General Relativity, MOND, and the problem of unconceived alternatives

# Abstract

Observational discrepancies in galactic rotation curves and cluster dispersion data have been interpreted to imply the existence of dark matter. Numerous efforts at its detection, however, have failed to turn up any positive result. As a dynamical theory is always operative on the assumed mass distribution to predict kinematic observations, some scientists see the discrepancy as telling against General Relativity. Among the many theories that seek to modify gravity, those that are built on Modified Newtonian Dynamics (MOND) or yield MOND behaviour at appropriate scales achieve remarkable empirical success without assuming dark matter. The continued non-detection of dark matter and the empirical success of MOND supports the claim that the current evidential and theoretical context underdetermines General Relativity. In this article, I clarify the kind of underdetermination that can be said to threaten General Relativity. Specifically, I argue that the present evidential and theoretical context increase the possibility of an unconceived alternative to GR which would be just as well supported by the available evidence.

*Keywords:* underdetermination; unconceived alternatives; General Relativity; dark matter; MOND

# 1. Introduction

Observational discrepancies in galactic rotation curves and cluster dispersion data have been interpreted to imply the existence of dark matter, a hypothesised form of matter that goes beyond the Standard Model of particle physics. Numerous efforts at its detection, however, have failed to turn up any positive result, leading to ever tighter constraints on how these particles interact (or rather, do not interact) with baryonic matter and photons and lending an air of poignancy to the term ‘dark matter’. As a dynamical theory is always operative on the assumed mass distribution to predict kinematic observations, some scientists see the discrepancy as telling against General Relativity (GR) instead of on the observed mass distribution. Among the many theories that seek to modify gravity, those that are built on Modified Newtonian Dynamics (MOND) or yield MOND behaviour at appropriate scales achieve remarkable empirical success without dark matter. Due to this, MOND can be seen as a plausible alternative to GR for explaining astrophysical observations. The continued non-detection of dark matter and the empirical success of MOND raises the possibility that GR, as the standard theory of gravitational dynamics, is empirically underdetermined.

The thesis of underdetermination – the claim that evidence does not determine a scientific theory uniquely – has been one of the more controversial philosophical theses of the 20th century. Underdetermination can be understood relative to a set of mutually exclusive theories, a set of evidence, and some standard of theory evaluation – differences over how these conditions are understood result in a variety of underdetermination. For the purpose of this essay, I will take evidential support as the standard of theory evaluation. The claim that I intend to argue for is that the available evidence underdetermines GR. Underdetermination, here, is not understood relative to some set of available theories. Indeed, what will be argued is that the claim that some as-yet unconceived theory fares better than GR is confirmed by available evidence. This is not merely to claim that GR has unconceived alternatives; such a claim should be fairly uncontroversial. Rather, I intend to argue that the present evidential and theoretical context increases the possibility of an unconceived alternative to GR.

# 2. Underdetermination of theory by evidence

Underdetermination has been usually understood as a consequence of empirical equivalence between ontologically irreducible theories (Quine, 1975); it has been claimed that there are theories which make the same empirical predictions but provide conflicting theoretical descriptions and which cannot be reconciled by any known translation scheme.[[1]](#footnote-1) Attempts to draw general epistemological insights by claiming empirically equivalent rivals to all theories quickly run into troubles – while it is possible to generate empirically equivalent theories through algorithmic manipulations of existing theories, such ‘rivals’ do not challenge the representational accuracy or the justificatory status of our best scientific theories (Laudan & Leplin, 1991; Stanford, 2006; Acuna & Dieks, 2014). And instances of genuine empirically equivalent theories, though identified in literature (for example, cf. Earman 1993, Belot 2015), cannot be generalised when discussing the epistemic import of underdetermination for science in general. More importantly for our purpose, GR and MOND are not empirically equivalent.

As opposed to strong underdetermination that results from empirical equivalence, weak forms of underdetermination are more easily identified and defended; Lawrence Sklar goes on to say that weak underdetermination “is a fact of epistemic life” (Sklar, 1975: 381).[[2]](#footnote-2) Weak underdetermination has generally been understood as involving empirical equivalence between incompatible theories relative to actually available evidence, as opposed to all possible evidence. However, the existence such empirically equivalent (relative to available evidence) rivals is nota necessary condition for a theory to be underdetermined. This line of argument rests on showing that otherwise reliable inductive strategies are unreliable in some scientific contexts. Kyle Stanford develops what he calls the ‘problem of unconceived alternatives’ by noting that the reliability of eliminative inference depends on our ability to exhaust the space of theories that are plausible relative to state of science; he writes that “there are theories that we should and/or would take seriously as competitors to our best accounts of nature if we knew about them […] but that are excluded from competition only because we have not conceived of or considered them at all” (Stanford, 2006: 23).[[3]](#footnote-3) Although Stanford does not think that all instances of eliminative reasoning are unjustified, he does see the problem of unconceived alternatives as stymieing the prospects of “virtually all our fundamental scientific theories” (2006: 212) [[4]](#footnote-4).

Stanford’s contention that unconceived theories are relevant for underdetermination warrants further scrutiny; after all isn’t theory choice about contrasting available alternatives? In defence, it can be said that what matters in theory choice is the exclusion of all relevant alternatives and not just the readily available ones. Unlike deductive inferences, the strength of inductive arguments depends on the content of the argument. In order to be reliable in an inferential context, elimination must proceed by evaluating all such theories that are strongly suggested by the available evidence, although they could be as yet unconceived. Failure to do so will undercut the justification we have for bestowing uniqueness on our theory. Otherwise stated, the increased likelihood of unconceived alternatives prevents us from claiming that the available evidence uniquely supports our current best scientific theory, thereby instating underdetermination.

