# ΛCDM and MOND: A Debate about Models or Theory?

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**Abstract**: The debate between ΛCDM and MOND is often cast in terms of competing gravitational theories. However, recent philosophical discussion suggests that the ΛCDM–MOND debate demonstrates the challenges of multiscale modeling in the context of cosmological scales. I extend this discussion and explore what happens when the debate is thought to be about modeling rather than about theory, offering a model-focused interpretation of the ΛCDM–MOND debate. This analysis shows how a model-focused interpretation of the debate provides a better understanding of challenges associated with extension to a different scale or domain, which are tied to commitments about explanatory fit.

## 1. Introduction.

The standard model of cosmology, the current received view within the cosmology and astrophysics community, is the Lambda Cold Dark Matter (ΛCDM) model. One of the most notable features of the ΛCDM model is the inclusion of *dark matter*—a previously unknown kind of matter that cannot be directly observed at any electromagnetic wavelength, and has only been detected via its gravitational interactions. According to the ΛCDM model, dark matter makes up 24% of the mass-energy content of the universe.[1] While most astrophysicists accept the existence of dark matter, others criticize the ΛCDM model and its inclusion of dark matter, arguing that this is an example of the model's overly flexible ability to accommodate a wide range of observations into the parameters. For some astrophysicists, dark matter is considered an unjustified *ad hoc* addition to ensure that the model fits with the empirical data. Some of these critics have proposed alternative models, which attempt to account for the same empirical data by revising the theory of gravity to a Modified Newtonian Dynamics (MOND), so that positing a new kind of matter is not required. However, the MOND approach is likewise viewed by some as unjustifiable. General relativity is a foundational pillar in the contemporary understanding of

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[1] Dark energy—a relativistic energy density that carries negative pressure which drives the expansion of the universe at an accelerated rate—is another unusual feature of the model, accounting for another 72% of the mass-energy content. This leaves all ordinary, baryonic matter accounting for less than 5% of the universe. In this paper I will focus discussion on only dark matter.

the universe. Abandoning general relativity would require strong reasons. Therefore, most astrophysicists regard the adoption of modified Newtonian dynamics as unjustifiable. Nevertheless, advocates of MOND claim that their models are equivalent, or even superior in some respects to ΛCDM for describing structural dynamics in the universe (Milgrom 2009; McGaugh 2014).

These two approaches to modeling structures in the universe include different elements in the models and differ fundamentally in terms of the theories on which they are based. Both models claim to fit the empirical observational data well, make adequate predictions, and even offer explanations. How should one understand this claim, that these two models, which differ in terms of their fundamental theoretical commitments, might both be evaluated as models having good fit? While the existence of multiple incompatible models of a phenomenon isn't necessarily problematic, these cases involve the expectation of eventual adjudication between incompatible theories (Giere 2006; Massimi 2018). The case of ΛCDM and MOND is puzzling because it fits the pattern of multiple incompatible models, yet the differences do not trace back to different representational choices, but rather disagreement about theory. So how should this conflict be understood?

On a theory-focused interpretation of the ΛCDM – MOND debate[2], one option is to understand this as a simple fundamental disagreement—it is a mistake to evaluate MOND models as successful, given that it is not based on the current best theory of gravity. Alternatively, it could be regarded as a subjective choice between two options (López-Corredoira 2014), or case of incommensurability between two paradigms (McGaugh 2014). A third option, given that both claim to account for the empirical data, is to understand the issue as indicative of possible underdetermination of the theory (Massimi & Peacock 2014). However, these analyses stem from a specific formulation of the question at issue: is there good evidential reason to think ΛCDM is the current best model (with general relativity as the best gravitational theory), and to believe in the entities it posits? This formulation, by focusing on the degree to which the evidence confirms each theory, seems to result in an argumentative stalemate, which may only be resolvable by obtaining additional observational evidence or through detection of a dark matter particle.

[2] In common practice, the use of the terms "model" and "theory" does not always respect the way they are defined in the philosophical literature. For example, a cosmologist might consider ΛCDM and MOND to be extended theories that are mistakenly called models—ΛCDM should be referred to and thought of as a *theory* for larger scale structure formation, not a *model* for large scale structure formation. Some of these varying expectations will be examined in the discussion to come, so at this point I simply would like to highlight the fact that these terms and conceptions of "model" and "theory" do not necessarily mean the same thing to all scientists, in all contexts. Furthermore, philosophically, the terms "model" and "theory" bring to bear their own varying philosophical commitments. As such one needs to pay attention to instances in which "model" or "theory" is used, and what these terms might commit one to—implicitly, explicitly, or accidentally.

In this paper, I will introduce the concept of a "theory-focused interpretation", in which a debate is understood as ultimately being about theory and prioritizes theory, theoretical commitments, and interpret success as tied to the theory. This will be contrasted with a model-focused interpretation, in which a debate is understood as being about models, and places the emphasis of analysis on the construction and use of models in science, and success is tied to the modeling practices.

