Chapter 6
Doing More with Less: Dark Matter & Modified Gravity

Niels C. M. Martens and Martin King

Abstract Two approaches have emerged to resolve discrepancies between predictions and observations at galactic and cosmological scales: introducing dark matter or modifying the laws of gravity. Practitioners of each approach claim to better satisfy a different explanatory ideal, either unification or simplicity. In this chapter, we take a closer look at the ideals and at the successes of these approaches in achieving them. Not only are these ideals less divisive than assumed, but moreover we argue that the approaches are focusing on different aspects of the same ideal. This realisation opens up the possibility of a more fruitful trading zone between dark matter and modified gravity communities.

6.1 Introduction

One of the most startling discoveries of twentieth century physics is that applying the gravitational theories of Newton and Einstein to the visible matter of the universe fails strikingly to account for the astrophysical and cosmological behaviour of that matter. The discrepancies with observations appear at many different scales: at the cosmological scale, in galaxy clusters, and in individual galaxies. In order to match observations, some new component must be introduced: either one postulates a significant amount of additional dark matter, or one modifies the laws of gravity, or perhaps both. Dark matter, as it is encapsulated in what is by now the standard

N. C. M. Martens (✉)
Freudenthal Institute and Descartes Centre for the History and Philosophy of the Sciences and the Humanities, Utrecht University, Utrecht, The Netherlands

Lichtenberg Group for History and Philosophy of Physics, University of Bonn, Bonn, Germany
e-mail: n.c.m.martens@uu.nl

M. King
Munich Center for Mathematical Philosophy, Ludwig Maximilian University of Munich, Munich, Germany

Lichtenberg Group for History and Philosophy of Physics, University of Bonn, Bonn, Germany

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model of cosmology, ΛCDM, has been heralded as the clear winner at the scales of cosmology and galaxy clusters, whereas modified gravity excels at the level of individual galaxies. Dark matter simulations of structure formation still suffer from several well-known "small-scale problems" (De Baerdemaeker and Boyd 2020) but are making progress in fitting some of the empirical correlations within and between individual galaxies which were once only accounted for by modified gravity. Dark matter and modified gravity are often seen as incompatible communities, as "two paradigms locked in mortal combat" (Milgrom 2012). Whereas Ryle (1954) welcomes contests such as those between ΛCDM and modified gravity, as they help to test and develop the power of the arguments in favour of the survivor, Galison (1997) is careful to add that, for the progression of science to be strong and stable, 'trading zones' between the various communities are required, i.e. local coordination of tools, problems, solutions, etc. via a local contact language. However, the relationship between the ΛCDM and modified gravity communities is notoriously polemical, with barely any trading zone existing (Martens et al. 2022).

We contend that there are at least four key aspects to understanding and thereby potentially alleviating this feud: (i) it cannot be won merely by pointing to which data is covered or not; (ii) there are sociological (or non-physics-based) reasons for the divide; (iii) against common lore, it is in fact possible to construct hybrid theories that do not exclusively take one approach; and (iv) lastly, even though proponents of the two approaches tout different aims, successes, and explanatory ideals, these can in fact be brought into a discussion together.[1] The latter of these will be the focus of this chapter. We find that one of the more significant reasons for the dispute—that the communities simply have different explanatory goals—is not such a good reason after all, since the goal is in fact shared. Understanding this may remove one obstacle between these communities and helps us to show that this divide is not unbridgeable. We will assume that each research programme has something of value to offer that the other does not—see also Sect. 6.5—and that a trading zone would therefore be mutually beneficial.

We briefly discuss each of the above four aspects in a bit more detail. The first key aspect is that current appeals to empirical adequacy will not by themselves resolve the debate. The presumption that solving the debate is a simple matter of comparing the data against the predictions of each research programme is not fruitful for reconciling the two research programmes. Neither dark matter nor modified gravity is fully empirically adequate as it stands: small-scale problems remain for ΛCDM and accurate descriptions of galaxy clusters and cosmological observables still plague modified gravity. Both communities understand and approach the data in different ways. It is common to hear that one of the research programmes accounts for "90% of the data" or for the "most important data". However, it is of course unclear how one would quantify the fraction of the data that has been accounted for or how to establish that certain data is more important than some other data. And

[1] This coheres with Vanderburgh's (2014, Sect. 6) insight that we should not artificially separate out different methodological aspects/theoretical virtues, but consider them in a holistic fashion.

although it may well be fair to prioritise certain explananda for now, the eventual aim is for an empirically adequate theory to account for all the data.

The second aspect, which is worth mentioning but will not be discussed much here, is that there are sociological factors that influence which research programme one adopts and which explananda are targeted as salient. In cosmology or relativity departments, institutes, and research groups, the focus is obviously on cosmological observables and it seems that dark matter is by far the favoured approach. Particle physicists follow suit in focusing on models of particle dark matter. Modified gravity approaches seem to gain their followers within communities of observational (galactic) astronomers.[2]

Third, the debate is often cast as a battle of incompatible paradigms with modified gravity and dark matter being mutually exclusive concepts—a newly postulated field can only be pure matter or a pure modification of the gravitational field. It has been argued by Martens and Lehmkuhl (2020a,b) that this is contested by a recent trend of hybrid theories that postulate a single novel entity that, in one of several possible ways, is both a dark matter field and an aspect of gravity. Such hybrid theories could thereby play an important role as boundary objects (Star and Griesemer 1989) or aspects of a trading zone.