Motivated by general observations about the reliability of elimination, the claim that unconceived alternatives underdetermine a theory is defensible. It is not, however, very helpful in deciding whether some particular scientific context underdetermines our current best fundamental theory more than some other context. In order to claim that the threat of the unconceived is more (or less) acute, we need to derive reasons from aspects of scientific theorising other than the suitability of inductive strategies, reasons which can be found by looking closely at the available evidence and available rivals.

Scientific theories, although designed for maximum observational coverage, fail to explain some known phenomena. This is the familiar Kuhnian claim that paradigms accumulate anomalies during the course of normal science. Such anomalies need not precipitate a theory change, as they could be resolved by theoretical innovations or further observations. Long standing anomalies, nonetheless, support the possibility that the theory fails to generalise across all domains of applicability. Under the assumption that related phenomena have a common explanation – that laws unify observations – long standing anomalies give us reason to believe that our best scientific theory approximates some unconceived theory with a wider applicability. It is certainly possible that further developments would allow our theory to explain those observations, and when it does, we have reasons to downgrade our credence in the claim that our theory fails to generalise. From the perspective of how things stand, however, unexplained patterns in observation, although they need not be a decisive evidence against a widely supported theory, increase the probability of an unconceived, better theory.

Additionally, it is also possible that the current best theory has empirically successful alternatives as rivals. An empirically successful alternative need not be empirically equivalent to our theory. Theory development is a temporally extended process involving multiple research groups. It is possible that theoretical developments and empirical findings could establish empirical equivalence between theories that are currently inequivalent.[[5]](#footnote-5) Additionally, there are numerous instances in the history of science where there were multiple theories which were well-confirmed (as opposed to being equally confirmed) by the available evidence, all pursued as serious candidates by scientists. The point of pursuing rival theories is not only to contrast their present empirical content but also to enable their development. Because it is not known in advance of the inquiry which of the theories is the correct one, the live options pursued by the scientific community should be seen as scientifically serious, their present empirical reach notwithstanding. In light of this, alternative rivals that do a better job of explaining anomalies could be seen as providing a template for realising some unconceived relations. It does not mean, however, that one or the other alternative is the unconceived rival to our theory.

To summarise, our fundamental theories are susceptible to underdetermination as it is likely that there are unconceived alternatives to them which are just as well supported by the available evidence. Although this is an ever present possibility, some features of the scientific context increase our confidence in such a scenario. The two features discussed here—unexplained observations, and empirically successful alternatives—are not meant as exhaustive; rather, they are relevant to the argument that the existing state of science makes it likelier that GR is underdetermined.

# 3. The current scientific context – inductive strategies, evidence, and alternative theories

The claim that our fundamental theories could have unconceived alternatives that underdetermine them relies on showing the unreliability of eliminative inference. I will motivate this worry in the context of theorising about gravity by arguing that eliminative inference has historically been unreliable in this context. I will also present some aspects of the current state of science that increase our confidence in the claim that GR is underdetermined.

## 3.1 Inductive risk in theorising about gravity

The threat of unconceived plagued the two paradigms preceding GR: the geocentric model based on Aristotelian physics, and the Newtonian conception of gravity as a force. In both these cases, the theoretical framework continued to be held despite the availability of alternative frameworks which got vindicated in the course of science. Tellingly, the continued support for the prevailing theories can be partly explained by the failure to consider alternatives to the prevailing theories.

Before the pioneering work of Johannes Kepler, the inobservance of stellar parallax was widely interpreted as supporting a geocentric model of the universe. This, despite suggestions as ancient as by Aristarchus of Samos, that the failure could just as well be explained under a heliocentric model in which the distance between the earth and the stars was much larger than planetary distances. Such large distances, however, seemed inconceivable; according to Harald Siebert, Tycho Brahe—on whose meticulous records Kepler based his laws—considered it “absurd to assume such an enormous gap […] this inconceivably huge void served as an argument against the heliocentric system” (Siebert, 2005: 253).[[6]](#footnote-6)

Part of the explanation for the continued acceptance of the geocentric system with its deferents and epicycles was a failure to conceive distances in stellar scales. Similarly, a failure to conceive physical reality in terms of chronospatial geometries can partly explain the continued existence of ether in the pre-relativistic models despite repeated failures at its confirmation. This is especially apparent in the early reception of relativity. Gravitational dynamics was understood in terms of a force being propagated through a medium and much theorising went into describing the physical properties of the medium that could explain its continued non-detection. Discussing the reception of relativity amongst British physicists, Stanley Goldberg notes their neglect and attributes it to their “inability to conceive of a theory which did not account for ‘apparent’ action at a distance in terms of pushes and pulls” (Goldberg, 1970:121).