More recently, Michela Massimi (2018) provides another alternative for making sense of the respective success claims of ΛCDM and MOND, proposing analysis of the debate in terms of multiscale modeling. She suggests that what is philosophically at stake in the ΛCDM – MOND debate is actually a manifestation of Robert Batterman's (2013) "tyranny of scales", and that the ΛCDM – MOND debate demonstrates the challenges of multiscale modeling in the context of cosmological scales. She advances the five claims regarding the nature of the ΛCDM – MOND debate, the first three[3] of which are:

1. ΛCDM and MOND, respectively, work best at a specific scale (large scale for ΛCDM, meso or galactic scale for MOND);
2. Each model faces challenges when modelling across more than one scale. The ΛCDM faces problems going down from large scale structure formation to the meso scale of individual galaxies—she calls this the "downscaling problem". MOND faces problems going up from the meso scale of individual galaxies to the large scale of clusters and structure formation—she calls this the "upscaling problem".
3. Philosophically, these problems are different in nature and different physical solutions to them have been given. The downscaling problem for ΛCDM is a problem about the *explanatory power* of ΛCDM for some recalcitrant phenomena at the meso scale of individual galaxies. The upscaling problem for MOND, by contrast, is a problem of *consistency*: how to consistently extend MOND at large scale where general relativity (GR) applies (and most of the large scale phenomena and even experimental techniques, such as gravitational lensing, rely on and presuppose the validity of GR).

(Massimi, 2018, p.27)

Massimi's discussion of the ΛCDM–MOND debate in terms of multiscale modeling implicitly suggests another route worth exploring more explicitly: shifting the emphasis away from understanding the debate as being about theory but rather as a debate about modeling. In this paper, I explore the philosophical implications of the ΛCDM – MOND debate cast as a debate about modeling rather than theory. My hope is that this approach might lay bare some of the commitments tied up in each way of thinking about the debate, and ultimately provide new avenues for advancing the points of disagreement between ΛCDM and MOND.

I begin by providing a brief background on the relationship between models and theories in philosophy of science and provide some conceptual tools from this philosophical literature (Section 2). This discussion will also serve to motivate a model-focused interpretation of the ΛCDM – MOND debate. By drawing on philosophical work on scientific models as the lens for analysis, in Section 3 I offer a model-focused interpretation of the ΛCDM – MOND debate, detailing how the ΛCDM and MOND models were originally constructed and justified. In Section 4, I turn to the philosophical implications. In light of this analysis of ΛCDM and MOND qua models[4], similarly to Massimi, I argue that both models can be evaluated as having good fit,

[3] I will set aside Massimi's fourth claim regarding hybrid models, but suspect my line of analysis will raise similar concerns detailed in her discussion. I will also set aside her fifth claim regarding what multiscale modeling in cosmology *ought* to do, as this claim merits a paper on its own.

[4] Again, some might consider ΛCDM and MOND to be extended theories mistakenly called models. Even if this is true, I propose to explore what happens if they are treated seriously as models.

but only when considering their fit within their original scale, or what I will refer to as domain of application. The apparent conflict between the two models arises due to extending both models past the domain in which they were originally intended to apply (meso to large scale for MOND, or large scale to meso for ΛCDM). Additionally, I suggest that there is a second, overlooked sense in which a model can be extended, in terms of the *purpose* (description, prediction, or explanation) for which the model is intended to serve or claim success. While I take Massimi's first two claims to be accurate interpretations of the ΛCDM–MOND debate, her third claim provides an entry point into thinking through what might be at stake if the debate is thought through a model-focused vs theory-focused interpretation: explanatory power and capacity for consistent extensions of models verses theories.

I argue that a model-focused interpretation (drawing on the concepts of the intended target system and the domain of application) offers the resources to formulate an alternative understanding to what is at issue: it is not a need for evidence for the theory per se, but rather evidence for claims about certain features of the model being part of the target system. A model-focused interpretation centers the debate on whether a justifiable extension of a model has occurred. What goes underappreciated in Massimi's analysis is that, in attempting to extend the model to new domains, there are commitments to the model accurately representing explanatory dependencies that exist in the target system. I argue that in this context, a justified extension of a model to a new domain requires confidence that the model is representing explanatory dependencies in the world. This is a kind of "explanatory fit" because, for a model to offer an explanation of a phenomenon, it must accurately represent the dependencies that exist in the real-world system that are responsible for producing the phenomenon.[5] I argue it is permissible to evaluate both the ΛCDM and MOND models as successful models, but only when considering their fit within their domain of application. Conflict arises when extending the models past their original domain. Justified extension of the model to a new domain requires a claim that a model has good explanatory fit, which includes a claim about the relations in the model capturing dependencies of the system. I conclude that in the specific context of ΛCDM and MOND, there is a need to be critical of attempts to extend models beyond their original domains, as the implicit reason that is given for their claim to being justified in their extension is connected to a commitment to the explanatory fit of the model.