The fourth aspect is that a large part of the stalemate is due to the fact that practitioners of each of these competing research programmes focus on distinct explanatory ideals and furthermore believe that by their own standards their own research programme is clearly favoured. We first establish that proponents of ΛCDM employ notions of explanation that draw on aspects of unification and that proponents of modified gravity employ those notions that focus on (parametric) simplicity (Sect. 6.3).[3] We then critically evaluate each approach according to both its own explanatory standard and that of the other approach. We argue in Sect. 6.4 that ΛCDM is less unifying than often assumed, but at the same time scores better with respect to simplicity/lack of fine-tuning or curve-fitting than its critics maintain.

[2] In future work, we intend to systematically quantify and further explore these suspected trends, using tools from the digital humanities.

[3] Compare this to Massimi's (2018) analysis of the debate between ΛCDM and MOND, where she identifies a "downscaling problem" for ΛCDM—going from the large scale of structure formation to the galactic scale—and an "upscaling problem" for MOND—going in the other direction. We agree with her claims (i), (ii) and (v) (ibid., 27). However, we would nuance her third claim, that the upscaling and downsaling problems are different in nature and that different physical solutions to them have been given. Massimi is right that different solutions are required for each problem, and also correct that the upscaling but not the downscaling problem is explicitly about consistency. However, we disagree that (therefore) only the downscaling problem is an issue of explanation. As explained in our Sect. 6.4, a central notion is that of unification, which goes beyond mere consistency and scope, in a way that renders it a form of explanation as well. For instance, some MOND advocates combine MOND with some neutrino dark matter to account for galaxy cluster phenomenology; while this may well increase consistency, it is not therefore an instance of (substantial) unification (when compared to the ΛCDM-only alternative). Thus, although there are important differences between the upscaling and downscaling problems, they are both best understood as problems (that are partially) about explanation.

Similarly, we find that modified gravity is less simple than often claimed, but also more unifying than often presupposed. Tackling this problem from an explanation viewpoint allows us to distil three important philosophical lessons in Sect. 6.5.

6.2 Astronomical and Cosmological Explananda

Let us begin by briefly describing the two research programmes that are at the centre of our analysis and the distinct explananda that they cover.

ΛCDM is the standard model of cosmology. It describes the universe's space-time geometry, its matter, and its dynamical evolution. It is developed around the Friedman-Lemaître-Robertson-Walker (FLRW) metric, which makes use of symmetry assumptions (that the universe is homogeneous and isotropic) in order to reduce the Einstein Field Equations to just two equations governing the scale factor. In this picture, the standard model of particle physics combined with general relativity lacks the resources for 'seeds' to develop the observed structures of the universe, such as galaxies. Measurements of the cosmic background radiation left over from atomic recombination in the early universe indicate that the majority of the matter and energy of the universe must be dark. After recombination, dark matter, in particular cold dark matter (CDM), would help provide the perturbations that seed structure formation. The model also includes a dark energy component that is, or mimics, a cosmological constant Λ to account for accelerated expansion of the universe.

A non-exhaustive list of some of the main quantitative and qualitative large-scale, cosmological explananda emphasized by ΛCDM advocates and typically best accounted for by the current state of their research programme is as follows:

1. The relative height of the second and third peak in the angular power spectrum of the anisotropies of the cosmic microwave background (CMB);
2. The velocity dispersion of galaxies within galaxy clusters, assumed to obey the virial theorem;
3. The strength of gravitational lensing around galaxies and galaxy clusters;
4. The displacement between the centers of mass of baryonic matter and of dark matter in clusters such as the Bullet cluster and El Gordo.

In a similar spirit to Le Verrier's hypothesis of the planet Neptune, here, more matter (though a different kind of matter) is proposed to account for deviations from theoretical predictions. Some find this addition of different matter ad hoc. A different approach is to liken the situation to the solution of the anomalous perihelion precession of Mercury, where not more matter, but a new theory of gravity was ultimately needed. This is the Modified Newtonian Dynamics (MOND) approach introduced by Milgrom in 1983 (Milgrom 1983). Milgrom proposed that the reason that there is a mass discrepancy is that we are attempting to apply a gravitational theory well beyond its well-tested domain of applicability, viz., solar systems. One version of MOND is a modification of Newton's inverse square law of gravity, which is replaced by:

$$F_G = G\frac{Mm}{\mu(\frac{a}{a_0})r^2} \qquad \begin{cases} \mu \approx 1, & \text{if } a \gg a_0 \\ \mu \approx a/a_0, & \text{if } a \ll a_0 \end{cases} \tag{6.1}$$

where a_0 is a new constant of nature with the dimensions of acceleration, which has been empirically determined to be $1.2 \times 10^{-10} \frac{m}{s^2}$ (Li et al. 2018; McGaugh et al. 2018).

A non-exhaustive list of some of the main quantitative and qualitative small-scale, galactic explananda emphasized by MOND advocates and typically best accounted for by MOND rather than dark matter, is as follows. Each item on this list comprises a different aspect of the tight connection between baryonic matter and the mass discrepancy. (From the perspective of ΛCDM this would correspond to a surprisingly tight connection between baryonic matter and dark matter.)