Motivating Stanford’s claim that eliminative inference is not reliable when theorising about inaccessible domains of nature is his observation that, historically, cognitive limitations have prevented scientists from giving sufficient attention to rival theories that were strongly suggested by the available evidence. The preceding discussion shows that the problem of unconceived alternatives has plagued theorising about gravitation as well. However, apart from the general threat from the unconceived, specific issues with the eliminations involved in the development of GR have been identified by John Norton (1995). Norton notes that while some eliminations (like arriving at covariant field equations) were instances of strong inductions, others were weak (like representing gravitational field using a scalar potential) or of intermediate strength. A requirement for eliminative inference to be successful is that the universe of theories in which eliminations are carried out should be sufficiently large; Norton claims that this was not always the case as Einstein worked his way to a relativistic theory of gravity (Norton, 1995: 59-60). Because an instance of eliminative inference can be shown as false only when it is contrasted with the true theory, it is too early to indict Einstein’s eliminations. Nevertheless, we have reasons to doubt the applicability of eliminative inference in the context of gravitation theories in general and GR in particular.

To compound this worry about the reliability of eliminative inference, it has been argued that universalising GR is not empirically warranted. William Vanderburgh (2003) points out that all available precision tests of GR involve interactions taking place over distances much less than a light-year. Models built using GR, however, describe interactions over distances that are orders of magnitude greater than this: galaxies have radii larger than 104 light-years, the distance between galaxies in clusters averages 106 light-years, and the observable universe has a radius of approximately 14x109 light-years. The disparity in distance scales is also reflected in PPN where the parameters are constrained using such stellar system tests. For Vanderburgh, the evidential context supports the possibility that “GR is simply the short scale limit of some other relativistic gravitation theory” (Vanderburgh, 2003: 830).

Pertinent to our discussion, however, is the possibility that GR deviates from observations at an acceleration scale instead of a distance scale. As with the distance scale, the strongly supported tests of GR probe only a small part of the acceleration regimes found in galaxies, their clusters, and the universe. The edges at the arms of a typical spiral galaxy, which are amongst the largest gravitationally bound structures in the universe, suffer an inward acceleration of ~10-10 m/s2. By contrast, the stellar scale tests which corroborate GR to a high degree of precision are all located in acceleration regimes of greater than 10-6 m/s2 (Milgrom, 1983b; Famaey and McGaugh, 2012). The available evidence thus does not support generalising GR to all observable acceleration regimes. The current theoretical context also favours the possibility of an acceleration-scale discrepancy over a distance-scale discrepancy. Alternative gravitation theories that modify Newtonian gravity (which GR reduces to in a weak field, non-relativistic limit) at distance-scales do not agree with the Baryonic Tully-Fisher relation (Milgrom, 1983b) and violate conservation laws (Aguirre, 2004). On the other hand, MOND theories, which differ in their predictions from GR at a characteristic acceleration scale, fare better on these counts.

The threat of the unconceived hangs heavy on our attempts at fundamental theorising; for the case of theorising about gravitation, I have argued from historical evidence that this is not merely an unactualised threat. This, and the fact that the evidential warrant for generalising GR is weak, support the claim that GR might not be uniquely supported by the available evidence.

## 3.2 Modelling gravitational dynamics using GR – an unqualified success?

Since its conception, GR has made several novel predictions and explained anomalous observations. The three ‘classical tests’ of GR—the explanation for Mercury’s precession, gravitational red-shift, and gravitational lensing—have all been confirmed by subsequent investigations. One of the earliest exact, non-trivial solutions, by Karl Schwarzschild, predicted the existence of non-rotating black holes. The effects of such regions of extremely warped spacetime have since been observed and studied, and direct observation of a black hole was made in 2019. GR, as well as other metric theories, predict the existence of gravitational waves, which were detected by LIGO in 2016.

Amongst alternative formulations of gravity, GR also offers the best fit with the Parameterised Post-Newtonian formalism (PPN). PPN provides a structured way to compare different gravitational theories in their weak-field, nonrelativistic limits. Different versions of the formalism involve different sets of parameters which characterise the weak-field behaviour of gravitational theories. These parameters are constrained using observations from various astronomical sources, and GR seems to be in good agreement with them (Earman, 1992: 177).

Perhaps the most impressive success of GR comes from its ability to explain cosmological observations. The theory forms the basis of the ΛCDM – the standard model of cosmology. On large scales, observable features of the universe like matter density, expansion rate, etc. can be parameterised and the values of these parameters are used to constrain cosmological models, amongst which ΛCDM fares the best. The model correctly predicts the accelerating expansion and the flat geometry of the universe. With some not entirely uncontroversial assumptions, the model is also able to accurately plot the power spectrum of the temperature spectrum in cosmic background radiation (CMB) and explain the abundance of light isotopes (of H, He, and Li) after Big Bang nucleosynthesis (BBN).

Despite its explanatory and predictive successes, GR faces both theoretical and observational challenges. Unlike other fundamental interactions (weak, strong, and electromagnetic), known quantisation procedures fail for gravity as described by GR. The open question is to describe how the dynamics of matter, as described by quantum mechanics, affects the curvature of spacetime. GR is also silent on the cause of gravity; although it is the best description of gravitational dynamics, it does not explain the relation between spacetime curvature and mass-energy distribution.

On the observational front, in order to make GR compatible with evidence from galactic and extragalactic systems, and the evolutionary history of the universe, models assume a significant contribution to the energy-momentum tensor from unobserved (and possibly, unobservable) sources: dark matter and dark energy. No candidate for either has been detected, and there does not even exist a consensus on their composition or properties. Yet the standard model of cosmology estimates that the baryons constitute only 5% of the total mass-energy of the universe. The remaining is made up of dark matter (~25%) and dark energy (~70%).