## 2. The Relationship Between Models and Theory

There is an extensive and ongoing discussion within philosophy of science regarding the relationship between models and theories. For instance, the syntactic view of theories (Carnap 1938; Hempel 1965) holds that a theory is a set of sentences in an axiomatized system of first-order logic. A model, then, is a system of semantic rules that offer an interpretation of those sentences. Most philosophers have abandoned this account in favor of the semantic view of theories. On the semantic view, a theory is constituted of a family, or set, of models (van Fraassen 1980; Giere 1988; Suppe 1989; Suppes 2002). While there are different versions of the semantic view, they all see models as the central unit of scientific theorizing. The function of the

[5] "Explanatory dependencies" is used to stand in for whatever physical dependencies in the world feature in a good explanation, be they counterfactual dependencies (as Bokulich 2011 argues) or causal dependencies.

model is to represent part of the world. The scientific model is what represents the phenomena, features of the world, or the collection of data we obtain from observations. These are often treated as distinct types of models: theoretical models and data models.

A third account for understanding the relationship between models and theories argues for understanding models as "autonomous agents", relatively independent of theory, and functioning as "instruments of investigation" (Morgan & Morrison 1999, 10). A model is not something that is entailed by a theory. Rather, a model is a result of skilled construction on the part of the modeler, and through this construction it gains a partial independence or autonomy from theory. In a sense, "models mediate between theory and the world" (Morgan & Morrison 1998, 242). On this "models-as-mediators" account, the role of a model in science is as a tool used in instances such as when theories are too complex to understand, or alternatively used in the development of a theory, or to complement a theory when the theory is incomplete.

These accounts can be placed on a spectrum for understanding of the relationship between models and theories. The models-as-mediators account, which views models as autonomous, suggests a stronger separation between models and theory. The semantic view—seeing theories as a family or collection of models—suggests little to no separation between models and theories, and thus a strong connection. Given the primary goal in this paper is to develop a model-focused interpretation of the ΛCDM—MOND debate, I will adopt a "strong" separation of model from theory and will base my model-focused interpretation on the models-as-mediators account.[6] My motivation for this choice is threefold. First, given my goal is to explore the philosophical implications of the ΛCDM—MOND debate cast as a debate about modeling rather than theory, adopting a stronger position of the relationship between models and theory will allow for this to be defined more sharply. Additionally, I think it may be possible for a semantic version of a model-focused interpretation to collapse into the theory-focused interpretation, given theories are considered to be families of models. Finally, I think the models-as-mediators framework provides a compelling account of the actual modeling practices undertaken by the cosmologists in both the ΛCDM and MOND camps. This point will be developed in the discussion in Section 3.

The models-as-mediators account of models draws attention to four basic elements: construction, representation, function, and how we learn from models (Morrison and Morgan, 1999). With respect to model *construction*, while one could think of a model as being derived entirely from theory or entirely from data, Morrison and Morgan argue that when attention is paid to the practice of model construction, it typically involves both: partially from theory and

[6] There is also certainly space to develop a "weak" model-focused interpretation of the ΛCDM–MOND debate. On this "weak" model-focused interpretation, following a semantic view of model and theories, one might say models represent subsystems or use models to represent whole spacetimes. And indeed—given that ΛCDM could be understood as a sub-branch of the Friedmann–Lemaître–Robertson–Walker (FLRW) models, which is a sub-branch of the Einstein's Field Equations (EFE) equations (as will be discussed in section 3.1)—this could very well be viable approach. This approach may also focus on questions such as embeddability relations between models. I thank one of my reviewers for pressing me on this point. Such a semantic based weak account may also have variations similar to those discussed in Le Bihan (2012). However, developing both strong (models-as-mediators) and weak (semantic view) versions of a model-focused interpretation is outside of the scope and goals of my paper.

also from data. This is what gives model their partial independence, and allows them to mediate between theory and world. And while models can rely on theory in their construction, the end product, or model itself, can be assessed mostly independently of theoretical considerations. It is this autonomy that allows a model to *function* as a tool or instrument. A model's capacity to *represent* the world is also a necessary element: models typically represent either some aspect of the world, some aspect of theories, or both at once. The model captures details at a certain level of resolution of the world, or target system. A representational relationship is how a model works as an *investigative* instrument or tool, rather than a simple tool or purely an instrumental device. It is also a model's representative power that allows it to also teach us something about the thing it represents.

Two additional concepts from the philosophical literature on scientific modeling to use in developing this model-focused interpretation of the debate are a model's target system and purpose. To construct a model, one first identifies a target system. A target system is select parts of the real-world phenomena that are to be represented in the model.[7] The decision about what constitutes the target system can be based on observations, a body of scientific evidence available, or even a more fine-grained set of data. A model represents target systems through various of approximations and idealizations. This is one of the challenges in using models in scientific reasoning; while models are intended to capture certain attributes, or features of the system, models are also partial and incomplete representations of their target systems as a result of such idealizations and approximations. Models can also serve a specific *purpose* or possibly a variety of purposes.[8] The purpose is the reason for which the model is created or for which the model is used, such as to offer a description, prediction, or explanation. A model might aim to serve one purpose, such as offering a prediction of future states based on initial inputs. The same model might then also offer an explanation for those future states. However, just because a model might be evaluated as offering a good prediction, it may not necessarily be evaluated as offering a good explanation or having strong explanatory power.

