Feyerabend's rule and dark matter†

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Abstract

Paul Feyerabend argued that theories can be faced with experimental anomalies whose refuting character can only be recognized by developing alternatives to the theory. The alternate theory must explain the experimental results without contrivance and it must also be supported by independent evidence. I show that the situation described by Feyerabend arises again and again in experiments or observations that test the postulates in the standard cosmological model relating to dark matter. The alternate theory is Milgrom's modified dynamics (MOND). I discuss three examples: the failure to detect dark-matter particles in laboratory experiments; the lack of evidence for dark-matter sub-haloes and the dwarf galaxies that are postulated to inhabit them; and the failure to confirm the predicted orbital decay of Milky Way satellite galaxies and other systems due to dynamical friction against the dark matter. In each case, Feyerabend's criterion directs us to interpret the experimental or observational results as an indirect refutation of the standard cosmological model in favor of Milgrom's theory.

Keywords Cosmology · Dark matter · Falsification · Paul Feyerabend · Mordehai Milgrom

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1 Introduction

An unresolved question of current interest to cosmologists and particle physicists is the nature of the dark matter that is believed to fill the universe. Laboratory experiments designed to detect the dark particles have been underway since the 1980s but so far, no unambiguous signal has been observed. This negative result is generally considered insufficient to refute the underlying theory, however, since that theory (the standard, or ΛCDM, cosmological model) does not specify the cross-section of interaction of the putative particles with normal matter, and the signal from an event might be too weak to stand out against the background, regardless of how sensitive or discriminating the detector.

Paul Feyerabend proposed that situations similar to the one just described are common in science, and furthermore that they sometimes *can* be interpreted as effective refutations of the underlying theory. What is required, he argued, is an *alternate* theory that explains the experimental result and that makes new, successful predictions. In one of the earliest formulations of his methodological rule, Feyerabend (1964a, p. 351-352) wrote:

> Consider a theory *T* … which entails that *F*. Assume that actually *F′* (where "*F* takes place" is inconsistent with "*F′* takes place"). Assume also that the laws of nature forbid the existence of equipment for distinguishing *F* and *F′*. The theory *T* is then obviously false; only we shall never be able to discover this by a consideration of "the facts" only.
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> …
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> Assume that, in addition to *T*, we introduce another theory *T′* … which covers the facts supporting *T*, makes successful additional predictions *A*, and entails that *F′*. The test of the additional predictions may be regarded as an indirect proof that *F′* and, thereby, as an indirect refutation of *T*.

As applied to the dark-matter detection problem, Feyerabend's *T* would be the standard cosmological model, *F* would be a statement something like "dark-matter particles are passing through my detector", and *F′* would be the negation of *F*. A viable alternate theory exists that entails this *F′* and that (arguably) satisfies the other conditions that Feyerabend sets for *T′*: it is Milgrom's (1983) modified Newtonian dynamics, or MOND, which indeed has made a number of "successful additional predictions." Taken at face value, Feyerabend's rule instructs us to treat the non-detection of dark particles as an (indirect) refutation of the standard cosmological model in favor of Milgrom's theory, and hence as a falsification of the dark matter hypothesis.

Feyerabend (1963; 1964a,b; 1965; 1970; 1978) was keen to draw some very general conclusions from his rule: about the nature of induction, the meaning of empirical content, the theory-ladenness of factual statements, the need for theoretical pluralism and so on. These generalizations have been criticized (and, less often, defended) by a number of authors. The criticisms (e.g. Worrall 1978, 1991; Laudan 1989; Preston 1997) are interesting and important, but for the most part, they have not been directed against the use of Feyerabend's criterion as a guide for choosing between theories.

I will argue that, in the context of current cosmological theory, the situation that Feyerabend describes is quite common: it crops up again and again in observations or experiments that test the postulates in the standard cosmological model relating to dark matter. In each of the three examples that I will discuss in detail, I will argue that Feyerabend's criterion directs us to decide in favor of Milgrom's theory and against the standard cosmological model.

2 Feyerabend's rule

The two cosmological theories discussed here are characterized by strikingly different ontologies. The standard cosmological model assumes the existence of dark matter; Milgrom's theory does not. The entity which standard-model cosmologists call `dark matter' is what scientific realists (e.g. Boyd 1984) sometimes label a `theoretical term' or `theoretical entity': the particles that make it up have never been detected in the laboratory via methods that an experimental physicist would consider decisive, hence the existence of the particles remains conjectural.

A comprehensive discussion of the sucesses and failures of the two cosmological paradigms can be found in the excellent review articles by Famaey & McGaugh (2012) and McGaugh (2015) and in the recent monograph by Merritt (2020). These authors point out that the two theories come close to achieving what philosophers of science call `empirical equivalence': that is: researchers in both camps can claim (with greater or lesser justification) to successfully explain a large body of observational and experimental results.[1] In the past, that claim could only be made with regard to data relating to galaxy-scale phenomena. But following the successful relativistic generalization of Milgrom's theory by Skordis & Złosnik (2020), the explanatory scope of Milgrom's theory has been expanded to include the cosmic microwave background (CMB) temperature fluctuation spectrum, the matter power spectrum, gravitational lensing statistics etc. — precisely the data that

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[1] Of course there are data which constitute anomalies for both theories. Two examples: (i) the measured abundances of lithium-7 and deuterium imply, via the equations of big bang nucleosynthesis, very different numbers for the mean density of nuclei (`baryons') in the universe. This anomaly is independent of assumptions about dark matter and exists with equal force in both theories. (ii) The observed dynamics of galaxy clusters is difficult to explain under either theory. Under the standard model, dark matter is invoked to explain the cluster data, but with limited success. Merritt (2020) also presents a list of anomalies that exist under the standard model but not under Milgrom's theory (the `core-cusp' problem, the `too big to fail' problem, the `problem of the satellite planes' etc.).

standard-model cosmologists (e.g. Dodelson 2011) have often insisted can only be explained by postulating dark matter.[2]

But there is one sort of observational result that is usually ignored when tabulating the successes and failures of these two competing theories. Consider, for example, the fact that laboratory experiments have so far always failed to detect the dark particles. One might be tempted to argue: "The non-detection of dark-matter particles constitutes a success of prediction for Milgrom's theory, since that theory does not postulate the existence of dark particles, hence it predicts that none will be observed." Such an argument is rarely, if ever, made. After all, Milgrom's theory does not postulate the existence of unicorns, but one would hardly claim that a failure to observe unicorns constitutes evidence in favor of Milgrom's theory.