The postulation of dark matter is motivated by observations at both astrophysical and cosmological scales, and its description (in terms of its possible composition and properties) enjoys a higher degree of confidence within the scientific community that those of dark energy. Subsequent discussions in this article focus on the astrophysical reasons for postulating dark matter as it is on those scales that MOND achieves success, but I briefly mention the cosmological motivations before turning to them. In order to reconcile the standard cosmological model with observations from the early universe, dark matter must be ‘cold’ and ‘non-baryonic’. The suffix ‘dark’ indicates that the proposed matter does not interact with photons and hence cannot be *seen*. Observations of BBN, which suggest that the early abundant light nuclei collectively constitute only about a fifth of the gravitating mass, support the hypothesis that dark matter is ‘non-baryonic’ and it interacts with baryonic matter only gravitationally. Additionally, the existence of large-scale structure in the observable universe requires the existence of slow-moving, hence dynamically ‘cold’ mass to seed early galaxies. Dark matter also imparts a degree of freedom to the cosmological model, allowing it to fit the acoustic power spectrum of CMB with high accuracy.

The astrophysical observations that motivate the postulation of dark matter have to do with the observed difference in the visible mass and gravitating mass of galaxies and their clusters.[[7]](#footnote-7) Fritz Zwicky was one of the first astronomers to observe a higher than expected velocity dispersion in galaxy clusters. From the observed redshifts in the Coma cluster, catalogued by Edwin Hubble and Milton Humason, Zwicky calculated the mass of the cluster in 1933, using which the velocity dispersion was then calculated. He found the observed average velocity dispersion was much larger than the calculated value which implied that the galaxies were rotating too fast to form a stable system unless there was some extra-mass to stabilise it. Zwicky called this extra mass *dunkle Materie* (dark matter), then thought of in terms of usual baryonic matter – “cool and cold stars, macroscopic and microscopic solid bodies, and gases” (Zwicky, 1937: 218). Similar observations were made by Sinclair Smith for the Virgo cluster.

The works of Morton Roberts, Vera Rubin and Kent Ford further highlighted the requirement of some unobserved matter to make the theory consistent with observations; improvement in observational techniques showed that the observed rotation curves of spiral galaxies do not match those predicted using GR.[[8]](#footnote-8) As with the dispersion data from clusters, this has been interpreted as showing the presence of large amounts of undetected matter on the edges of galaxies. In addition to the problems with rotation curves and dispersion velocity of galaxies in clusters, analysis of weak gravitational lensing by galaxies and clusters also require more mass than is visible in them. Simulations show that, contrary to the observations, a rotationally supported galaxy is unstable. The existence of a massive spherical dark matter halo extending beyond the edges of the galaxy can provide the required stability.

As a consensus developed on the particle nature of dark matter, experimental efforts at detecting it proliferated. For the longest duration of this search, weakly-interacting massive particles (WIMPs) have remained the most described and searched candidate.[[9]](#footnote-9) Although the exact description of the hypothesised particle varies with the model, the lower limit of its local density can be observationally constrained. By using this limit, an experimental set-up can be designed to detect collisions between dark matter and normal matter – a *direct detection*. In addition to the local density of dark matter, the detector design also requires knowledge of the cross-section of the dark matter particle to interact with normal matter. Only an upper limit can be found of this property, that too by interpreting the results of a failed detection to mean that the hypothesised particle has a smaller cross-sectional area than anticipated. As existential statements are not easy to falsify, the continued non-detection does not require forsaking the dark matter hypothesis as an explanation for the missing mass problem. Other methods of detecting dark matter attempt to track the signature of the particle’s decay or annihilation. Experiments designed for such *indirect detection* involve measurements of astrophysical gamma rays, cosmic antimatter, and neutrino flux. All the measurements that have been done can be largely explained by conventional sources, though the possibility remains that a part of these measurements could be due to the annihilation or decay of dark matter particles (Bertone & Tait, 2018; Famaey and McGaugh, 2012). Another source of confirmation is from the experiments conducted at the Large Hadron Collider – if they confirm supersymmetry, the dark matter paradigm could base its evidential successes on a surer experimental footing. But despite around three decades of concerted search, dark matter has eluded both direct and indirect detection.

Non-detection of a candidate particle is not the only problem plaguing the dark matter hypothesis. There is an unexpected appearance of an acceleration scale in observations, which finds a natural explanation in MOND (discussed in 3.3). As Stacy McGaugh writes, “[t]he signature of modified gravity in the data are the appearance of the mass discrepancy at a particular physical scale. This should not happen in CDM, which is scale free” (McGaugh, 2015: 252). Galaxy formation is a stochastic process, yet the mass discrepancy kicks in at a characteristic scale (at around 10-10 ms-2) for each galaxy.

Furthermore, a number of astrophysical predictions made by GR-based models have either not been observed (fewer galaxies in the Local Void, fewer satellites of Milky Way, etc.) or have turned out wrong (the cusp-core problem), necessitating feedbacks in simulations. Proponents of MOND have taken a dim view of feedbacks, which invoke chaotic baryonic processes like supernovae to distribute mass in galaxies, and have likened them to “a modern version of epicycle: a deus ex machina that is invoked to excuse any failing of the standard model, no matter how bizarre” (McGaugh, 2015: 253).[[10]](#footnote-10)

In summary, GR is the most successful theory of spacetime geometry and gravitational dynamics, which partly explains why scientists prefer tweaking the auxiliaries as opposed to a wholesale reformulation of the theory. It is, however, not an unqualified success. The fact that there is no independent evidential support for possibly the most important auxiliary hypotheses—the mass-energy budget of the universe—that are needed to reconcile predictions based on GR with observations supports the possibility that GR fails to universalise. This, in turn, strengthens the threat of the unconceived.