Some philosophers (such as Cartwright 1983, Giere 2006, and Weisberg 2012) argue that successful scientific models stand in a relation of *similarity* to their real-world target systems in the desired respects and to an implied degree of accuracy relative to the model's purpose. Others, (such as Parker 2010) argue that successful models are evaluated as being *adequate*, or sufficient relative to a given purpose for which the model is used.[9] Finally, models have a *domain of application*, a scale over which the model is intended to apply—such as over a particular time or distance scale. A model's domain is also relevant in its evaluation. This conception of domain of application is similar to what Massimi and Batterman consider to be the "scales" of modeling—one domain of application might be the micro-scale, another domain of application could be at the meso-scale.

## 3. Model-focused Interpretation of the ΛCDM–MOND Debate

[7] For extended discussion of the concept of a target system, see Elliott-Graves (2020).

[8] The variety of purposes models can serve is an extensive and implicit discussion throughout much of the philosophical literature on scientific modeling. For work that takes up the topic of modeling purposes more explicitly, see for instance Giere 2006, Parker 2010 & 2020, and Jacquart 2016.

[9] I introduce similarity and adequacy understandings as two possible tools to draw upon in this discussion.

With this background discussion in place, I now turn to offering a model-focused interpretation of the ΛCDM–MOND debate, starting by detailing the construction of the ΛCDM model. By doing this, I highlight where theory enters, where data enters, and how modeling practices address representation and impact model function. This allows this section to serve both as development of a model-focused interpretation of ΛCDM–MOND debate, as well as providing general background set-up and context of the debate itself.

The foundation of the ΛCDM model is the current best theory of gravity, general relativity. The important relations in general relativity are specified by Einstein's field equations (EFE). Since gravity is expected to be the dominant force on large length scales, models of the evolution of the universe at this scale are based on general relativity. By providing conditions, or assumptions, for the global properties of the spacetime within general relativity, EFE can be applied to model the structure of our entire universe. The ΛCDM model is one exact solution to EFE.[10] The parameterization of ΛCDM is based on empirical data, and includes the best estimates of the overall curvature ($\Omega_k$) of the universe, mass-energy density ($\Omega_m$), and other parameter values. In what follows, I will briefly highlight the idealizations and approximations made to obtain the ΛCDM model from EFE.[11] These steps are important because they provide insight into the assumptions, idealizations, and approximations that go into developing a model in cosmology.

Framed in terms used in the modeling literature, the target system for the model is the entire universe, but the domain over which the model is to apply involves only very large distance scales. The intended purpose of such a model is to provide a mathematical description of the evolution of the universe, and the growth of large-scale structures over extremely long periods of time. More specifically, the model primarily serves a predictive purpose, given a desire to make claims about the possible evolution, past and future states, of the universe. Not of concern is the inclusion of smaller features, such as stellar populations within galaxies; rather the model is restricted to regularities above the length scale of galaxies, but below that of the Hubble radius. Finally, having taken general relativity theory as the starting point, the model has assumed a specific explanation as the dynamics of the system, and from this, attempts to describe and predict the structure of the universe.

In order to develop tractable mathematical models from EFE to describe the global characteristics of the entire universe, certain assumptions must be made. That is, justifiable

[10] In the cosmology literature, the FLRW models are referred to as a class of *exact solutions* (rather than class of models) to Einstein's field equations specified by the FLRW metric. Any specification of parameter values, such as curvature ($\Omega_k$) and mass-energy density ($\Omega_m$), that is consistent with EFE is referred to as a solution to the model (Hamilton 2014). In the context of this paper and the model-focused interpretation being offered, the ΛCDM model is a parameterization of the perturbed FLRW models. The reader should understand the FLRW solution as a set of models; any specification of parameters yields a particular model, such as the ΛCDM model. For extended detail of the construction of ΛCDM model, see Hamilton (2014).

[11] Extended detail of the construction of ΛCDM model it outside of this paper's scope. See Hamilton (2014).

idealizations or approximations of the target system according to the accepted understandings in astrophysics. Two critical assumptions are that the universe, on very large scales (i.e., > 100 Mpc), is homogeneous and isotropic. These two idealizations are supported by a variety of observational data (Hamilton 2014, 71), and provide the large-scale smooth metric, the Friedmann–Lemaître–Robertson–Walker (FLRW) metric. It is also assumed that spacetime can be treated as a perfect fluid.[12] The motion of points through this fluid is used to represent objects such as galaxies. By applying these idealizations and approximations to EFE, and taking into account symmetries in the equations, one obtains the FLRW class of models.[13]