But Paul Feyerabend argued that negative experimental results like this can, if certain conditions are satisfied, be interpreted as effectively refuting one theory while providing a warrant for belief in another.

Feyerabend (e.g. 1965, p. 176) motivated his proposed methodological rule using the example of Brownian motion. Already in the 19th century, French physicist Louis Georges Gouy had argued that the seemingly unending motion of pollen grains submersed in a fluid medium constituted a potential problem for the theory of phenomenological thermodynamics, but (Feyerabend argued) inconsistency with that theory was impossible to demonstrate experimentally, since doing so would have required precise measurement of the particle's kinetic energy and of the amount of heat transferred from the fluid. Whereas the kinetic/corpuscular theory of heat as developed by Einstein and Smoluchowski in the early 20th century was not only accommodating of Brownian motion but also entailed novel predictions about the long-time statistical nature of the motion, predictions that were subsequently confirmed by Jean Baptiste Perrin and others. After these consequences of the kinetic theory had been developed and tested, Feyerabend argued, the earlier observations of Brownian motion could be (re-)interpreted as refutations of the phenomological theory.

As a second example, Feyerabend (1969, 1981) discussed the discovery of "observer dependence" (in the sense of relativistic frame dependence). He noted that the Newtonian

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[2] Skordis & Złosnik were not the first to demonstrate empirical equivalence of this sort. At least two earlier versions of Milgrom's theory (Angus 2009; Bereshziani & Khoury 2015) successfully accounted for all large-scale cosmological data, but they did so by postulating forms of dark matter. Skordis & Złosnik were the first to achieve this without invoking any form of dark matter.

postulate of observer *in*dependence appeared to conflict with some "second-order effects of motion" in electrodynamics,[3] but that

> it was assumed, for some time, that a solution could be found within the framework of classical physics; i.e. it was assumed that the difficulties were difficulties of the *application* of the classical point of view rather than of some basic assumptions of this point of view itself (Feyerabend 1969, p. 52).

Einstein's special and general relativity theories were inconsistent with the idea of observer independence and were adopted because of their empirical successes. But, Feyerabend argued, the failure of the classical point of view was "a *consequence* of the success of the new theory and could not have been demonstrated without this theory."

Feyerabend claimed that situations like these—in which there exist experimental results that suggest a theory refutation or anomaly, but where limitations in the experimental method, or uncertainties in the interpretation of the theory, make it essentially impossible to establish the refutation—are common in science. He argued not only that an alternate theory is needed to demonstrate the refutation, but that "a refutation that is based on a successful alternative is much *stronger* than is a refutation resulting from the direct comparison of theory and "facts" " (Feyerabend 1965, p. 249). Because a potential anomaly can always be put aside, or dealt with by ad hoc theory adjustments, alternate theories are needed to force adherents of the original theory to accept the refuting character of the experimental result.

But in what sense (if any) was it reasonable for Feyerabend to claim that *success* of the alternate theory constitutes a *refutation*—if only indirect, or effective—of the original theory? One interpretation (e.g. Laymon 1977) runs as follows: The fact that T' successfully predicts novel phenomena A lends support to T' ; and since T' is inconsistent with T (T' entails F', T entails F, and F is inconsistent with F'), then, to the extent that T' is corroborated by the occurrence of A, T is disfavored. The success of T' in explaining A is thus seen as a reason for rejecting T. Stated differently: given two viable theories that are both consistent with an ambiguous experimental result, we should prefer the theory that is better corroborated through confirmed novel predictions. One might argue further that the `refutation' is strengthened to the extent that the novel predictions of T' are improbable or unexpected from the standpoint of T : that is: to the extent that A constitutes a severe test

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[3] Feyerabend does not state explicitly, in either of the cited articles, what he means by "second-order effects of motion". I believe that "second-order" here means order V^2/c^2 where V is the speed of the observer relative to the Ether and c is the speed of light. The famous Michelson and Morley experiments were of second-order in this sense. Cei (2020, Chapter 7) remarks that "by 1895 the genuinely troubling results [from the standpoint of Lorentz's theory] were only the ones of second order."

for T' given the background knowledge represented by T (as in Popper 1959, chapter 10 or 1983, chapter IV).

This interpretation is reasonable enough, but it omits one element that Feyerabend often emphasized: that from the standpoint of the original theory T, the experimental result is *anomalous*; it appears, at least superficially, to *require an explanation*. For instance (italics his):

> 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* (Feyerabend 1965, pp. 249-250).

In the Brownian motion example, for instance, the unending motion of the pollen grain, as interpreted from the standpoint of phenomenological thermodynamics, appeared to conflict with the conservation of energy, even though that conflict could not be demonstrated through measurements; while the same observed motions did not present a *prima facie* problem for the kinetic/corpuscular theory.

Laudan (1989), who was concerned primarily with Feyerabend's broad claims about the meaning of `empirical content', points out that there is no guarantee, in general, that theory T itself might not entail A; and if so it would be problematic to claim that confirmation of A can refute T. While this exact circumstance does not arise in any of the examples that I discuss in this paper, it is nevertheless true that adherents of the standard cosmological model (theory T in this case) will often claim to have explained (`accommodate' would be a better word here), in a post-hoc sense, some confirmed Milgromian prediction (that is, some A). Typically such claims are based on large-scale computer simulations that incorporate a number of adjustable parameters describing sub-grid physics, initial conditions and so forth. Worrall (1985, p. 313) argues 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.

