* used in the theory's construction may be explainable without requiring the theory to be true.

And following Alan Musgrave (1974), Leplin proposes a "uniqueness condition": that at the time a theory predicts some observed regularity in nature (as opposed to a singular event), there exists no alternative theory that "provides a viable reason to expect" that regularity. "Truth is not to be attributed to a theory in explanation of its explanatory success if the result explained can also be explained another way" (pp. 64-5). (In Musgrave's words (p. 15): "in assessing the evidential support of a new theory we should compare it, not with 'background knowledge' in general, but with the old theory which it challenges.")

Leplin then argues (p. 102–103) for a link between novel success, as he defines it, and what he calls "partial truth":

> My argument defends the inference from a theory's novel success to its partial truth, interpreted as degree of representational accuracy. Minimally, I am com-mitted to the claim that the greater the novel success uncompromised by empiri-cal failure that a theory sustains, the less likely are the theory's predictive and explanatory mechanisms to be wholly unrepresentative of the physical entities and processes actually responsible for the relevant observations.

(He continues "I am vague by default as to how much novel success merits what level of confidence in representational success.")

As Leplin notes, his argument can make claims both for specific theories, and, at the meta-level, for science as a whole. In the case of the science of cosmology, those claims pull in opposite directions. On the one hand, Leplin would argue that it is appropriate to attribute some measure of truth to MOND. Several of Milgrom's successful predictions—the BTFR, the CSDR, the RAR among them—clearly satisfy both of Leplin's conditions for novelty. Information about these observed regularities did not contribute in any way to the formulation of Milgrom's theory: indeed they were not observationally established until some years after 1983. And, as discussed above, the competing theory (the standard cosmological model) provides no "viable reason to expect" these regularities to exist. And at least since the addition (*c*. 1980) of the postulates relating to dark matter, the standard model can claim no comparable successes of novel prediction. So Leplin's argument would imply that we interpret Milgrom's theory, and *not* the standard cosmological model, in a realistic way: as a (at least partially) true representation of nature.

It is common to find comparisons of the two theories on the basis of their ability to accommodate the observations, without regard to predictive *novelty*. Many cosmologists (e.g. van den Bosch & Dalcanton, 2000; Dodelson, 2011; McGaugh, 2015; Freese, 2017; Bertone & Hooper, 2018) and philosophers (e.g. De Baerdemaeker & Boyd, 2020; Massimi, 2018) have noted that one theory successfully accounts for data in certain regimes (galaxies; galaxy groups) while the other successfully accounts for data in complementary regimes (the early universe; large-scale structure). This observation is often followed by a sentiment like "Both theories have had their successes and their failures. Let's give due credit to both!" That attitude may be socially commendable but it is epistemically bankrupt. Both theories may be false but at most one of them can be true. The 'success' of (at least) one of these theories is a red herring: it can be telling us nothing about *that* theory's validity.

Given recent developments (e.g. Skordis & Złosnik, 2020), there is no longer any basis for claiming that Milgrom's theory is successful only on galactic scales. But even if the two theories were equally successful at explaining all existing observations, Leplin's criteria would still lend us a warrant for favoring one (Milgrom's) over the other as a (partially) true representation of nature. And by favoring a realist interpretation of Milgrom's theory, those criteria simultaneously lend support to the *anti*-realist position: that current, mature theories in the physical sciences, even successful ones, are susceptible to replacement by ontologically incommensurate ones.

5.2. *Convergence*

A second argument for realism is often invoked in the context of the atomistic hypothesis. Jean Baptiste Perrin (1913) noted that—under the assumption that atoms exist—one could interpret the results of varied experiments as determinations of Avogadro's number, and that there was good numerical agreement between the values so obtained. He concluded from this coincidence that "the real existence of the molecule is given a probability bordering on certainty" (1916, p. 205-6). Wesley Salmon (1984, p. 220) endorsed Perrin's argument:

> If there were no such micro-entities as atoms, molecules, and ions, then these different experiments designed to ascertain Avogadro's number would be genuinely independent experiments, and the striking numerical agreement in their results would constitute an utterly astonishing coincidence.

Losee (2004, 2005) argued that a similar claim could be made about early experimental determinations of Planck's constant. He used the term 'convergence' to describe the phenomenon of diverse experimental determinations agreeing on a single value for a proposed, new constant of nature.

In the case of Planck's constant, there is no physical entity the real existence of which is in question. In fact Losee did not argue (as Salmon had) for a link between convergence and entity realism. Losee proposed rather that an instance of convergence constitutes "a sufficient condition of progressive theory-replacement … what is warranted by the convergence criterion is transitions between one *type* of theory to a second" (2004, p. 156-7).

We can try to apply arguments like Salmon's and Losee's to the two cosmological theories. The standard cosmological model, like the atomistic theory of matter, postulates the existence of a new entity: dark matter. And Milgrom's theory, like theories of energy quantization, postulates the existence of a new constant of nature: Milgrom's constant, a_0.