The FLRW models describe a universe with two unknowns; a global scale factor, *a(t)*, for the universe, and the constant curvature of the universe. The scale factor is not directly observable, and its value must be determined indirectly from observations. Similarly for the curvature. Much of contemporary astrophysicists' efforts aim to determine the values for these unknown parameters. That is, the work aims to determine features of the target system in effort to further refine the model used to represent the target system. From the observable part of the universe, observational data from various independent sources (such as WMAP, BOOMERanG and Planck) indicates that the curvature of the universe is almost perfectly flat. However, the global scale factor for the universe is more uncertain. A global scale factor is a function of time and represents the relative expansion of the universe. The differential equations for the scale factor *a(t)* depend on the content of the universe, which is parameterized by various cosmological parameters: $\Omega_m$, the average matter density (including baryonic and dark matter) that undergoes dilution with the scale factor; $\Omega_\Lambda = \Lambda/3H^2$, where $H=\dot{a}/a$ is the Hubble expansion rate, and $\Lambda$ is the cosmological constant, a constant that does not dilute with the scale factor; and $\Omega_k$, the average curvature of the universe (Hamilton 2014). These parameters are related through $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$. A negative value corresponds to an infinite hyperbolic universe, a positive value corresponds to a closed spherical universe, and zero is an infinite flat Euclidean universe.

Since the goal of ΛCDM modeling is to describe the evolution of structure formation, it requires a slight alteration to the standard FLRW matter-density assumptions. FLRW has a uniform matter density. However, with a uniform distribution of matter, gravitational effects would be acting equally from all directions on all points. This is a uniform model that will not develop structure. In order to generate large-scale structure, ΛCDM needs to assume that there are random perturbations in the matter density distribution at very early times in the evolution of the universe. The regions with higher-than-average matter density will attract matter from surrounding lower-density regions, leading to a concentration of matter that will become the large-scale structure of the universe. This evolution is what is governed by the linearized field equations in this model. The use of these equations is justified because, on the scales, or *domain*, relevant for ΛCDM, gravity is weak, and spacetime metric is nearly flat. The standard Big Bang theory of cosmology does not give rise to the necessary density perturbations. ΛCDM requires matter density perturbations, which are inconsistent with the assumptions of the Big Bang theory. One common way to generate these inhomogeneities in the model is by including another

[12] This is the assumption that the stress-energy tensor is that of a perfect fluid.

[13] The class of FLRW models includes any model related to the FLRW models, including the perturbed FLRW models.

assumption about an inflationary period during the early universe to generate the density perturbations that allow for the formation of large-scale structures.

Through obtaining observational data about the universe, astrophysicists have narrowed down the values for the cosmological parameters. The model with parameter values in agreement with those observations (aspects considered part of the target system) is the ΛCDM model of cosmology. The model's name, ΛCDM, comes from the two features, dark energy and dark matter, which were added to the model in order to accommodate the observational data obtained about matter content and structure formation, and as such determine a certain range of permissible parameter values.

The critical point to emphasize here is the essential priority placed on using general relativity as the foundational theory of gravity in constructing the model. As astrophysicists attempted to learn more about the universe, and determine appropriate model parameter values, they had to consider they might not have known everything about the constitution of target system. In order for the model based on general relativity to continue to fit with the observations, there may be new features about the universe, dark matter and dark energy, not previously known. Modelers introduced these new target system features as part of the model in order to preserve general relativity as the fundamental underlying theory, the dynamical considerations, in the model. While including a new feature of the target system was not seen as something problematic, the loss of general relativity would be.

**3.1 ΛCDM and the Macro-scale**

As discussed, ΛCDM model works best for large scale structure. Since the ΛCDM model provides a mathematical description of the evolution of large-scale structure of the universe, computer simulations have been developed to aid in this visualization and understanding of said large-scale structure. For example, the Millennium Run I and II. With the parameter values in best agreement with observational evidence at the time, the Millennium Runs produced visualization of the ΛCDM large-scale structure description of the matter content of the universe from 13 Gyrs ago through to the present, as well as its future evolution. The Millennium II simulation used the ΛCDM model with parameter values in best agreement with observational evidence at the time: $\Omega_{tot} = 1.0$; $\Omega_m = 0.25$; $\Omega_b = 0.045$; $\Omega_\Lambda = 0.75$; $h = 0.73$; $\sigma_8 = 0.9$; $n_s = 1$, where $h$ is the Hubble constant at redshift zero in units of 100 km $s^{-1}$ $Mpc^{-1}$, $\sigma_8$ is the rms amplitude of linear mass fluctuations in 8 $h^{-1}$ Mpc spheres at z = 0 and $n_s$ is the spectral index of the primordial power spectrum (Boylan-Kolchin et al 2009, 1151). Running the simulation involved following 21603 particles within a cubic simulation box of side length $L_{box} = 100\ h^{-1}$ Mpc. Each simulation particle has mass of 6.885 × 106 $h^{-1}$ M⨀, and particles were allowed to have individual adaptive time steps. The goal in the simulation is to evolve these particles in accord with the ΛCDM parameter values and the linearized field equations, to represent the evolution of the regions of higher mass density (or "seeds"), in order to show how the ΛCDM model describes structure formation evolution over time (Boylan-Kolchin et al 2009).