1. The baryonic distribution suffices (in combination with a single fundamental parameter a_0) to determine the full galaxy rotation curves. Moreover, this deterministic algorithm is in accord with Renzo's rule: qualitative features in the baryonic galaxy rotation curve are mimicked in the total galaxy rotation curve;
2. The baryonic Tully-Fisher relation, i.e. the relation between baryonic mass and rotation velocity in galaxies ($M \propto V_{rot}^4$);
3. The mass-discrepancy acceleration relation (MDAR), i.e. the anti-correlation of the mass discrepancy with the baryonic acceleration within galaxies;
4. The small scatter of the observed MDAR, consistent with zero intrinsic scatter;

Going beyond galactic phenomena in an attempt to compete with the full empirical scope of ΛCDM requires a relativistic extension of MOND. The modified gravity research programme thus consists of MOND plus a plethora of relativistic theories which each have MOND rather than standard Newtonian gravity as the appropriate limit, such as Tensor-Vector-Scalar Theory (TeVeS) and Relativistic MOND (RMOND).

6.3 Unification and Simplicity

This section elaborates upon the two differing explanatory ideals that practitioners of each of the two research programmes emphasize when motivating their own approach. Dark matter advocates tend to focus on the explanatory ideal of unification—the characteristic virtue of ΛCDM, the 'concordance model', is that it can bring together so many different kinds of phenomena. Modified gravity advocates focus on the benefits of simplicity in number of parameters and in avoiding problems of falsifiability.

Although the dark matter story is typically told by starting with Zwicky's work in the 1930s, it was not until the 1970s that the dark matter concept was taken seriously (de Swart et al. 2017), when it was realised that it provided a *single solution to multiple problems*: velocity dispersions in clusters, flat rotation curves in galaxies, instabilities of simulated disk galaxies, and the cosmologist's need for extra massive matter given their *a priori*, philosophical, Machian desire to close the universe (de Swart et al. 2017; de Swart 2019; Sanders 2010). The solutions to these problems could have a single, common origin: dark matter.

From that point onward, one cannot discuss the motivations and justifications for dark matter without the broader context of the cosmological model in which it became embedded, ΛCDM, as well as the various more specific accounts, often from particle physics, for filling in the titular CDM slot. ΛCDM is often referred to as the concordance model, as it manages to incorporate, to unify, a large swath of cosmological and astrophysical phenomena from all epochs from the very early universe up till now. It turns out to be the case that there exists a choice of values for the six or seven parameters of this single model, such that it is consistent with most of the 'relevant' data (Hawley et al. 2005; Olive 2014; Merritt 2017).[4]

Importantly, unification is more than merely scope. When Kitcher (1981, 1989) argued for the explanatory power of unification, for example, he emphasised the need for particular derivations of phenomena to be part of a theory—a set of consistent argument patterns used to derive different kinds of phenomena. The explanatory power of unification does not come from the logical structure of the derivation of the phenomenon alone—it involves more than merely providing a potential common origin (as will be discussed further in Sect. 6.4 when discussing the link between unification and simplicity)—but stems from its bringing new phenomena into a broader theory or set of laws that provide an explanatory structure. This is an aspect of explanations in physics that has been recently highlighted by Wayne (2017) and King (2020).

This is the condition that aims to prevent merely tacking one theory onto another and considering it as one theory with increased scope—so called 'spurious unification'. This condition for unification may indeed be satisfied for a particle model of dark matter, which may embed a local description of a phenomenon into a global theory like supersymmetry.

Indeed, the strongest emphasis on unification appears when going beyond pure ΛCDM by considering various popular particle physics candidates precisifying the rather high-level dark matter concept as it features in ΛCDM. They are typically motivated in terms of solving several independent problems, while also solving the dark matter problem 'for free': " '[multiple] birds with one stone' theor[ies]". "Theoretical constructions that extend the [Standard Model of particle physics] are clearly more appealing when they are able to solve more than one [...] issue [...] with the same amount of theoretical input" (Di Luzio et al. 2020, Sect. 1). For instance, supersymmetric WIMPs, a popular dark matter candidate, provide a solution to the

[4] See Liddle (2004) for a discussion of the number of parameters.

hierarchy problem, they can unify the coupling constants of the three interactions of the standard model of particle physics, and supersymmetry is claimed to play a role in solving the matter-antimatter asymmetry problem and the problem of quantum gravity.

An additional important fact is that supersymmetry was not introduced in order to solve the dark matter problem. Many take it as a sign that a theory might be true, or viable, if it can solve a problem it was not introduced to solve (Dawid 2019). This notion is called 'unexpected explanatory interconnections' by Dawid. For example, axions, which were introduced to solve the strong CP problem,[5] are also a dark matter candidate—a stable field that interacts gravitationally and at most very weakly electromagnetically. Sterile neutrinos, introduced to account for the suppression of the mass scale of the standard model neutrinos, also naturally solve the matter-antimatter asymmetry problem and are dark matter candidates. All of these mainstream dark matter candidates are motivated by solving several independent problems at once, thereby allegedly unifying the associated phenomena. The real benefit comes not from simply including more phenomena, but bringing more different classes of phenomena that would otherwise be unrelated together in the same theory.