## 3.3 Missing mass or incorrect dynamics?

Non-detection of dark matter, coupled with the need for fine-tuning and feedback to make observations compatible with model predictions, have led some scientists to pursue a different track, that of modifying the operative theory of dynamics. In a series of three papers in 1983, Mordehai Milgrom considered the possibility that “in the limit of small accelerations, the inertia force is not proportional to the acceleration” (Milgrom, 1983a: 366), but rather to a more general function of it. The function is so chosen that it leads to asymptotically flat rotation curves for galaxies and yields Newtonian dynamics at large values of acceleration. Implementing this requires the introduction of a new constant, 𝑎0, with the dimensions of acceleration. From independent methods, Milgrom (1983b) estimated 𝑎0 to be of the same order of magnitude as 𝑐𝐻0, where *c* is the speed of light and 𝐻0 expresses the present-day expansion rate of the universe. Apart from this relationship with other fundamental constants, 𝑎0 plays an integral role in MOND. Most prominently, it determines the transition from Newtonian dynamics to MOND which “occurs within a range of accelerations of order 𝑎0” (Milgrom, 1983b: 371).[[11]](#footnote-11)

The modification proposed by MOND can be interpreted in two ways. Under a weaker reading, the modification affects only gravitational dynamics. The effects of MOND have been extensively studied for purely gravitational systems, where it enjoys a degree of empirical success. The stronger interpretation of MOND suggests a modification of dynamics in the limit of small acceleration for all combination of forces and necessitates a new understanding of inertia. Under both interpretations, observational constraints require that MOND violate the Strong Equivalence Principle (SEP). Data from open clusters show a smaller mass discrepancy than would be required if MOND obeys SEP. Milgrom takes this as an indication of an external field affecting internal dynamics (Milgrom, 1983a: 368). Additionally, the role of cosmology (in terms of external effect) in local dynamics, as well as the connection between 𝐻0 and 𝑎0 could point to a Machian understanding of inertia. The departures signalled by MOND go beyond just gravitational dynamics and could turn out to be as fundamental as relativity.

In addition to asymptotic flat curves, MOND leads to the Baryonic Tully-Fisher relation. The Baryonic Tully-Fisher relation is an empirical relation between a spiral galaxy’s baryonic mass and its rotational velocity, and states that gravitating mass is proportional to some power of rotational velocity. The power index is experimentally found to be close to 4. This relation finds a natural explanation in MOND, which relates the mass of a galaxy with the fourth power of its rotational velocity at large radii (Milgrom, 1983b).

MOND has also made predictions which have been borne out by subsequent observation. Most notable of these is the claim that low surface brightness galaxies should show a large mass discrepancy (predicted by Milgrom, 1983c and confirmed by de Blok & McGaugh, 1998). MOND also allows the calculation of rotation curve (not just its flat tail) using only the baryonic mass distribution of a galaxy and is consistent with scaling relations like Faber-Jackson for elliptical galaxies (Sanders & McGaugh, 2002).

MOND is less successful in clusters. From his analysis of galaxy systems—binaries, groups, clusters, and Virgo supercluster—Milgrom (1983b) concludes that modifying Newtonian dynamics reduces the mass discrepancy. Whatever mass that must be assumed, furthermore, can be baryonic matter. Robert Sanders suggests that sterile neutrinos can explain cluster dynamics in MOND (Sanders, 2003). The type of neutrinos posited violates limits in the standard cosmological model, and their detection would favour a MONDian cosmology (Aguirre, 2004).

The biggest shortcoming of MOND is that it is not a fundamental theory but a set of phenomenological laws that provides an alternative account of nonrelativistic, low acceleration dynamics. But without a relativistic theory, MOND is of limited use in cosmology. Efforts have been made at constructing a relativistic theory which would yield MOND at appropriate scales. Jacob Bekenstein (2004) formulation, TeVeS, achieves a good measure of successes in describing CMB observations and weak lensing, although the original formulation was falsified by LIGO observations. While TeVeS reproduces MOND at low acceleration regimes and yields Newtonian gravity for high acceleration, nonrelativistic regimes, it does not tend to GR at high acceleration, relativistic limits. Milgrom (2009) has proposed a bimetric formulation, BIMOND, which tends to GR at high acceleration limits. There also exist theories which replicate MOND phenomenology from microscopic interactions, such as Erik Verlinde’s (2017) entropic gravity in which gravity is seen as an emergent interaction, as opposed to a fundamental interaction.

Comparing MOND with GR can be a cause of confusion. Many of the predictions of GR, especially at the cosmological scale, are obtained from a description of dynamics as provided by GR in conjunction with auxiliary assumptions. Accordingly, a complete theory from which MOND laws can be derived, and which has not been disconfirmed can be considered as an empirically successful rival. A number of MOND theories satisfy these requirements at present. Theoretical developments may enable one of the existing MOND theories to match the full suite of observations where GR excels. The common feature of this otherwise disparate set of theories is the appearance of a new constant, 𝑎0, with the dimensions of acceleration; most notably, it allows these theories to deviate from standard dynamics at a characteristic acceleration value around 𝑎0. A further common feature which distinguishes them from GR, and which follows from the modification of the nonrelativistic dynamics at low acceleration, is that they violate SEP. These commonalities allow us to talk of a MOND paradigm; referring to any of these theories by ‘MOND’ should be seen as motivated by concerns of brevity.