Ideally, one would compare this simulated structure to the actual large-scale structure of the universe. However, there is no observational access to large-scale structure, nor is it possible to do observations over the relevant timescales (13 billion years). Since large-scale structure cannot be directly observed, indirect observations, such as those of smaller-scale structures, must suffice. Comparison of the simulation outputs to smaller-scale systems, such as galaxy distributions over shorter time scales (~1.5 billion years), was done to see if these structures are consistent with simulations.[14] At these scales, the model was evaluated as being similar enough to actual observations, and assessed as being adequate for providing a description of evolution of the large-scale structures of the universe. In this sense, the ΛCDM model is considered an incredibly successful model, fitting well with empirical observations of large-scale structure formation.

### 3.2 Extending ΛCDM (The Downscaling Problem)

While the ΛCDM model was originally constructed to apply on a large-scale domain, it has been "extended" to different domains, such as the meso-scale structure of a single galaxy. For the meso-scale structure domain, the field equations can reduce to Newtonian dynamics by using both the weak-field approximation and the slow-motion approximation, which are considered justified approximations for single galaxies or clusters. This allows the ΛCDM model to be "extended" to model galaxy rotation structures.

From a historical perspective, it should be noted that it was actually the single galaxy rotation curves and work by Vera Rubin in the 1930s that served as a line of evidence in favor of the inclusion of dark matter as a feature of the ΛCDM model. A galaxy rotation curve plots the orbital speeds of visible stars or gas in a galaxy against their radial distance from that galaxy's center. Initial observations of galaxies, however, did not match the expected curve. For the galaxies to rotate in the way the observations indicated, there must be significantly more mass in the galaxy than the mass we are able to see. Interpreted through a model-focused lens, dark matter was postulated as a feature of the target systems and added to the model.

### 3.3 Development of MOND Galaxy Rotation Curve Model (The Upscaling Problem)

MOND attempts to account for galaxy rotation without dark matter by modifying the underlying laws of physics. It suggests a modification to Newtonian dynamics such that a new effective gravitational force law applies at extremely low acceleration scales ($a_0$ ~ 10-10 m/s2). By modifying the underlying physics, they provide a model for galaxy rotation that not only does not posit dark matter as part of the target system, but also matches the observed data with a higher degree of accuracy than the extended ΛCDM model (McGaugh 2014; Milgrom 2009).[15] The ΛCDM-based galaxy rotation model can be said to fit the rotation curves, in that it generally gets the curve shape correct. However, if one wanted the model that, with the smallest amount of deviation and fits the data, one must say that MOND is the better model. The MOND model

[14] For a nice visual of what this looks like, consult Springel et al. 2006, 1138. Structural comparison from observational surveys of CfA2 'Great Wall' (blue north and west quadrants) to the Millennium Run simulations (red east and south quadrants), with matching survey geometries and magnitude limits.

[15] See (McGaugh (from Milgrom) 2009) for an illustration of this rotation curve. The measured rotation curve of the galaxy NGC1560 shown by the data points. Newtonian curve based on the measured mass distribution (in blue), MOND (in green), and Newtonian + dark matter halo of the type predicted by CDM simulations (in red).

provides rotation curves of galaxies with higher degree of accuracy to the real observations than ΛCDM, and is thus a better fitting model.[16]

If evaluated only for the ability to describe and predict galaxy rotation curves, then MOND model proponents are permitted their success claims. The key point however is that the proponents of MOND also want to serve the purpose of offering an explanatory model, in that the explanation for these data points *is* modified Newtonian dynamics and not general relativity. MOND "explains almost all aspects of the mass discrepancies in galactic systems with no need to invoke dark matter. This is what MOND claims to achieve" (Milgrom 2009, 5). Like ΛCDM, MOND proponents consider their model for galaxy rotation to be heavily based on theory, and thus believe that their models are actually capturing dynamical dependencies in the target system. Therefore, MOND proponents have attempted to extend its domain to large-scale structure formation. The MOND-based models for large scale structure also achieve similar structures as are observed, but in MOND the structures develop too soon (McGaugh 2014, 13). What astrophysicists consider to be the current structure ($z=0$ in ΛCDM) occurs in MOND at $z=3$. This is what leads some astrophysicists to consider the MOND-based model of structure formation not to fit with our observational data-based claims of the large-scale structures (McGaugh 2014; Dodelson 2011). Therefore a MOND model, on the large-scale, is not considered to fit well with the data, whereas the ΛCDM model does.

## 4. Philosophical Implications

I have just offered a model-focused interpretation of the ΛCDM–MOND debate. I now turn to the philosophical implications of this analysis. The first relates to a key conceptual difference between a model-focused and theory-focused interpretation of the debate. The second relates to explanation and justified extensions of models to new domains of application. The third puts this discussion in dialogue with Massimi's multi-scale modeling analysis, drawing out the implications for the broader discussion of what is philosophically at stake in this debate.