Milgrom's theory explains the same facts "without contrivance". Following Worrall, I would argue that Laudan's objection does not apply in such cases: that is: that the successful Milgromian prediction of A trumps any post-hoc, standard-model accommodation of A via parameter adjustment.

In some formulations of his rule, Feyerabend placed a stronger condition on the predictions entailed by *T′* (called *A* in the above). For instance, in his (1965) he wrote (p. 176; note that *M* is used here in place of *A,* and *C* in place of *F*):

> assume that a theory *T* has a consequence *C* and that the actual state of affairs in the world is correctly described by *C'*, where *C* and *C′* are experimentally indistinguishable. Assume furthermore that *C′*, but not *C*, triggers, or causes, a macroscopic process *M* that can be observed very easily and is perhaps well known. … What is needed in order to discover the limitations of *T* implied by the existence of *M* is another theory, *T'*, which implies *C′*, connects *C′* with *M*, can be independently confirmed, and promises to be a satisfactory substitute for *T* where this theory can still be said to be correct.

Exactly what Feyerabend meant here by "triggers, or causes" is not obvious. John Worrall (1991, p. 346) writes: "Now, according to Feyerabend, C′ "triggers" M. I suppose this means that the state of affairs described by C′ causes (*via* the operation of natural laws) the process M." (Feyerabend, in response, was not very helpful: "Worral has difficulties with `triggers': any dictionary will tell him what the word means."[4])

I would suggest an alternate reading to Worrall's. It would be reasonable to argue that *some* novel predictions of *T'* are more relevant than others in the (effective) refutation of *T*. For instance, to the extent that the postulates comprising *T′* are independently testable, it is possible that the same postulate(s) of *T′* that entail *C′* might also entail *M*. Whereas novel predictions of *T′* that are logically unconnected from *C′* (if such exist) could reasonably be considered less relevant in the refutation of *T*.

Feyerabend often emphasized that theories in the early stages of development are less widely applicable than the theories they are meant to eventually replace; for instance in *Against Method* he writes:

> Theories which effect the overthrow of a comprehensive and well-entrenched point of view, and take over after its demise, are initially restricted to a fairly narrow domain of facts, to a series of paradigmatic phenomena which lend them support, and they are only slowly extended to other areas. … Later on, of course, the theory is extended to other domains; but the mode of extension is only rarely determined by the elements that constitute the content of its predecessors (Feyerabend 1978, p. 176).

Such a state of affairs would be difficult to reconcile with the statement in his (1964a) version of the rule that "we introduce another theory *T′* … which covers the facts supporting *T*." It would seem more reasonable to reformulate this as: "we introduce another

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[4] Feyerabend (1987, p. 293). The misspelling of Worrall's name is Feyerabend's.

theory T' … which covers the facts supporting *T, in whatever domain both theories are deemed capable of making valid predictions given their respective stages of development*." And indeed, in some formulations of his rule, Feyerabend inserted language that appears to be consistent with this interpretation; for instance in his (1964b, pp. 306-307) he begins the statement of his rule as follows (italics added):

> Consider a theory *T* which makes predictions *P in a domain D*, and assume also that the actual state of affairs P' is different from *P* but to such a small extent that the difference is far below the experimental possibilities.

In what follows I will assume that when Feyerabend requires T' to "cover the facts supporting *T*," he intends that statement to apply only to facts that lie in whatever domain(s) both theories are expected to be valid. This qualification (or clarification) is important, since there is no consensus yet on the proper, relativistically-invariant version of Milgrom's theory.[5] Both Milgromian and standard-model researchers do claim, however, that their theories are applicable to galaxies and to groups of galaxies, in regimes of density and velocity where relativistic corrections are not important (e.g. Famaey & McGaugh 2012).

3 Example no. 1: direct detection of dark matter

The standard cosmological model accounts for discrepancies in the rotation of disk galaxies by postulating additional gravitational force from unseen matter. The dark matter is assumed to have whatever spatial distribution is required to reconcile the observed motions with the gravitational force from the observed (non-dark) mass, assuming the correctness of Newton's laws of gravity and motion.[6] This postulate of the standard model has been formulated in various ways; for instance, Milgrom (1989, p. 216) writes "The DMH [dark matter hypothesis] simply states that dark matter is present in whatever quantities and space distribution is needed to explain away whichever mass discrepancy arises." Henceforth I will refer to this postulate of the standard cosmological model as the DMH. Note that the DMH can be used to generate predictions only about individual, observed galaxies, and only about the *dark matter* in those galaxies; it implies nothing about

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[5] Nevertheless there do exist relativistic versions of Milgrom's theory that are, apparently, as successful as the standard model at explaining data from the cosmic microwave background, the matter power spectrum on cosmological scales etc. See Angus (2009) and Skordis & Złosnik (2020) for two examples.

[6] Even some normal matter is expected to be `dark'; for instance, the black hole and neutron star remnants that are believed to be produced during the late evolution of massive stars. Astrophysicists (both standard-model and Milgromian) typically try to account for the presence of these objects when computing the gravitational force from the normal matter.

the properties of the normal matter, or about (for instance) the large-scale distribution of dark matter, the behavior of dark matter in the early universe etc. The standard cosmological model does contain additional postulates that are relevant to such questions but those postulates are logically and empirically independent of the DMH, and they do not enter in any way into the predictions that are tested via the direct-detection experiments described in this section.

In the case of the Milky Way galaxy, the density of dark matter required to reproduce the measured rotation curve given the observed distribution of normal matter (stars, gas dust), under simple assumptions about the dark-matter distribution (e.g. that it is smooth and spherically symmetric), is approximately 0.011 $M_\odot$ pc$^{-3} \approx 1.0 \times 10^{-24}$ g cm^{-3} near the Sun (Iocco, Pato & Bertone 2015). Assuming in addition (as standard-model cosmologists routinely do) that the dark matter is distributed macroscopically in a steady-state manner implies a local velocity dispersion of the dark particles of approximately 270 km s^{-1}. `Dark' is typically taken to mean `not interacting with photons' (e.g. Weinberg 2008, p. 186). No known particle is believed capable of constituting the dark matter (Tanabashi et al. 2018).