Modified gravity advocates on the other hand emphasise simplicity, in particular the parametric simplicity of MOND with its single parameter a_0.[6] Once one fixes the stellar mass-to-light ratio of each galaxy and the acceleration parameter a_0 that applies universally, the MOND formalism serves as an "algorithm" that spits out galaxy rotation curves from the distribution of baryonic matter in each galaxy (Sanders and McGaugh 2002; Sanders 2019). Moreover, it uniquely predicts the correlations mentioned in Sect. 6.2. If we were to allow a_0 to vary across galaxies, this would not even improve the fit to, for instance, the radial acceleration relation (which is equivalent to the MDAR) (Li et al. 2018).

Simplicity is not desired merely for simplicity's sake or for tractability. The appeal to simplicity by modified gravity sympathisers is typically motivated in terms of avoiding two related negative features attributed to dark matter approaches to galactic data: curve-fitting/fine-tuning and unfalsifiability (or being less falsifiable than its competitor). Manually fitting dark matter halos to galaxies typically

[5] This problem refers to the non-observation of Charge+Parity symmetry violation in the context of quantum chromodynamics, although violation of this symmetry is allowed in the most general Lagrangian.

[6] Modified gravity advocates typically give no explicit justification for only focusing on a specific type of syntactic simplicity (i.e. parametric simplicity) and not (also) on ontological simplicity (i.e. either qualitative parsimony—minimising the number of types of entities postulated by the theory—or quantitative parsimony—minimising the number of (token) entities (of a given type) postulated by the theory). It could be that it is simply too difficult to measure and compare the ontological simplicity of dark matter vs. modified gravity (especially without having quantised the modified gravitational field), and/or that these other notions of simplicity are not (obviously) connected to explanatory power (and falsification). See Vanderburgh (2014) for a discussion of both these considerations—particularly interesting is his footnote 3. See also (Vanderburgh 2001, Sect. 6.4.1).

includes, besides the stellar mass-to-light ratio, at least two parameters describing the halo, which are barely constrained and can take on different values for each galaxy. Simulations take into account the common origin story of all these dark matter halos, but they still require many parameters, for instance to describe the astrophysical contribution of gas to galaxy formation and evolution—sometimes called ‘gastrophysics’—including important feedback processes (i.e. relatively small processes that have large effects), such as the reheating of gas via supernovae feedback. MOND advocates disapprove, referring to this approach as a mere exercise in curve-fitting or fine-tuning. Not only does MOND have only one parameter (besides having to fix the stellar mass-to-light ratio), this parameter could in principle have differed between galaxies which, one might have expected, could make it much easier to fit multiple galaxy rotation curves, but (as indicated above) it turns out that a universal value of a_0 suffices. The reason curve-fitting/fine-tuning is considered undesirable is not so much that a probability distribution over parameter values is presumed under which the fine-tuned values are highly improbable, as is the case in other fine-tuning worries, but because the large freedom to curve-fit makes it (more) difficult for the dark matter approach to fail. Whatever observation there is for a given galaxy, the right amount of dark matter can be postulated. Observing more galaxies, therefore, does not make a strong test of the hypothesis that there is dark matter and would not confer much confirmation. This is an explicit result, e.g. on the error statistics approach (e.g. Mayo 1996), where a hypothesis can only be confirmed by a test if that test could reasonably show that the hypothesis is false if it in fact is. MONDians accuse the dark matter approach of being difficult to falsify because it makes no unique predictions, as varying the parameters would result in substantially distinct values of the observables. Dark matter, as a class of models, thus does not go out on a limb as much as MOND when it comes to matching observations to theoretical predictions.

6.4 Assessment

In this section we provide a brief evaluation of the extent to which each research programme is unifying and the extent to which it is simple. Since unification and simplicity are the two explanatory ideals that dominate the discussion, we will avoid discussing other accounts of explanation, or assessing the theories’ empirical confirmation, pursuitworthiness, etc.[7]

[7] Vanderburgh (2001, Sect. 6.4.1) argues that in such situations—that is, when we do not have any theory on the table that is fully empirically adequate, nor are we comparing two theories that are completely empirically equivalent—it is premature to use theoretical virtues such as simplicity to attempt to break a non-existent tie. We take our paper to be complementary to this point: given that both communities do in fact invoke different virtues, we argue that this does not justify the divide that currently exists between the communities (since these virtues are misunderstood and misapplied), not even in this current, premature, empirical situation.

Consider first the extent to which ΛCDM is unifying. That there exists a set of values of the six or seven parameters of this concordance model such that it is consistent with the data is just to say that it is empirically adequate. This is an issue merely of empirical scope; the model (supposedly) can account for the data but this does not by itself imply that the stronger notion of ‘explaining the data by unifying it’ is appropriate. Without theoretical reasons for the values of the parameters and/or *convergence* of independent lines of empirical evidence for the values of each parameter, concordance boils down to curve-fitting (which is being condemned by MOND advocates). The ability of the model to accommodate is due to its flexibility, the variability of its parameters. Merritt (2017) argues that such convergence of independent lines of evidence does not obtain. On the one hand, there are various degeneracies between some of these parameters, e.g. between the matter density and the dark energy density when applying the Hubble diagram test. On the other hand, in some of the scenarios where we do have independent determinations of a single parameter, these do not converge: the infamous and controversial Hubble tension, and the Lithium problem. Add to this that ΛCDM is not even empirically adequate in that it cannot account for various small-scale problems and it becomes quite clear that while it has a broad empirical scope, it does not unify everything.