First consider MOND. Under the assumption that Milgrom's theory is correct, one can use its predictions to determine the value of a_0 from various sorts of observational data. For instance, a_0 appears as an adjustable parameter when fitting any galaxy's rotation curve, and one sort of convergence would consist of demonstrating that the same value is obtained for every galaxy, modulo errors. Li et al. (2018) and McGaugh et al. (2018) find not only that MOND successfully predicts rotation curves (with an average accuracy of 13%) but that the data are best fit by assuming the same value of a_0 for all galaxies.

Methods that combine data from a large sample of galaxies are able to determine a_0 with greater precision. For instance, one can 'read off' a_0 directly from the vertical normalization of the BTFR as plotted in the left panel of Fig. 1. One finds a value consistent with the rotation curve fits, but with less uncertainty:

$$a_0 = (1.29 \pm 0.06) \times 10^{-10}\ \mathrm{m\ s^{-2}}$$

(Lelli, McGaugh, & Schombert, 2016). Consistent results are obtained from fitting to the RAR and the CSDR (Lelli, McGaugh, Schombert, et al., 2016; McGaugh et al., 2016).

One can object that these experimental determinations are not as diverse or as independent as those cited by Perrin or by Planck. Some rather different methods for determining a_0 have been discussed, although all have substantially larger (systematic) errors. One example is the observed, upper limit on the surface brightness of galaxy disks (e.g. Davies, 1990) which (under Milgrom's theory) can be plausibly linked to a_0 via an evolutionary argument (Brada & Milgrom, 1999); the value of a_0 so inferred is only approximate but it is consistent (at a factor-of-two level) with the value given above. Other approximate techniques are discussed by Famaey and McGaugh (2012).

Next, consider how arguments like those of Salmon and Losee might be applied to the standard cosmological model, which postulates the existence of a new entity: dark matter. Now, a realist (or indeed almost any experimental physicist) is likely to argue that the strongest case for the reality of dark matter would be based on laboratory detection of the dark particles and not on a convergence criterion like Salmon's. But the failure (so far) to detect the particles does not inhibit standard-model cosmologists from arguing that dark matter must exist. The key observation, for them, is the CMB fluctuation spectrum. The mean, or cosmological, density of dark matter, ρ_{dm}, is determined from those data via a parameter fit. The fitting parameter is the dimensionless quantity Ω_{dm} where

$$\rho_{dm} = 3H^2/(8\pi G)\ \Omega_{dm}$$

and H is the cosmological expansion parameter ('Hubble's constant'); one typically sees the result expressed as the product $\Omega_{dm}\,h^2$ with $h \equiv H/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$. The value of $\Omega_{dm}\,h^2$ as determined from CMB data is 0.1187 ± 0.0017 (Schneider, 2015, Table-8.1) — a remarkably high, formal precision.

One could choose Ω_{dm} as the 'new constant of nature' and look for convergence. Unfortunately there do not exist any independent methods for determining Ω_{dm} that are of usefully high precision.

But there is another fitting parameter which — surprising as it may seem — is a good proxy for Ω_{dm} and which can be determined in a number of independent ways. It is the parameter that specifies the density of *normal* ('baryonic') matter, ρ_b, where

$$\rho_b = 3H^2/(8\pi G)\ \Omega_b\ .$$

When analyzing the CMB spectrum, the best-fitting values of Ω_b and Ω_{dm} are strongly correlated; in other words, the value inferred for Ω_{dm} is highly dependent on the value assigned to Ω_b, and vice-versa. Furthermore there are a number of methods that can be used to estimate the baryon density with high precision, including methods that (like Perrin's examples) are based on very different physical arguments.

Before about 2000, the standard method for estimating Ω_b was based on nucleosynthesis arguments. The abundances of the light nuclear species, like helium or lithium, is believed to have been set during the rapid phase of big-bang nucleosynthesis (BBN) when the universe was a few minutes old. The predicted abundances depend on the total density of nucleons, hence on Ω_b. Those predictions can be compared with the measured abundances to determine Ω_b. Since the method yields independent estimates of Ω_b for each nuclear species examined, a test of convergence is possible even without comparison with the CMB-based result.

The biggest difficulty in applying the method is ensuring that the measured abundances have not been affected by processes of creation or destruction *after* the era of BBN. For technical (but fascinating) reasons, the strongest case can be made for lithium-7 (see Spite et al., 2012). Estimates of Ω_b based on lithium were made as early as the 1970s and have remained remarkably unchanged since then; one current estimate (Sbordone et al., 2010) is

$$\Omega_b h^2 = 0.0139 \pm 0.0016$$

Between about 1980 and 2000, abundance determinations of deuterium, helium-3 and helium-4 gave consistent results, although with larger uncertainties. This convergence of measured values of Ω_b (astrophysicists used the term 'concordance') was felt to lend strong support to the big bang model — although the fact that the nucleosynthesis argument depended only on the *baryon* density meant that no claims could be made about dark matter.

Another method for estimating Ω_b (also unaffected by assumptions about dark matter) consists of carrying out a census of normal matter in the nearby universe. Here the main difficulty is ensuring that all 'baryons' have been detected (and none have been double-counted). The study by Shull et al. (2012), considered by many astrophysicists to be the most careful and complete of its kind, found

$$\Omega_b h^2 = 0.0159 \pm 0.0029$$

consistent with the determination based on lithium abundance and with the pre-2000 'concordance' value.