A prediction of the standard cosmological model is therefore that P_1: dark particles are passing through any Earth-based laboratory, with a mass density of ~10^{-24} g cm^{-3} and a velocity dispersion of ~270 km s^{-1} . Experimental tests of P_1 are called direct-detection experiments (Cerdeño & Green 2010; Marrodán Undagoitia & Rauch 2016) and about a half-dozen are currently underway (e.g. Kisslinger & Das 2019); some of these are updated or improved versions of experiments that have been ongoing since as early as the 1980s. 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 (Liu et al. 2017; Ko 2018; Schumann 2019).

The failure to detect the particles constitutes a *prima facie* anomaly for the standard cosmological model, just as the occurrence of Brownian motion presented a *prima facie* anomaly for phenomenological thermodynamics. One way to describe the problem is to say that existing experimental results are consistent both with P_1, and with P_1', its negation.

Application of Feyerabend's rule requires that "P' is different from P but to such a small extent that the difference is far below the experimental possibilities." There are two ways to demonstrate that Feyerabend's requirement is satisfied here. First: regardless of how senstive or discriminating the detectors become (the current generation of detectors are about 10^7 times more sensitive than those of the 1980s), failure to detect a signal will always be consistent both with the presence and absence of dark particles, since nothing is known (aside from experimentally-determined upper limits) about the interaction cross section of the particles with the normal matter in the detectors (e.g. Schumann 2019). Second: a consensus has emerged that the limits of detectability set by the `neutrino floor' will soon be reached: neutrinos are believed to be abundant, there is no way to shield the detectors against them, and they could induce nuclear recoils in a detector that would be difficult or impossible to distinguish from those caused by dark-matter particles (Vergados & Ejiri 2008; Billard et al. 2014). Hence (many experimenters acknowledge) the likelihood of a detection is becoming very small even if the dark particles exist.

Milgrom's theory (theory *T′* in Feyerabend's rule) does not postulate the existence of dark matter. The anomalous rotation of galaxies that is addressed in the standard model via the DMH, is explained in Milgrom's theory by assuming a modification to Newton's laws of gravity and motion (Milgrom 1983). Thus Milgrom's theory explains, in a natural way, the experimental anomaly: the lack of any experimental detection of dark particles. To satisfy the additional requirements set by Feyerabend for alternate theory *T′*, we need to identify confirmed, novel consequences of the theory; and following the discussion in the previous section, we would prefer that those consequences derive from the same postulates that correctly predict galaxy rotation, that is, the same postulates that remove the need for dark matter in galaxies like the Milky Way.

Milgrom (1983) postulates a relation different from Newton's between gravitational force and acceleration, for accelerations less than about $a_0 \approx 10^{-8}$ cm s^{-2}, where a_0 (`Milgrom's constant') is assumed to be a universal constant. In the asymptotic regime, i.e. $a << a_0$, Milgrom's modified dynamics predict that galaxy rotation curves will be `flat', that is, that the rotation speed V will be independent of R, the distance from the galaxy's center. Asymptotic flatness of rotation curves was a well-established fact already by 1980 and Milgrom has acknowledged (Milgrom 1983) that he designed his postulates to yield this result. But the same postulates that explain asymptotic rotation-curve flatness turn out to have a great deal of additional, testable content. Using the modified dynamics, one can predict the *full* rotation curve of any disk galaxy given the observed distribution of normal matter alone: both in the low- and high-acceleration regimes (Milgrom 1988; Brada & Milgrom 1995; Begeman, Broeils & Sanders 1991). Such predictions have been confirmed for dozens of disk galaxies of all sub-types; most remarkably, for galaxies that (according to a standard-model cosmologist) are `dark-matter dominated', that is, for which the observed rotation speed greatly exceeds the predictions of Newton at all radii (McGaugh & de Blok 1998).

A number of additional predictions are entailed by the same postulates that correctly account for rotation curves without dark matter. A functional relation is predicted, and has been observationally confirmed, between the asymptotic rotation speed and the total mass (normal, not dark) of a galaxy: the so-called `baryonic Tully-Fisher relation' (Lelli et al. 2016a). Milgrom's theory also successfully predicts a universal relation between the central surface density of a disk galaxy and the surface density that a standard-model cosmologist would assign to the dark matter in that galaxy (Lelli et al. 2016b).

Thus the remaining conditions set by Feyerabend are amply satisfied in this case: Milgrom's theory "covers the facts supporting *T"* and "makes successful additional predictions" within the domain where both theories are considered to be valid. Feyerabend's rule would therefore direct us to interpret the failure of the direct-detection experiments as (indirect) proof that the dark particles are not present.

Suppose we stop here for a moment and play devil's advocate. How do the two theories fare if we imagine reversing their order when applying Feyerabend's rule? Would the asymmetry that we have seen so far—Milgrom's theory favored, the standard model disfavored—survive the reversal, or might we find that the standard model can also `win' according to Feyerabend's criteria?

Thus: theory T is now Milgrom's, which predicts that P, i.e. that no dark particles exist. And here we notice the asymmetry already: because from the standpoint of Milgrom's theory, there is no experimental anomaly; the lack of any laboratory detection is now the *expected* outcome.

Continuing doggedly ahead, we next define as theory T' the standard cosmological model, which predicts that P' , i.e. that dark particles *are* present. We are assuming, of course, that P' is true. Now if we are going to claim that P' , like P, is consistent with the experimental results (no detections), we might want to include an additional hypothesis in T' that explains this fact. (No such additional hypothesis was required when Milgrom's theory played the role of T' .) And as noted above, standard-model cosmologists do not shrink from doing precisely this: for instance, by postulating arbitrarily small interaction cross sections. So we might want to re-define T' as the standard model plus an auxiliary hypothesis, something like `The interaction cross section of the dark particles with normal matter is so small that no detections are expected.'