As mentioned in Sect. 6.3, the strongest claim of dark matter’s explanatory power in terms of unification comes from various particle models to be paired with ΛCDM, such as WIMPs, axions, or sterile neutrinos. The problem here is that colliders and direct and indirect detection methods have failed, as of yet, to detect any such particle. Their explanatory power is thus currently only a promise. However, as the parameter space gets constrained further and further, these promises not only become less likely to be true, but are also being watered down. For instance, attention is redirected towards axion-*like* particles, which do not solve the strong CP problem as is the case for the original axion—which has been severely constrained. This reduces the explanatory power (in terms of unification) of such dark matter approaches.

Myrvold (2003) looks at the evidential import of unification. He finds that, on a Bayesian scheme, the evidential benefit of unification is only found for explanations where distinct phenomena provide additional information about each other, by for example providing constraints on the values of parameters, but not in the general case where an explanation accommodates different phenomena by providing a common origin. He finds that the common origin unification is at best heuristic and he poses a challenge for defenders of this kind of unification to demonstrate the epistemic value of these common origin cases. As we saw above, one of the key reasons for thinking that dark matter is unifying is that the theory or model that contains a dark matter candidate has the potential to explain many cosmological puzzles as well as the entirety of Standard Model physics and account for some of its explanatory deficiencies. This is a fairly dramatic increase in scope, but this unification would only be explanatory to the extent that these distinct phenomena provide mutual information about each other. This may well be the case as the dark sector is likely to couple to the SM and thus provide some constraints that may help explain the values of certain parameters. Of course, no such theory has been confirmed and the parameter spaces where many such theories may dwell has been greatly reduced (e.g. Bechtle et al. 2016).

It is thus fair to say that the typical claims of the explanatory power of ΛCDM in virtue of its unifying nature are somewhat exaggerated. At the same time, there is a sense in which dark matter does score some points with respect to avoiding fine-tuning—a desideratum associated with the simplicity ideal of the modified gravity advocates. Both the hierarchy problem—addressed by supersymmetric WIMPs—and the strong CP problem—addressed by the original axion—can be construed as fine-tuning problems (of course, as described above, these explanatory powers are currently only a promise). Additionally, where MONDians accuse ΛCDM of curve-fitting to the extent that it could fit any possible data and thereby be vacuous, we have seen that ΛCDM is currently not empirically adequate and thus to some extent falsifiable after all.

We now consider the extent to which modified gravity approaches are as simple as claimed. MOND is indeed parametrically simple in that it only contains a single parameter, a_0. Applying it to a galaxy further requires fixing the stellar mass-to-light ratio, but that is all. However, we not only know theoretically that MOND must be embedded in some relativistic theory, but such relativistic extensions are indispensable when accounting for observables at scales larger than galaxies. Perhaps unsurprisingly, the relativistic theories that stand a chance at accounting for this larger scope of empirical phenomena tend to be much less simple than MOND. Take for instance TeVeS, Bekenstein's 2005 tensor-vector-scalar theory, which was the flagship theory of the modified gravity research programme until the disastrous constraints arising from LIGO's 2017 detection of gravitational waves from the coalescence of binary neutron stars. The action describing it is rather elaborate, and includes besides a dynamical ('Einsteinian') metric field a dynamical, timelike unit vector field, a dynamical scalar field, a non-dynamical scalar field, a free dimensionless function, two dimensionless parameters and a parameter/constant with the units of length (as well as Newton's gravitational constant). Moreover, matter is coupled to a physical metric that is determined in terms of the dynamical Einstein metric, vector and scalar fields, rather than being coupled directly to the Einstein metric. This is a substantial reduction in simplicity compared to MOND (Abelson 2022, 31), construed narrowly in terms of parametric simplicity as well as when one considers a broader notion that also takes into the account the additional fields being postulated. The new, TeVeS-inspired flagship theory of MOND sympathisers, a version of RMOND by Skordis and Złośnik (2021), which improves upon TeVeS by dealing with the constraints arising from gravitational waves detected by LIGO and by accounting for the cosmic microwave background and matter power spectra, only manages to do so by being yet more complex than TeVeS was. According to Spergel, such models only work by "effectively positing a complex form of dark matter"—they are "baroque" dark matter (Schirber 2021).

On the other hand, MOND arguably does score some points with respect to unification. Each new galaxy rotation curve is an independent test of MOND. The same is true for the (otherwise) independent correlations mentioned in Sect. 6.2.[8] Moreover, the rotation curves and correlations all constitute independent determinations of the acceleration scale—and they converge on the same value.

If ΛCDM would score very high in terms of unification and very low in terms of simplicity, with the opposite being the case for MOND, this would provide some justification for a divide between the communities associated with each research programme. However, it has been argued that each programme is somewhat less successful with regards to their own favoured standard of explanation than is typically claimed to be the case, and somewhat more successful with regards to the standard of explanation typically favoured by the other community. This reduces one further obstacle in bringing these communities together.

6.5 Philosophical Lessons

In this section, we wish to distil three philosophical lessons from the foregoing discussion. Firstly, it is interesting to distinguish between explanations that arise from the common core concept of a research programme, and those that arise from specific models/theories. The common core concept of all dark matter models (De Baerdemaeker 2021; Martens 2021) is rather thin, both semantically and explanatorily speaking; the unificatory promises arise predominantly from specific dark matter models. On the other hand, the common core of most modified gravity models, i.e. its MOND-limit, contains most of its explanatory power, with its relativistic extensions typically reducing the simplicity and hence the explanatory power of modified gravity. This adds an extra dimension to the way in which the two communities talk past each other: in a sense, dark matter advocates focus on a promising-but-not-guaranteed future whereas MOND advocates focus on a somewhat outdated past.