### 4.1 Conceptual difference between the model-focused and theory-focused interpretation

Models can differ in terms of their theoretical commitments, simply because different scales and different systems may need different theoretical treatments. Therefore, different models might be used for different purposes or for different phenomena at different scales. While a modeling-focused interpretation would not necessarily find this troublesome (depending on the purpose the model was intended to serve), a theory-focused interpretation would. A theory-focused interpretation of the ΛCDM – MOND debate is akin to what Batterman describes as a reductionist view, "whatever the fundamental theory is at the smallest, basic scale, it will be sufficient in principle to tell us about the behavior of the system at all scales" (2013, p.256-257). This is to say, the theory-focused interpretation of the debate will prioritize theoretical commitments and interpret success as tied to the theory.

[16] See Begeman et al. 1991, Sellwood & McGaugh 2005, and Famaey & McGaugh 2012 for comparisons of MOND and ΛCDM with respect to rotation curves.

On the theory-focused interpretation, when ΛCDM is extended from the large scale structure down to galaxies, it is not merely the ΛCDM model being extended, but rather an assumption about the relationship between general relativity theory for large scales with appropriate assumptions about approximating Newtonian gravity (with an assumption about dark matter) on smaller scales. This is not an extension of ΛCDM model, but rather a new model from the general GR theoretical framework that posits dark matter's existence. Similarly, the MOND model of galaxies cannot simply be extended to the whole universe. On the theory-focused interpretation, to consistently extend MOND to large scale structure formation would entail taking MOND as the background theory, and developing a new, and most importantly, different model. This is not extension of MOND as a model to a new domain or scale, but rather development of a new model based on MOND as the background theory. What is extended to this new scale (or domain of application) is only the theory. In developing this new MOND-based model, other modeling choices will need to be made, such as initial conditions similar to ΛCDM (with only luminous matter).[17] For these reasons, through a theory-focused interpretation, ΛCDM cannot simply be extended to the meso-scale, and MOND models cannot be extended to the Universe. Ultimately, the debate is between modified Newtonian dynamics and general relativity, not between MOND and ΛCDM; ΛCDM is simply one very specific parameterization of GR theory. Through the theory-focused lens, the upscaling problem of MOND is not about extending MOND to large scale where general relatively applies, because that is not the goal of MOND—the goal is replacing general relativity on all scales.

### 4.2 **Explanation and Justified Extension of Models.**

This brings me to my second, more substantial claim that emerges from interpreting the debate through a model-focused lens related to explanations in the context of modeling. According to Bokulich (2011), the conditions under which it is reasonable to take models to be genuinely explanatory are (1) the explanans must make essential reference to a scientific model, and that scientific model involves a certain degree of idealization and/or fictionalization; (2) the model explains the explanandum by showing how the elements of the model correctly capture the patterns of counterfactual dependence of the target system; (3) there must be a "justificatory step", in which we specify what the domain of applicability of the model is and show that the phenomenon in the real world to be explained falls within that domain.

The component of this account most relevant to my argument is the third condition. Bokulich takes the "justificatory step" as specifying the model's domain of applicability. This step is intended to "draw explicit attention to the detailed empirical or theoretical process of demonstrating the domain of applicability of the model. In other words, it involves showing that it is a good model, able to adequately capture the relevant features of the world" (Bokulich 2011, 39). She thinks justification for the model's domain of applicability can proceed in two ways. The justification can proceed "top-down" from theory, in which an overarching theory specifies "where and to what extent the model can be trusted to be an adequate representation of the world" (Bokulich 2011, 30). However much more commonly, it proceeds "bottom-up", through various empirical investigations. The main result of this step is to distinguish between models

[17] I would like to thank an anonymous referee for their comments on an earlier version of this paper, which lead me to further develop the idea that this debate is about theory versus modeling.

that are genuinely explanatory and models that are merely phenomenological (Bokulich 2011, 39-40).

In the case of both MOND and ΛCDM, it seems the justification has proceeded rather "top-down" from theory (namely, the gravitational theories). In the context of the ΛCDM model, since highly confirmed fundamental physical theories (like general relativity) are taken to apply everywhere in the universe, then it is natural to think a model that relies strongly on a theory would be universally applicable on all scales.[18] Likewise, when a model is constructed such that it includes a strong theoretical component, like a gravitational theory accounting for the dynamic nature of spacetime, then the model is evaluated as providing an explanation. For these reasons, it is quite natural to want to extend the model to other domains. A similar line of reasoning applies to the entities posited. In the case of ΛCDM, this involves accepting dark matter as a feature or attribute in the real-world target system, and thus needing to be represented in the model. If a model contains explanatory mechanisms that are considered not only to be fundamental to the construction of the model, but an actual part of the target system, then the model should have explanatory extendibility to other domains. Not only are these models being viewed as explanatory in their original domain of construction and applicability, but they are considered to have justified extension of their domain of applicability.

However, there is a second point to be made here that this model-focused interpretation brings into focus: there are two senses in which a model can be extended. The first is extension to different scales or domains, from large scale to meso or galactic scale. The second is extension in terms of the *purpose* for which the model is intended to serve or claim success—that is, effectively accounting for phenomena verses offering good predictions verses offering an explanation.