Feyerabend next directs us to show that T' explains the other facts successfully explained by T. And here the asymmetry is dramatic: because T' explains *nothing* that is successfully explained by T . No standard-model algorithm exists that can predict an observed galaxy's rotation curve. The same is true with regard to the requirement that T' have corroborated excess content compared with T : both the dark matter postulate DMH, and the auxiliary hypothesis about interaction cross sections (if we choose to include it), are *ad hoc* manœuvres; both instruct the scientist to adjust the assumed properties (macroscopic or microscopic, respectively) of the dark matter as needed to maintain consistency with whatever data are available.

4 Example no. 2: primordial dwarf galaxies

Standard-model cosmologists have devoted considerable effort to understanding how galaxies like the Milky Way might evolve to their currently observed states, starting from some postulated initial conditions describing the dark matter, and including auxiliary hypotheses that describe the behavior of the normal matter (Longair 2008; Mo, van den Bosch & White 2010). While predictions that follow from such simulations can only be statistical in nature, some of the simulation results are robust enough that they can be used, with greater or lesser certainty, to generate testable predictions about single galactic systems. One often-discussed example is the prediction (Klypin et al. 1999; Moore et al. 1999) that much (~20% − 50%) of the dark matter surrounding a galaxy like the Milky Way should not be smoothly distributed: rather it should be clumped into bound `sub-halos', and the sub-halos should be distributed according to a mass hierarchy that is statistically well-determined by the simulations: roughly speaking, $N(m) \propto m^{-1.9}$, with m the mass of a single clump (Springel et al. 2008). Furthermore the spatial distribution of the sub-halos about the host galaxy should be approximately spherically symmetric and their velocity distribution should be approximately isotropic, that is, exhibiting little if any ordered motion (Pawlowski et al. 2014). In the case of a galaxy with the mass of the Milky Way, the number of such clumps is predicted to be quite large: about 500 with (dark) masses above $10^7\ M_\odot$ (Zavala & Frenk 2020). The mass of the largest such clump is not robustly predicted by the simulations but is estimated to be of order $10^{10}\ M_\odot$ for a galaxy similar in size to the Milky Way (Boylan-Kolchin et al. 2010). For comparison, the mass (in stars and gas) of the Milky Way disk is about $10^{11}\ M_\odot$.

The Milky Way (like many other, nearby galaxies) is known to be surrounded by a contingent of dwarf satellite galaxies: most famously the two `Magellanic Clouds' that are visible to the naked eye, but surveys have identified a few dozen of lesser mass (that is: lower luminosity), some as small as a few hundred solar luminosities (e.g. Drlica-Wagner et al. 2015). Since the 1990s, standard-model cosmologists have routinely identified these satellite galaxies with the dark-matter sub-halos in their simulations.[7] For instance, Willman (2010, pp. 1-2) writes

> The intrinsically faintest dwarfs (which can only be found and studied close to the Milky Way) likely inhabit the least massive dark matter halos that can host stars. Such dwarfs may thus provide the most direct measurement of the mass spectrum, spatial distribution, and clustering scale of dark matter.

The hypothesis here is that the stars of the observed satellites were formed out of gas that condensed in the gravitational potential wells of the dark sub-halos. This hypothesis is consistent (from a standard-model perspective) with the observed internal motions of the dwarf galaxies, which (as in the case of spiral galaxy disks) require dark matter in order to be reconciled with Newton's laws.

The postulated identification of the observed satellite galaxies with the sub-halos in the simulations is vulnerable to observational tests. I will focus on two standard-model predictions that appear, at least on the surface, to conflict with the observations. The first anomaly is similar to the direct-detection anomaly discussed above: it is the failure of so-

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[7] Indeed there is growing momentum, on the part of standard-model cosmologists, to *define* `galaxy,' quite generally, as `a stellar system containing dark matter'; see Willman & Strader (2012).

called `indirect detection' experiments to detect radiation from the sub-halos due to self-annihilation of dark matter particles. The second anomaly, called by standard-model cosmologists the `missing-satellites problem', is the fact that the observed number of Milky Way satellite galaxies is far smaller than the predicted number of dark-matter clumps. I will argue that both failures of prediction satisfy Feyerabend's condition: they are potentially falsifying instances, but the falsifications are difficult or impossible to demonstrate.

Indirect-detection experiments (e.g. Funk 2015) are based on the idea that dark-matter particles might sponaneously undergo reactions that result in photons or other standard-model particles, e.g. neutrinos, that could be detected even from great distances. One class of postulated reactions are the self-annihilations which have the form $\chi + \chi \rightarrow (\gamma, \nu, \ldots)$, that is, the dark particles (χ) act as their own anti-particles, yielding photons (γ) and neutrinos (ν) among other possible products. Spontaneous decays of the dark particles might also occur. Photons produced via such reactions would be expected to have gamma-ray energies and could be detected by existing gamma-ray observatories, either on the ground or in space (e.g. Porter, Johnson & Graham 2011). Among the many experimental challenges is the difficulty of distinguishing any detected photons from those produced by known astrophysical sources, e.g. pulsars, in the targeted galaxies (Buckley et al. 2013; Strigari 2018).

There is intersubjective agreement that no signal has yet been detected that can convincingly be interpreted as evidence for a dark matter sub-halo (Gaskins 2016; Conrad, Cohen-Tanugib & Strigari 2018; Rinchiuso et al. 2019). Most experiments have (quite reasonably) been `targeted' searches, that is, the telescopes have been directed toward known satellite galaxies, particulary those nearest the Earth. Untargeted searches (e.g. Glawion et al. 2019) could, in principle, detect sub-halos where there is no known satellite galaxy but such searches are much more time-consuming.