Unfortunately, the currently-accepted value of Ω_b based on the CMB is substantially larger than either of these estimates:

$$\Omega_b h^2 = 0.02214 \pm 0.00024$$

There is currently only one other method of estimating Ω_b that yields a result consistent with the CMB-based value. The abundance of *deuterium* can be combined with the equations of nucleosynthesis to yield estimates of Ω_b. Deuterium is a problematic nuclide to use in this way because of its ease of destruction by nuclear reactions, even at temperatures that occur in the atmospheres of stars. Estimates of Ω_b using deuterium were consistent (within the large uncertainties) with the lithium estimate before about 2000, but after that date, estimates (or at least a subset of them) have rather mysteriously converged on the CMB value.[22]

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[22] The apparent conflict between the lithium- and deuterium-based estimates of Ω_b is independent of any assumptions about dark matter and so will be equally puzzling to Milgromian and standard-model researchers. It is currently unclear whether RMOND requires the same Ω_b as the standard model in order to fit the CMB spectrum, or whether (for instance) it might fit those data with the lower, pre-2000 concordance value. If so, the 'lithium problem' and the 'missing baryons problem' would disappear but they would be replaced by a 'deuterium problem.'

Standard-model cosmologists acknowledge the failures of convergence of independent determinations of Ω_b: they refer to the failures as the ‘lithium problem’ and the ‘missing-baryons problem’. But recognition that a problem exists has not, apparently, generated in any uncertainty in their minds about the correctness of the CMB-based determination. For instance, Fields (2011, p. 48) writes:

> measurements of the cosmic microwave background (CMB) radiation have precisely determined the cosmological baryon and total matter contents … It is difficult to overstate the cosmological impact of the stunningly precise CMB measurements.

In summary: as in the case of the novelty argument, the convergence argument—in supporting the reality of Milgrom's theory—works against the realists' belief that current, ‘mature’ theories in the physical scientists are approximately correct.

6. Discussion

As discussed above, the fact that the properties of dark matter in the standard cosmological model are only vaguely specified, and the reliance of that theory (much more than Milgrom's) on auxiliary hypotheses to explain observations of galaxies and galactic systems, makes it difficult to determine whether the two theories are empirically equivalent, even if that term is limited to existing (as opposed to all possible) observations. But an anti-realist position does not demand a demonstration of empirical equivalence. As Stanford (2006, p. 17) emphasizes, the threat posed by theory underdetermination to the realism thesis

> was not initially concerned with the possibility of empirical equivalents at all, of course, but instead with any alternatives sharing the impressive empirical achievements of our own best scientific theories. … our grounds for belief in a given theory would be no less severely challenged if we believed that there are one or more alternatives that are not empirically equivalent to it but are nonetheless consistent with or even equally well confirmed by *all of the actual evidence we happen to have in hand at the moment*. Following Larry Sklar (1975), we might call this a transient underdetermination predicament: that is, one in which the theories underdetermined by the existing evidence are empirically inequivalent and could therefore be differentially confirmed by the accumulation of further evidence.

I would argue that the current situation in the field of cosmology is, to adopt Sklar's words, a “predicament of transient underdetermination”: that is: that the two competing theories are, in fact, empirically *in*equivalent but that this fact has not yet been convincingly demonstrated due to the vagueness of the dark matter hypothesis. Nevertheless, following Stanford's argument, the impressive predictive successes of Milgrom's alternative theory already pose a significant challenge to the realist position that current, mature theories in the physical sciences are likely to be correct.

Suppose we assume for the sake of argument that the standard cosmological model is due to be overturned, by Milgrom's theory or by some variant of that theory. What aspect(s) of Milgrom's theory are likely to be retained following that transition? Leplin's argument from novel success warrants only (in Leplin's words) a belief in some degree of “representational accuracy” for the novelly-successful theory. But other philosophers (e.g. Kitcher, 1993; Psillos, 1999) have argued for ‘selective confirmation’: that there is a warrant for believing those *parts* or *aspects* of a theory that are responsible for their predictive successes, and hence that those parts are likely to be preserved following theory change. In the case of Milgrom's theory, it is easy to identify the relevant parts, since the successes of novel prediction all follow from the theory in its early, non-relativistic formulation: that is: from the postulates in his 1983 papers that imply the BTFR, the RAR, and the algorithm for prediction of galaxy rotation curves (Merritt, 2020).

Whether or not Milgrom's theory is true (or ‘true’), by testing the novel predictions of the theory, astrophysicists have been led to a number of discoveries that almost certainly would not have been made by standard-model cosmologists, at least in the near future and possibly ever. *Pace* Psillos, Niiniluoto and other realists, this would seem reason enough not to counsel cosmologists to be timid in their theorizing. And any philosopher, realist or otherwise, should be willing to acknowledge the possibility that even a theory as mature and as successful as the standard cosmological model *might* turn out to be fundamentally wrong.

CRediT authorship contribution statement

David Merritt: Conceptualization, Methodology, Validation, Writing – original draft, Supervision.

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