The basic features shared by the theories in MOND paradigm allow for the derivation of MOND laws based on which they all share MOND phenomenology, a set of detailed astrophysical predictions.[[12]](#footnote-12) How the different MOND theories fare with respect to other astrophysical and cosmological observations depends on the specific detail of each theory. Although some of these questions have been posed for individual MOND theories, it is not known if any of the existing MOND theories can reproduce all the observed cosmological details.[[13]](#footnote-13) MOND based cosmological models are accordingly not seen as serious alternatives to ΛCDM by most cosmologists. On the other hand, the detailed observations for individual galaxies can be explained using GR only through simulations based on ΛCDM, which require fine-tuning to reproduce MOND’s predictions. Although the fact that parameters in the model are currently fine-tuned does not preclude a more explanation natural explanation in the future, it does arouse suspicion in MOND proponents. At present, there is little clarity on how a comparison between GR and MOND can be made across different scales. Assessing the relative strengths of the two paradigms, McGaugh writes “[w]here one makes clear predictions, the other tends to be mute. This makes comparison of the two fraught with pitfalls” (McGaugh, 2015: 258).

Michela Massimi (2018) has discussed this difficulty of comparing GR and MOND in terms of problems inherent in multi-scale modelling. She notes that models based on these two paradigms face challenges in reproducing phenomenology across different scales – while ΛCDM faces problems when going down from the large scale of structure formation to the meso scale of individual galaxies, MOND faces difficulties in going up from the meso to the large scale. According to Massimi, the downscaling problem associated with ΛCDM is related to the model’s explanatory power, i.e., the model does not causally explain the MOND phenomenology and has to retrieve them using fine-tuning. The upscaling problem associated with MOND, on the other hand, is related to the inability of existing MOND theories to match observations from clusters and structure formation consistently.

At this point, it can be objected that because models based on these two paradigms face problems when moving up or down the scale and that comparing across scales is “fraught with pitfalls”, GR and MOND are not rivals in an appropriate sense. However, it must be stressed that both *target* the same domain even though they *achieve* different degree of success in different parts of it. There is nothing in the present context that precludes any of the rival theories from succeeding across observational arenas. Of course, which theory will be actually able to do so is a matter of scientific investigation and hence can only be answered within science. From a philosophical perspective, it is important to note that empirical success is relative to the available theories and evidence. Given the present context, it is reasonable to claim that MOND is promising alternative to GR that has achieved some empirical success.

The purpose of this discussion is not to argue that MOND is better confirmed than GR; on the contrary, both evidential and theoretical values considered, GR fares better than MOND. However, as far as the problem of unconceived alternatives is concerned, MOND’s success need not be equivalent to GR. Three features of MOND make the threat of the unconceived acute – first, MOND is an empirically successful alternative to GR as it does a better job at explaining some observational discrepancies. Second, *a0*, which determines MOND regime, is related to other fundamental constants. And finally, MOND requires violation of some cherished principles which would signal radical departures from our current best account of dynamics. While the first two features support the possibility of a MOND-like unconceived alternative to GR, the third feature partly explains the difficulty in exhausting the space of MOND-like alternatives to GR.

# 4. The underdetermination of GR

The present state of science supports the claim that GR is underdetermined by some presently unconceived alternative. It is possible that, given the inductive risk associated in theorising about gravity, there could be an alternative to GR that is presently unconceived. GR relies on controversial auxiliaries to explain known observations, which lends support to the possibility that GR fails to universalise over known phenomena and there would be an alternative theory which it approximates to on relevant scales. Furthermore, the empirical success of MOND increases the likelihood of an unconceived alternative to GR. The proponents of MOND take its empirical success as evidence for being on the right track while acknowledging the shortcomings of existing formulations. Milgrom hypothesises that none of the existing MOND theories is the basic theory, one which presumably will be able to excel where current variants fail. He notes that existing MOND theories “involve an interpolating function that is put in by hand to artificially interpolate between the MOND and the high-acceleration regimes” (Milgrom, 2015: 111). Because existing theories do not allow a derivation of this interpolating function and the value for in terms of cosmological parameters appears coincidentally in them, Milgrom concludes that none of the existing theories is the fundamental MOND theory. Elsewhere, he suggests that the laws on which the paradigm is based be seen as analogous to Kepler’s laws – they describe the motion of galaxies but await an underlying theory to unify and explain them (Milgrom, 2014). Milgrom’s contention that the existing MOND theories have only ‘scratched the surface’ of the universe of possible MOND theories has a familiar ring to it, and I have attempted to argue that this compounds the worry that GR is underdetermined.

Given the conclusion that the available evidence and the theoretical alternatives amplify the threat of the unconceived, it seems fruitful to ask what plausible developments would reduce this threat. For one, the mere detection of one or the other dark matter candidate will not falsify MOND, although it would certainly place the dark matter hypothesis on a surer footing. In order to lessen the worry of the unconceived which arises from the empirical success of MOND, the particle must have the properties needed to explain the distribution that physicists assume in their simulation, i.e. it must explain the MOND phenomenology. Additionally, detection of nonbaryonic dark matter will not automatically imply that Newtonian dynamics holds at low accelerations as dark matter-modified gravity are not mutually exclusive solutions to the astrophysical discrepancies discussed earlier.