Secondly, in contrast to what sometimes seems to be implicitly assumed by both communities, it is far from clear a) why unification and simplicity would be mutually exclusive explanatory ideals, and b) that there is a research programme-independent way of privileging one of the two explanatory ideals over the other. More importantly, not only does it seem to be false that these explanatory ideals would be mutually exclusive, they are not conceptually independent in the first place. For many, the core of a good explanation is: doing more with less. Unifying more phenomena (or, as Thagard 1978 and Whewell 1840 call it, ‘consilience’) focuses on the ‘doing more’ part of this slogan, with simplicity focusing on the ‘with less’ part. Simplicity and unification are thus best understood as being two sides of the same coin, rather than competing or even mutually exclusive ideals. Unification is, as we stressed, not merely a matter of scope or coherence. A good explanation

[8] Indeed, Milgrom has quite recently used the terms “convergence” and “unifying” when referring to MOND (Milgrom 2020).

is one that maximises coherence while minimising flexibility. For example, in Kitcher's (1981; 1989) formulation of unification, the stringency of the argument pattern used also plays an important role. Kitcher notoriously never provides a method for quantifying or trading off stringency against scope, but both are in tension with each other.[9] One can derive just about everything from the simple argument pattern 'God wills X, therefore X', but because this pattern is so flexible that any phenomena can be fit, it fails to be explanatory. This is not a novel point, but something important to keep in mind, as dark matter and modified gravity camps that seem to favour different explanatory ideals, often imagined to be exclusive, are in fact focusing on different aspects of the same explanatory ideal. This is not as strong of a division as one group aiming at a goal the other group will not or cannot accomplish—they in fact share a goal with different emphases.

This is good news for the viability of a trading zone. It had already been pointed out by Galison (2010) that trading between enemies is generally possible, since trading does not require that both groups of merchants share the same understanding and *value* of the goods that are to be traded—local coordination is all that is required. We have argued that the common ground for trading between dark matter and modified gravity sympathisers is more fertile than this minimal requirement, as their explanatory values are in fact much closer to one another than is usually assumed. This should reduce to some extent Galison's worry that the concept of a trading zone loses its applicability in the limit of an asymptotically large power difference, with the asymmetry in size and popularity between the dark matter and modified gravity communities indeed being rather pronounced.

Thirdly, it is important to determine whether the ideals of explanation in terms of unification and simplicity are epistemic or non-epistemic: are they 'merely' aesthetic, heuristic or fruitful; or are they a sign of a theory latching on to the truth? If they are non-epistemic, this strengthens our case against an inevitable divide between the dark matter and modified gravity communities. Their differing ideals would just resemble a difference in preference, not a more fundamental disagreement about essential characteristics of a theory for it to be correct.

So can these explanatory ideals be understood as having epistemic value? Some have argued for the epistemic benefits of unification (see Myrvold 2003). We have already covered this so here we focus on simplicity. There is a strand of literature on (the philosophy of) statistics that motivates the epistemic relevance of parametric simplicity as follows (Forster and Sober 1994; Myrvold and Harper 2002; Sober 2002). Assume the true curve describing some system, say the rotation curve of a galaxy, is an nth order polynomial, i.e. it contains n parameters/coefficients. Given that data always exhibits some measurement error, i.e. the data points are scattered around the true curve, one would always obtain a better fit—for instance in terms of the least sum of squares—by fitting the data to a polynomial of a higher order than n. "Curves that fit a given data set perfectly will usually be false; they will perform

[9] We do not endorse Kitcher's particular account of explanation but use this description to highlight that unification is more than scope and itself involves simplicity.

poorly when they are asked to make predictions about *new* data sets" (italics in original) (Forster and Sober 1994, 8).

Various so-called information criteria/ theorems—most notably the Akaike and Bayesian information criteria—aim to address this overfitting to the noise in the data. Such information criteria subtract a penalty from the log-likelihood of a (polynomial) curve that is fitted to the data, where that penalty is a function of the number of parameters of the polynomial that is used. Without this penalty, more parameters would always reduce the sum of least squares and thereby increase the log-likelihood; with the appropriate penalty the sweet spot will occur when the 'true' number of parameters is being used. Now, if we keep observing more and more galaxies, it may seem to be the case that although the dark matter and MOND fits will incur an equal penalty for the stellar mass-to-light ratio, MOND will only receive a one-off penalty for the universal parameter a_0 whereas the penalty for the dark matter approach will keep increasing with every two new parameters introduced per new galaxy. It thus seems to be the case that one can make the penalty for a dark matter fit arbitrarily large by observing sufficiently many galaxies, such that the parametrically simpler MOND fit will always win. Difficulties with this type of argument are that the information criteria apply to a single curve, e.g. fitting a single galaxy rotation curve, and it is not obvious how to apply them to fitting a collection of data sets, each with a member of dark matter or of a MOND family of curves. Even if this difficulty is overcome, the burden is on MOND advocates to perform this quantitative analysis, and to show that the increasing penalty indeed disfavours dark matter, i.e. to show that the bare log-likelihoods (without the penalty) of the dark matter fit are not so much better than those of the MOND fits that they can overcome the subsequent penalty.