As in the case of the direct-detection experiments, the results are consistent both with the presence and the absence of the sub-halos. The reason is that the self-annihilation cross section, or decay lifetime, of the dark particles is unknown, and a failure to detect a signal can always be `explained away' by postulating small cross-sections or long lifetimes.[8]

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[8] Standard-model cosmologists sometimes invoke, in this context, the so-called `WIMP miracle': the fact that the self-annihilation cross-section needed to obtain the correct cosmological abundance of dark matter via thermal production in the early universe is similar to what is expected for a new particle (a `WIMP') that interacts via the electroweak force. However there is an emerging consensus that this paradigm for dark matter has already been experimentally ruled out (e.g. Siegel 2019). Karl van Bibber, in the *Summary* talk of the July 2016 *Identification of Dark Matter* (IDM2016) meeting in Sheffield, England, encouraged the experimenters in his audience not to be discouraged: "No hand-wringing over fraying of the `WIMP miracle'! … Often a deceptively too simple argument is just what's required to get the ball rolling."

Consider next the missing-satellites problem.[9] There is intersubjective agreement that the observed satellites of the Milky Way can account for only a small fraction of the predicted sub-halos in the relevant mass ranges; e.g. Silk & Mamon (2012, p. 939): “The excessive predicted numbers of dwarf galaxies are one of the most cited problems with ΛCDM. The discrepancy amounts to two orders of magnitude.” Stated differently: the vast majority of the sub-halos would need to contain few if any stars to avoid being observed as dwarf galaxies. There is no shortage of auxiliary hypotheses that have been proposed to explain the anomaly (e.g. Simon 2019); for instance, the infalling gas could have been heated by the first generation of stars, causing the gas to be removed and star formation to cease. But no single mechanism `works' across the full spectrum of satellite galaxy (that is, sub-halo) masses, and standard-model cosmologists routinely invoke different mechanisms, as the need arises, to explain the data on different mass scales. For instance, Bullock (2010, p. 12), after listing the various mechanisms that have been proposed for suppressing star formation in the sub-halos, remarks: “each imposes a different mass scale of relevance … If, for example, we found evidence for very low-mass dwarf galaxies … these would be excellent candidates for primordial H_2 [molecular hydrogen] cooling `fossils' of reionization in the halo.” Indeed, standard-model researchers often simply *assume* whatever mapping of dark mass to stellar mass (the `stellar mass-halo mass’ relation) is required to reconcile their dark-matter simulations with the observed population of dwarf galaxies (e.g. Jethwa, Erkal & Belokurov 2018).

The attitude of standard-model cosmologists toward the missing-satellites problem is similar to the attitude, described by Feyerabend (1947/1967), of scientists toward Eherenhaft’s experiments on electron charge. Feyerabend writes (appendix 2, p. 5) that when confronted with Ehrenhaft’s seemingly anomalous results, scientists

> occasionally acted almost as some of Galileo's opponents must have acted when confronted with the telescope. They pointed out that no conclusions could be drawn from them as they were the result of the interaction of many complex phenomena. In short, they were *Dreckeffekt*.

In the case of the primordial dwarf galaxy hypothesis, the “many complex phenomena” are the many physical processes invoked for suppressing star formation in the sub-halos.

The alternative theory is, once again, Milgrom’s. Milgromian researchers postulate a different formation mechanism for the satellite galaxies, one that does not invoke the existence of dark matter and which (as we will see) implies a number of testable and (from a standard-model perspective) extremely improbable consequences. The argument goes as follows (Kroupa 2014):

There is a formation mechanism that is well-established for dwarf galaxies like the satellites of the Milky Way: it is the removal, via tidal forces, of clumps of stars or gas

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[9] Milgromian researchers prefer the name `dwarf over-prediction problem.’

from the disks of spiral galaxies. Observations of interacting galaxies (e.g. Mirabel, Dottori & Lutz 1992; Weilbacher et al. 2000; Lee-Waddell et al. 2016) leave little doubt that this occurs, and this conclusion is reinforced by high-resolution simulation studies (e.g. Bournaud et al. 2008; Bílek et al. 2019). Thus, there is intersubjective agreement, among both Milgromian *and* standard-model researchers, that `tidal dwarf galaxies' (TDGs) exist around many spiral galaxies.

There may exist other dwarf-galaxy formation mechanisms. But from the standpoint of a Milgromian theorist, one mechanism that definitely can *not* exist is the one postulated by standard-model cosmologists for the Milky Way satellites: that is, formation inside of dark-matter sub-halos. Stated differently: In a Milgromian cosmology, `primordial dwarf galaxies' (PDGs) do not exist. It follows that some, and perhaps all, of the Milky Way satellites are TDGs. As in the standard cosmological model, there is no definite prediction of the expected number of satellites, but the observed population sizes (around the Milky Way and some other nearby galaxies) are consistent with expectations based on simulations of tidally-interacting galaxies (Okazaki & Taniguchi 2000; López-Corredoira & Kroupa 2016). Thus, both of the experimental anomalies discussed in this section—the `missing satellites,' and the failure to detect radiation from the dark sub-halos—are naturally explained under Milgrom's theory.

Feyerabend's second condition states that the alternate hypothesis must successfully predict novel facts, and this requirement is satisfied as well (Kroupa 2012; 2014). TDGs in interacting galaxies are observed to fall along `tidal tails': streams of material that (apparently) have been pulled out of one galaxy's disk during the interaction. Conservation of angular momentum implies that after the close encounter, the TDGs will continue to move in correlated orbits around their host galaxy—that is: they should be found to lie in approximately planar or toroidal structures, with most or all members orbiting in the same sense. And indeed, it has been known since the 1970s that almost all of the brighter Milky Way satellites lie in a stream that aligns (on the plane of the sky) with the two largest satellites, the Magellanic clouds.[10] Observations since the 1970s have added to the number of known satellites and have also yielded information about the line-of-sight distances and space velocities of many of them. The results (as reviewed by Pawlowski 2018) are remarkable: The vast majority of the Milky Way satellites appear to lie on or near the same plane defined by the orbits of the two Magellanic Clouds. This `vast polar structure' (VPOS) is a 200 kpc diameter torus with a thickness-to-diameter ratio of ~0.2, and an orientation that is nearly perpendicular to that of the Milky Way's disk (hence the `polar' in VPOS). The Magellanic Stream, a narrow structure of stars and gas emanating from the Magellanic Clouds, is also part of the VPOS as are a number of other, gaseous and stellar streams. Obtaining orbital velocities of the satellites is challenging, however it