The worry of underdetermination can be lessened if GR fares better than MOND at scales where they differ in their prediction. Such an observation would disconfirm the modification required by MOND. Although no dedicated experiment for the same has been conducted, there has been some work done in this regard. The observations, however, are shot with interpretation and are taken, by different scientists, to both confirm and disconfirm MOND. The weak-lensing observed from the interaction of ‘bullet cluster’ has been interpreted as a proof of dark matter (Clowe et al, 2004). Proponents of MOND, however, do not find the result conclusive. Famaey and McGaugh (2012) point out in their review that the discrepancy in the mass distribution as observed from lensing and X-ray maps can be accommodated within the MOND paradigm by assuming the presence of neutrinos or gas clouds while TeVeS can explain these features of the bullet cluster without any extra matter (Famaey & McGaugh, 2012: 105). That MOND needs extra mass in clusters, furthermore, is something that has been known since its inception and hence does not present a new challenge to the paradigm.[[14]](#footnote-14) And at the same time, different data from the bullet cluster has been used to challenge GR based ΛCDM – the collision velocity of 3100 km/s is very improbable within ΛCDM. In contrast, such velocity can be naturally produced within MOND because of increased attraction (Famaey & McGaugh, 2012: 13).[[15]](#footnote-15)

Similarly, studies of ultra-diffuse galaxies DF2, and later DF4, show that they lack dark matter, when modelled using GR (van Dokkum et al., 2018; Shen et al., 2021). These were initially interpreted as falsifying MOND as MOND interprets the putative effects of dark matter as arising due to a modification in gravity and that should be observable in all galaxies. Consequently, a galaxy shorn of dark matter would severely disconfirm MOND. Others, however, have pointed out that the observation bears the signature of an external field effect, which arises as MOND violates SEP (Kroupa et al., 2018; Haghi et al., 2019; Islam & Dutta, 2019). As with the bullet cluster, the observations can be interpreted to be in agreement with both MOND and GR.

The almost simultaneous detection of gravitational waves and gamma radiation from GW170817 by the LIGO interferometers fares better in evaluating the relativistic theories of gravity as it rules out theories in which electromagnetic and gravitational waves couple to different metrics, notable being the original TeVeS (Boran et al., 2018). However, a recent formulation inspired by TeVeS, RMOND, claims to avoid this while managing the achieve the success of TeVeS (Skoridis & Zlosnik, 2019); neither is BIMOND falsified by the observation. This implies the observation is better interpreted as placing constraints on what qualifies as a plausible alternative to GR and does not disqualify all MOND theories.

Observations from tidal dwarf galaxies (TDG), by contrast, have been interpreted as favouring MOND over GR. By observing three TDGs, Bournaud et al. (2007) find that they are dark matter dominated, whereas they are not expected to contain dark matter within ΛCDM. Gentile et al. (2007) show that the observed rotation curves can be naturally derived from MOND. Staying within ΛCDM requires tweaking the dark matter halos of parent galaxies or postulating some novel kind of dark matter. More recently, observations made on open star clusters suggest an asymmetry in the distribution of stars in tidal tails (Jerabkova et al., 2021). Under GR-dark matter based simulations, the asymmetry can be explained by assuming interaction with dark matter lumps, while it arises from baryonic mass distribution alone in MOND-based simulations (Kroupa et al., 2022).

There are two key takeaways from these conflicting interpretations of observations, as far as the underdetermination of GR is concerned. First, the predictive and explanatory novelty of MOND increase the likelihood of an unconceived alternative to GR. Accordingly, MOND could be justifiably seen as a template for exploring the space of alternative theories to GR, including in regimes of quantum gravity. And second, both material and intellectual resources should be allotted for designing experiments which probe regions where GR and MOND differ in prediction. Such experiments would reasonably constrain possible interpretations of the observation, thereby facilitating agreement on the better supported account of gravitational dynamics.

# 5. Conclusion

Non-detection of dark matter candidate is a worry for GR. Dark matter could yet turn out to be like Neptune, with the prediction of its existence preceding its actual discovery. But its story could also turn out like that of Vulcan, of discovering the limits of a long-cherished gravitation theory. Against the backdrop of this uncertainty, I have attempted to argue in this essay that GR is underdetermined, not because of any actual existing empirically equivalent rival to it but because the current state of science strongly supports the possibility that there could be one such rival which remains unconceived. The argument relies crucially on the empirical success of MOND to argue for an increased confidence in the possibility of an unconceived alternative to GR. This could serve as a philosophical argument for the proponents of MOND to employ in the ongoing debate on the correctness of our standard picture of gravitational dynamics, although not on the correctness of MOND as the alternative. Existing MOND theories, too, suffer from the general problem of unconceived alterntaives.

Philosophical arguments in the ongoing dispute between GR and MOND are not new; proponents of MOND have appealed to methodological criteria and theoretical virtues to argue in favour of MOND.[[16]](#footnote-16) Adherence to methodological criteria and possession of theoretical virtue, however, do not support MOND over GR. For one, methodological criteria do not provide epistemic support. Additionally, there is no community-wide standard for either identifying or ranking theoretical virtues, such that it is not the case that appealing to them will decisively favour MOND over GR. In a recent discussion of the prospects of MOND from a meta-empirical framework of assessment, Baerdemaeker & Dawid (2022) argue that the predictive and explanatory novelty of MOND are not sufficient to justify its preference over GR-dark matter models. The claim being defended in this essay, however, is not that MOND fares better than GR on the basis of some or the other philosophical criteria. Rather, it seems reasonable to conclude that the current state of gravitational science increases the worry of underdetermination. In that respect, I have argued that the proponents of MOND have a philosophical argument for questioning GR, although this need not serve as an argument in support of MOND.