Perhaps then the best shot at justifying the epistemic nature of simplicity would be as follows. MOND advocates do not emphasise simplicity (just) because of the aesthetically pleasing elegance of a simpler theory. They claim that it is in virtue of the relative simplicity of MOND compared to dark matter fits to galactic data that MOND is more falsifiable. Due to its smaller number of parameters, it could account for a smaller fraction of all the imaginable observations of galaxies, and thereby makes stronger predictions. Even if this is true in some restricted sense (which, Vanderburgh 2001, Sect. 6.4.2. argues, is not the case)—e.g. when comparing only galactic dynamics, and only the manual fitting of dark matter halos without taking into account their common origin by simulating structure formation from the early universe until now—we have already seen that the complete situation is more intricate. When simulating structure formation, the resulting distribution of various types of halos is indeed inconsistent with observations in a variety of ways—the so-called small-scale problems. This is an example of dark matter being falsifiable. MONDians are right though in pointing out that the typical response by dark matter advocates is that these will be solved when the messy gastrophysics is taken into account, i.e. when more parameters are added (De Baerdemaeker and Boyd 2020) and parametric simplicity is thus further reduced. However, modified gravity theories tend to predict the wrong answers at the level of galaxy clusters and the CMB (if they say anything about the latter at all). In order to avoid falsification of their research programme, the response is to add dark matter in galaxy clusters (for instance in the form of neutrinos) and/or to design ever more complex relativistic extensions of MOND. Both of these options tend to reduce the simplicity and falsifiability of the theory, in order to remain epistemically viable.

6.6 Conclusion

We contend that there are at least four important aspects to understanding and perhaps resolving some of the tensions in the dark matter/modified gravity debate. Here in this chapter, we shed light on the role that different explanatory ideals play in the assessment of these theories. We find that a careful look at the explanation literature, in particular that involving unification and simplicity, shows that these two approaches are in fact focusing on different aspects of the same explanatory ideal: to explain more with less. The chapter concludes that, although part of the divide between the dark matter and modified gravity communities may have arisen in a self-reinforcing way, i.e. from each community believing that different explanatory measures are important and that by their own favoured measure only their own approach is satisfactory, the actual explanatory structure of both approaches is much more complex and does not justify a strong divide between the two communities. This realisation opens the door towards a dark matter/modified gravity trading zone.

Earlier work on the conceptual interpretation of hybrid dark matter/modified gravity theories (Sect. 6.1) (Martens and Lehmkuhl 2020b,a) pushed back against an abstract obstacle that stood in the way of a trading zone, i.e. the idea that both camps are enemies in the sense that their approaches are conceptually exclusive of one another, and that it was therefore impossible for both camps to be (partially) 'right' at the same time. The positive, more concrete upside to the removal of this abstract obstacle is that the hybrid theories themselves, by providing a natural (i.e. non-ad-hoc) physical mechanism for combining the strengths of both camps, could provide the required common ground for both communities to come together and trade ideas, solutions, methods and tools. Similarly, this chapter has pushed back against another obstacle, the idea that each camp has diametrically opposed aims, in terms of explanatory ideals. (Even if these aims were diametrically opposed, we have argued that they do not favour their associated research programmes as straightforwardly as is usually being assumed.) On top of this, the positive message is that, rather than it being inevitable that both camps talk past each other, there turns out to be a point of contact. Unification and simplicity are different nuances within the 'doing more with less' language of explanation. Although it is well known that trading between different communities is possible even if there is no common currency—recall in this regard that anthropological work on trading of material goods between communities is one of the motivations for Galison's concept of a trading zone between scientific communities—there is to some extent a single explanatory currency in use in the context of dark matter and modified gravity, with explanation in terms of unification and simplicity being two sides of the same coin.

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References

Abelson, S.S. 2022. The fate of tensor-vector-scalar modified gravity. *Foundations of Physics* 52(1): 31.

Bechtle, P., et al. 2016. Killing the cMSSM softly. *European Physical Journal* C76(2): 96.

Bekenstein, J.D. 2005. Modified gravity vs dark matter: Relativistic theory for MOND. *PoS* JHW2004: 012.

Dawid, R. 2019. The significance of non-empirical confirmation in fundamental physics. In *Why trust a theory? Epistemology of modern physics*, ed. Dardashti, R., Dawid, R., and Thebault, K., pp. 99–119. Cambridge: Cambridge University Press.

De Baerdemaeker, S. 2021. Method-driven experiments and the search for dark matter. *Philosophy of Science* 88(1): 124–144.

De Baerdemaeker, S., and N.M. Boyd. 2020. Jump ship, shift gears, or just keep on chugging: Assessing the responses to tensions between theory and evidence in contemporary cosmology. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 72: 205–216.

de Swart, J. 2019. Closing in on the cosmos: Cosmology's rebirth and the rise of the dark matter problem. *Einstein Studies* 16: 257–284.

de Swart, J., G. Bertone, and J. van Dongen. 2017. How dark matter came to matter. *Nature Astronomy* 1(3): 59.

Di Luzio, L., M. Giannotti, E. Nardi, and L. Visinelli. 2020. The landscape of QCD axion models. *Physics Reports* 870: 1–117. The landscape of QCD axion models.