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[10] This remarkable fact—established already in the 1970s (Lynden-Bell 1976; Kunkel & Demers 1976)—was all but ignored by standard-model cosmologists until quite recently, in spite of (or perhaps because of) the fact that it is so clearly at odds with the predicted distribution of dark sub-halos.

has been shown that at least eight of the satellites are orbiting in the same sense around the Milky Way while one is counter-orbiting.[11]

Furthermore the Milky Way satellite system is not unique in displaying a remarkable degree of coherence. About one-half of the satellite galaxies belonging to the Milky Way's giant companion galaxy, M31 (the `Andromeda Galaxy'), also define a planar structure (Ibata et al. 2013); remarkably, the plane so defined passes very nearly through the Milky Way, a fact that has motivated formation models for the two planar structures that invoke a past interaction between the two galaxies (e.g. Bílek et al. 2018). Other, nearby galaxies show evidence for similar structures (Tully et al. 2015; Müller et al. 2018). That these observations are unexpected is attested by the fact that standard-model cosmologists have not yet come up with any, even remotely plausible, way to reconcile the observed correlations with their dark-matter simulations (Pawlowski 2018).

If *all* dwarf galaxies are TDGs, a natural expectation (Kroupa 2012) is that all of the satellites should define a homogenous set in terms of observable properties (compostion, structure, internal dynamics etc.) or relations between those properties. And indeed, this appears to be the case (e.g. Collins et al. 2015). Such homogeneity would be quite unnatural if some satellites were TDGs and some PDGs, given the very different postulated modes of formation.

In view of these successful predictions of the alternate theory, I conclude that Feyerabend's criterion directs us to interpret the failure to detect either annihilation radiation from sub-halos, or the `missing satellites' that are postulated to inhabit them, as effective refutations of the standard model in favor of Milgrom's theory.

5 Example no. 3: dynamical friction

Standard-model postulate DMH instructs the researcher to distribute dark matter in or around a galaxy, as needed, to accommodate the available kinematical data, under the assumption that Newton's laws are valid. Since the motions of stars and gas clouds in observed galaxies always respect (as near as one can tell) Milgrom's modified dynamics, and not Newton's, this means that dark matter is used, by the standard-model cosmologist, as a sort of `MOND-emulator': an ad hoc device to augment the gravitational force and render the observed kinematics consistent with Milgrom's laws of motion. One consequence is that the trajectory of a test-body around a galaxy will be roughly the same whether predicted by a standard-model or a Milgromian cosmologist, since the body `sees' approximately the same effective potential in either case.

However there are terms in the equations of motion that are different in the two theories. Particle dark matter behaves (by assumption) as a collisionless fluid, and so a mas-

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[11] The fact that the satellites lie spatially in a thin planar structure already implies a great deal of velocity correlation, unless one postulates that we are observing the structure at a special time.

sive body[12] moving through it would experience dynamical friction: a gradual transfer of energy from the directed motion of the body to the random motion of the background. The rate of deceleration is proportional both to the mass, M, of the body and to the (mass) density, ρ, of the background, i.e. $dV/dt \propto -M\rho F(V)$ with $F(V)$ a function of the body's velocity (e.g. Merritt 2013, chapter 5). If the massive body is orbiting around some larger system, dynamical friction will cause the orbit to decay, in much the same way that the orbit of an artificial satellite decays due to friction with the Earth's atmosphere.

In the absence of dark matter, predicted timescales for orbital decay of the Milky Way satellites would be very long. But if galaxies are embedded in dark-matter halos, orbital decay times can be orders of magnitude shorter, for two reasons: the mass M of the satellite is increased due to its dark halo, and the density ρ of the background is also increased by a similar factor due to the dark halo surrounding the Milky Way. Thus, the same satellite galaxy that would experience little frictional force under Milgromian dynamics, could experience rapid orbital decay according to standard-model assumptions.

In fact, straightforward calculations suggest that orbital decay times for the more massive Milky Way satellites should be much less than 10^{10} yr under the standard model (Kroupa 2015). As an example, the Sagittarius[13] dwarf galaxy has a mass in stars of about 10^8 $M_\odot$ and its current distance from the center of the Milky Way is about 16 kpc (Gómez-Flechoso, Fux & Martinet 1999). Standard-model cosmologists would predict a *dark* mass of about 10^{10} $M_\odot$ for a galaxy with this stellar mass (Ferrero et al. 2012). If the Sagittarius dwarf started out on a circular orbit of radius 50 kpc—well out in the Milky Way's dark halo—and with a dark mass of 10^{10} $M_\odot$, the dynamical friction timescale (the time for the orbit to shrink by a factor of two, say) would be only about 3 Gyr, much shorter than the age of the Galaxy.

Thus a prediction of the standard cosmological model is that the orbits of (at least) the brighter Milky Way satellite galaxies should have decayed substantially over the lifetime of the Galaxy. Consistent with this prediction is the possibility that the orbits of some, pre-existing satellite galaxies have shrunk so much that the satellites have already merged with the disk or bulge of the Milky Way and disappeared from view.

The potentially falsifying observation here would be demonstration of the absence of the effects of dynamical friction. A measurement of the instantaneous rate of energy loss of an orbiting body would be decisive, but (much as in the Brownian motion problem) that rate is far too small to be determined observationally. A tractable, but somewhat model-dependent, alternative consists of carrying out backward time-integrations of a

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[12] "Massive" means here that the mass of the body is much greater than the mass of a single dark-matter particle, i.e. $M \gg m_\chi$.

[13] Dwarf galaxies are traditionally named after the constellation in which they sit. This naming scheme has become cumbersome as the number of identified dwarves has increased, e. g. Bootes I, Bootes II, Bootes III etc.

satellite's trajectory to test whether its current orbit can plausibly be seen as the end result of decay starting from reasonable initial conditions (e.g. Laporte et al. 2018). But Angus et al. (2011) find that reconciling the current orbits of the brighter Milky Way satellites with the effects of dynamical friction always requires finely-tuned or improbable initial conditions.