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1. Discussion on underdetermination predate Quine’s articulation. Most notably, Duhem (1991[1914]) argues that unlike mathematics, physical sciences entertain the possibility of two contradictory theories being equally supported based on the predictions they make. [↑](#footnote-ref-1)
2. Sklar uses the term ‘transient underdetermination’ to describe the scenario where available evidence underdetermines theory. [↑](#footnote-ref-2)
3. He supports his conclusions by looking at the debate around inheritance in mid-19th century England among biologists and naturalists and shows that scientists engaged in the debate failed to consider relevant alternatives to their views on inheritance that would later be accepted (2006: chapters 3, 4, 5). [↑](#footnote-ref-3)
4. According to Stanford, eliminative inference is likely to be unreliable when we regularly fail to conceive alternatives to theories that attempt to describe constituents of nature that are “too small or too large or too amorphous for us to readily perceive; because the causal interactions between those entities are too fast or too slow or too rare or take place on too grand a scale for us to engage with in ordinary ways; these entities and interactions occur in times and places either far removed from our own or otherwise inconveniently located (e.g., at the dawn of life on Earth, in remote regions of the universe, at the center of the Sun), and so on” (Stanford, 2006:3). [↑](#footnote-ref-4)
5. This point has been noted in the underdetermination literature by Andre Kukla, cf Kukla, 1996: section 3. [↑](#footnote-ref-5)
6. On the possibility that the stars are vastly distant from the earth than the planets, Ann Blair quotes Brahe: “It is necessary to preserve in these matters some decent proportion, lest things reach out to infinity and the just symmetry of creatures and visible things concerning size and distance be abandoned” (Blair, 1990: 364). [↑](#footnote-ref-6)
7. The mass of a distant astronomical object can be calculated either by studying its luminosity or by studying its kinematics in conjunction with a theory of gravity. From the observed luminosity of a large astronomical object, its mass can be calculated by comparing the ‘mass-to-light ratios’ of analogous systems. The mass calculated by this method includes contributions from gas, dust, dim stars and other objects that emit too little light to be detectable over astronomical distances. The other method begins with finding the velocity at the edges of any rotating astronomical object, usually done by spectroscopic methods. The mass interior to a given radius can then be calculated from the observed radial velocities in conjunction with some theory of gravitational dynamics. [↑](#footnote-ref-7)
8. A rotation curve is a plot of radial velocities against the distance from the centre of a galaxy. As GR yields Newtonian gravity at large distances from the galactic centre, the rotation curves of galaxies should be similar to the one observed for the solar system – it should rise to a peak that then falls asymptotically. Such a curve would be expected of a system which has its mass concentrated in its centre with mass density falling at the edges. The observations, however, show the curve becomes asymptotically flat instead of falling. [↑](#footnote-ref-8)
9. The postulation of such particles as possible dark matter candidates is most often motivated by existing problems in particle physics. The most discussed WIMP models (neutralinos, gravitinos) arise from considerations of supersymmetry, a proposed extension to the Standard Model of particle physics that aims to solve other existing problems like the hierarchy problem. [↑](#footnote-ref-9)
10. The point of McGaugh’s quote is to highlight a manoeuver that some see as non-scientific. McGaugh’s characterization of feedback as epicycles, however, need not be taken at face value. While the specifics of the process can be questioned, supernovae induced redistribution of mass does take place. Admittedly, such processes introduce a degree of freedom in the models which allow for agreement with the observations. However, having a parameter that can be tweaked across a range of scenario does not constitute a falsification. [↑](#footnote-ref-10)
11. For a list of predictions where appears, cf. Famaey & McGaugh (2012: 30). [↑](#footnote-ref-11)
12. Cf. Milgrom, 2014 for the derivation of MOND laws, and Famaey &McGaugh (2012, especially section 5) for MOND phenomenology. [↑](#footnote-ref-12)
13. A slightly dated review of how existing relativistic MOND theories fare for cosmological observations can be found in Famaey & McGaugh (2012: section 9). [↑](#footnote-ref-13)
14. The presence of dark baryons—ordinary matter that evades luminous detection—is required even in ΛCDM. Its use in MOND tells us that exponents of MOND are not averse to using dark matter-like explanations to rescue their hypothesis when such case arises. [↑](#footnote-ref-14)
15. The significance of the bullet cluster for dark matter and modified gravity has also received attention from philosophers of science. Peter Kosso (2013) has argued that, because weak lensing requires only EEP and not the entire GR, it constitutes a novel proof for the existence of dark matter. Adan Sus (2014) rightly points out that it need not be the kind of nonbaryonic dark matter needed in ΛCDM as MOND theories like TeVeS can explain the observations without the need for such nonbaryonic dark matter. Finally, Vanderburgh (2014) asserts that the observations do not preclude the possibility that GR is incorrect *and* dark matter exists in the clusters. [↑](#footnote-ref-15)
16. Milgrom (1983a) calls the dark matter hypothesis ‘ad hoc’; McGaugh (2015) likens it to ether, hence unfalsifiable; while Merritt (2017) terms the GR-based models ‘conventionalist’. [↑](#footnote-ref-16)