Forster, M.R., and E. Sober. 1994. How to tell when simpler, more unified, or less ad hoc theories will provide more accurate predictions. *British Journal for the Philosophy of Science* 45(1): 1–35.

Galison, P. 1997. *Image and logic: A material culture of microphysics*. Chicago: University of Chicago Press.

Galison, P. 2010. Trading with the enemy. In *Trading Zones and Interactional Expertise*, ed. Gorman, M.E., chap. 2, pp. 25–52. Cambridge: The MIT Press.

Hawley, J.F., J.F. Hawley, and K.A. Holcomb. 2005. *Foundations of modern cosmology*. Oxford: Oxford University Press.

King, M. 2020. Explanations and candidate explanations in physics. *European Journal for Philosophy of Science* 10(1): 1–17.

Kitcher, P. 1981. Explanatory unification. *Philosophy of Science* 48(4): 507–531.

Kitcher, P. 1989. Explanatory unification and the causal structure of the world. In *Scientific explanation*, ed. Kitcher, P., and Salmon, W. Minneapolis: University of Minnesota Press.

Li, P., F. Lelli, S. McGaugh, and J. Schombert. 2018. Fitting the radial acceleration relation to individual SPARC galaxies. *Astronomy & Astrophysics* 615: A3.

Liddle, A.R. 2004. How many cosmological parameters? *Monthly Notices of the Royal Astronomical Society* 351(3): L49–L53.

Martens, N.C.M. 2021. Dark matter realism. *Foundations of Physics* 52(1): 1–19.

Martens, N.C.M., M.Á. Carretero Sahuquillo, E. Scholz, D. Lehmkuhl, and M. Krämer. 2022. Integrating dark matter, modified gravity, and the humanities. *Studies in History and Philosophy of Science Part A* 91: 1–5.

Martens, N.C.M., and D. Lehmkuhl. 2020a. Dark matter = modified gravity? Scrutinising the spacetime–matter distinction through the modified gravity/dark matter lens. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 72: 237–250.

Martens, N.C.M., and D. Lehmkuhl. 2020b. Cartography of the space of theories: An interpretational chart for fields that are both (dark) matter and spacetime. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 72: 217–236.

Massimi, M. 2018. Three problems about multi-scale modelling in cosmology. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 64: 26–38.

Mayo, D.G. 1996. *Error and the growth of experimental knowledge*. Chicago: Chicago Univiersity Press.

McGaugh, S.S., P. Li, F. Lelli, and J.M. Schombert. 2018. Presence of a fundamental acceleration scale in galaxies. *Nature Astronomy* 2: 924.

Merritt, D. 2017. Cosmology and convention. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 57: 41–52.

Milgrom, M. 1983. A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *The Astrophysical Journal* 270: 365–370.

Milgrom, M. 2012. Light and dark in the universe. arXiv:1203.0954 [physics.pop-ph].

Milgrom, M. 2020. MOND vs. dark matter in light of historical parallels. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 71: 170–195.

Myrvold, W.C. 2003. A Bayesian account of the virtue of unification. *Philosophy of Science* 70(2): 399–423.

Myrvold, W.C., and W.L. Harper. 2002. Model selection, simplicity, and scientific inference. *Philosophy of Science* 69(S3): 135–149.

Olive, K. 2014. Review of particle physics. *Chinese Physics C* 38(9): 090001.

Ryle, G. 1954. Dilemmas. *Philosophy* 69(269): 378–380.

Sanders, R.H. 2010. *The dark matter problem: A historical perspective*. Cambridge: Cambridge University Press.

Sanders, R.H. 2019. Dark matter – modified dynamics: Reaction vs. prediction. https://doi.org/10.48550/arXiv.1912.00716

Sanders, R.H., and S.S. McGaugh. 2002. Modified Newtonian dynamics as an alternative to dark matter. *Annual Review of Astronomy and Astrophysics* 40(1): 263–317.

Schirber, M. 2021. Dark matter alternative passes big test. *Physics Magazine* 14. https://physics.aps.org/articles/v14/143

Skordis, C., and T. Złośnik. 2021. New relativistic theory for modified Newtonian dynamics. *Physical Review Letters* 127: 161302.

Sober, E. 2002. Instrumentalism, parsimony, and the Akaike framework. *Philosophy of Science* 69(S3): 112–123.

Star, S.L., and J.R. Griesemer. 1989. Institutional ecology, ‘translations’ and boundary objects: Amateurs and professionals in berkeley’s museum of vertebrate zoology, 1907-39. *Social Studies of Science* 19(3): 387–420.

Thagard, P.R. 1978. The best explanation: Criteria for theory choice. *Journal of Philosophy* 75(2): 76–92.

Vanderburgh, W. 2001. Dark matters in contemporary astrophysics: A case study in theory choice and evidential reasoning. Ph.D. Thesis.

Vanderburgh, W.L. 2014. Quantitative parsimony, explanatory power and dark matter. *Journal for General Philosophy of Science/Zeitschrift für Allgemeine Wissenschaftstheorie* 45(2): 317–327.

Wayne, A. 2017. Explanatory integration. *European Journal of Philosophy of Science* 8: 347–365.

Whewell, W. 1840. *The philosophy of the inductive sciences, founded upon their history*. New York: Johnson Reprint.