Other examples exist. There is a group of galaxies similar in size and composition to the Local Group and that is located about 3.6 Mpc from the Sun: the so-called M81 group, an assemblage of about three dozen galaxies surrounding the giant spiral M81. There is intersubjective agreement (based on observed tidal features and on the distribution of gas) that the brighter galaxies in the group have experienced close interactions in the recent past (e.g. Yun, Ho & Lo 1994). But modeling of the system under standard-model assumptions suggests that the brighter galaxies would merge, due to dynamical friction, in a time not much longer than the time required for a *single* encounter, unless the initial conditions are highly contrived. Oehm et al. (2017, p. 273) write:

> Long living, non-merging initial constellations that allow multiple galaxy–galaxy encounters comprise unbound galaxies only, which are arriving from a far distance and happen to simultaneously encounter each other within the recent 500 Myr.

The lack of unambiguous evidence of the predicted effects of dynamical friction satisfies Feyerabend's condition: it is a potentially falsifying circumstance, but the falsification is difficult or impossible to establish, due to the long associated timescales and to uncertainties about initial conditions.

Milgrom's theory naturally explains why the effects of dynamical friction should not be observed. One reason, of course, is that under the modified dynamics, the presence of dark matter is not needed to explain the internal kinematics either of giant galaxies like the Milky Way and M81, or of dwarf systems like the Sagittarius satellite galaxy, and so dynamical friction timescales are predicted to be much longer. Another factor, relevant to orbital decay of the Milky Way satellites, is the different formation mechanism of the dwarf galaxies under Milgrom's theory: the dwarves are not assumed to be primordial, and so they would only have been present as distinct systems since the tidal encounter that produced them, thus shortening the time available for their orbits to decay (Angus et al. 2011).

Feyerabend's final condition, of corroborated excess content, is also satisfied for Milgrom's theory, as documented in the previous two sections.

6 Discussion

There are two reasons why a scientist might be interested in a criterion like Feyerabend's as it relates to the dark-matter problem. First, Feyerabend's rule applies to situations that are normally not considered when tallying up the successes or failures of a given theory: namely, instances in which the implications of an experimental result with regard to a given theory are ambiguous. Second, as discussed briefly above, the two cosmological theories under discussion here come close to satisifying the condition of empirical equivalence: both provide (according to their adherents) successful explanations of a wide variety of observational data, hence one would like to have a criterion other than empirical success for deciding between them. Feyerabend's rule provides such a criterion.

The three examples discussed here are not the only standard-model tests to which Feyerabend's rule can be applied. For instance, attempts by standard-model cosmologists to explain galaxy rotation curves (that is, to explain why every type of galaxy should have just the `right' distribution of dark matter to mimic Milgromian dynamics) have repeatedly failed, but those failures have generally not been interpreted as falsifications, since one can always argue (for instance) that the computer simulations have not properly accounted for the behavior of the normal (non-dark) matter (Silk & Mamon 2012; Bullock & Boylan-Kolchin 2017). As Feyerabend might have said, anomalies of this sort, like the existence of Brownian motion, can always be explained away as "Dreckeffekte", as the "interaction of many complex phenomena," rather than as refuting instances. Whereas Milgrom's theory finds no anomaly in rotation curves—that is, it explains those data naturally—and it does so while simultaneously presenting the observer with a raft of additional, testable, and (in many cases) verified predictions, thus satisfying all of Feyerabend's requirements for the preferred theory T'.

There is an underlying reason why Feyerabend's rule finds such broad application in the context of cosmology. The standard cosmological model is not well suited to making testable predictions. As in the case of rotation curves, its predictions concerning normal matter almost always depend in a complicated and often poorly-specified way on the past behavior of both normal and dark matter. Whereas Milgrom's theory—the `alternate' theory—is able to make genuinely testable predictions about the *normal* matter, predictions that are completely independent of the details of galaxy formation and evolution. Furthermore, those predictions often turn out to be correct.

Although Feyerabend formulated his rule in a number of slightly different ways, a common element was the requirement of (increased) testability of the alternate, that is, the preferred, theory. It was Feyerabend's commitment to the importance of testability—that is, to (the growth of) empirical content—that motivated his argument that refuting instances could sometimes be identified only with the help of an alternate theory, and, therefore, that theoretical pluralism was essential for the progress of science:

> Both the relevance and the refuting character of decisive facts can be established only with the help of other theories … *Hence the invention of alternatives to the view at the centre of discussion constitutes an essential part of the empirical method* (Feyerabend 1978, p. 41).

But one need not accept Feyerabend's entire argument here in order to recognize the more basic implication of his methodological rule: that when given a choice between two hypotheses that are both consistent with a given, ambiguous, experimental result, one should prefer the hypothesis that has a greater degree of testability, and which has been shown to survive (at least some) tests. This is, of course, a thoroughly Popperian view of progress[14], and even critics of Feyerabend's broad generalizations can be supportive of this more limited interpretation of his rule.[15]

In his discussions of Brownian motion and observer dependence, Feyerabend was considering cases for which, at the time of his writing, the scientific community had already reached a consensus about which of two competing theories provided the correct explanation. In the new examples discussed here, no such consensus has yet been reached. At the same time, it is probably fair to say that the standard cosmological model is overwhelmingly the more favored of the two theories, at least in the eyes of the scientific and educational communities taken as a whole. And so it is all the more interesting that Feyerabend's rule instructs us to prefer Milgrom's theory over the standard model.

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[14] E. g. Popper (1959, p. 108): "We choose the theory … which not only *has hitherto stood up to the severest tests*, but the one which *is also testable in the most rigorous way*."

[15] See, for instance, Laudan (1989, p. 316, note 33) or Worrall (1978, pp. 308-309 and 1991, pp. 343-344). Both authors note that Feyerabend's rule directs us to choose the theory that has (in Laudan's words) more "heuristic potential" in a Lakatosian sense; that is, greater potential for generating novel predictions.

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