In the case of ΛCDM and MOND, each of these models in its original intended domain of application (meso for MOND, large-scale for ΛCDM) is successful with respect to its originally intended purpose, a descriptive and predictive purpose. By focusing on the model's purposes, this analysis can illuminate this complexity. Construction of a model is made relative to a certain domain, *and* a certain purpose. A model's good fit or success can then be later assessed relative to different purposes. However, a model evaluated as a good fit for a predictive purpose does not necessarily mean it fits well for all purposes (such as for the purpose of offering an explanation). Furthermore, these two senses in which a model can be extended can also be paired together: a model is constructed with a certain purpose, as well as certain domain of application in mind. For instance, the MOND galaxy rotation curve model was originally constructed in order to offer descriptions and predictions of galaxy rotation on a specific scale size of single galaxies. A model evaluated as being a successful model for a certain domain does not necessarily mean it will be evaluated as a good fit when extended to a different domain—this can mean either the move from offering predictions at the meso scale to predictions at the large-scale scale, *or* the move from offering predictions at the meso scale to offering explanations at the meso scale.

[18] That is, unless there is some specific assumption makes it ill-suited for a particular scale.

This analysis suggests a further way to dissect the challenges the models are facing: the models may not be justified in their extension not only to a new scale domain, but also the extension from predictions to explanations in their originally constructed scale domain. This implicit assessment of the models as explanatory is perhaps a result of the role of theory. What is important in the case of MOND and ΛCDM is that, given the significant role of theory in the construction of these models, there is some embedded, implicit commitment to its explanatory success. What the extension of the models to their new scale domain shows is that if the model did accurately represent the correct dependencies, then the extension to the new scale domain should not have been so problematic. These challenges related to extension should indicate that the assessment of these models as explanatorily successful in their original domains is somewhat more complicated and may involve domain-relative elements. This analysis also illuminates another point. While it may be relatively straightforward to see if a model's predictions or descriptions extend beyond the original domain, that there is perhaps something privileged connected to models offering explanations, and in extending explanation specifically to new domains.

Justification for extending a model's domain and for making inferences from claims about a model to the world requires strong commitments to explanatory dependences and their representation in the model. When extending a model outside of the domain, attention needs to be paid as to why one thinks that is appropriate. Extending the model requires strong commitments to the explanatory dependences and their representation in the model. And this occurs most frequently when a model has good explanatory fit. In general, when a model is constructed such that it includes a strong theoretical component, then it is very likely that the model will be evaluated as having good explanatory fit. Since fundamental physical theories are to apply at all times and to all scales, then a model closely based on them should also apply at all times and all scales.[19]

In the case of this debate, both ΛCDM and MOND were constructed to be predictive and descriptive in their original scale domains. The implicit assessment of also being explanatorily successful is where the problem for extension to a new scale domain originates. This explanatory success requires an accurate representation of the dependency relations in the target system they aim to model.[20] But in both of these cases, the failure of extendibility to another scale shows that the dependences represented in each model have scale-dependent features, which mean they are not explanatorily generalizable to other scales. This failure to extend in turn casts doubt as to whether ΛCDM and MOND should be thought to be explanatory even within their original scale domain. Nonetheless, they are both successful with respect to their original purpose within their original domain.

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[19] I also suspect that a theory-focused interpretation of the debate may align with an ontic conception of explanation (according to which explanations are full-bodied things in the world), while a model-focused interpretation may align with what Bokulich (2018) calls an "eikonic conception" (according to which explanations are the product of an epistemic activity involving representations of the phenomena to be explained). However, exploration of this is outside of the scope of the goals of this paper.

[20] I thank a reviewer for pressing me to make this commitment of accurate representation of dependency relations more explicit.

This is the sense in which both models can be evaluated as successful, yet be based on fundamentally different physical theories. While both ΛCDM and MOND are good predictive and descriptive models each is less successful as an explanatory model. The original purpose for each model was descriptive and predictive, and so they did not require accurate representation of the system's explanatory dependencies. However, each model's extension involved a wider domain, and so requires these features to be present. This means there is a way to understand models as not in conflict when applied and confined in their original intended domains. It is only when they are taken to be assessed as good explanatory models, and when those explanations are used to make inferential claims about the actual world that they come into conflict. Given their assumptions about what features might constitute the target system, both can offer candidate how-possibly explanations. But what is interesting in cases from astrophysics such as this is the extreme uncertainty about what constitutes a given target system. A consequence of having uncertainty with respect to what is in the target system is that there is some uncertainty with respect to our assessment of how confident we can be in thinking our model is similar in the right ways to the world.

A claim that a model has good explanatory fit means that the model is offering an adequate explanation, but also that the model represents the proper dependencies to generate that explanation. If the model is a good explanatory fit, then it should be the case that the model has features that represent actual explanatory dependencies in the target system. The relations established in the model should also be there when the model is extended; the model still accurately represents the relevant features of the target system. This is why it is considered justified to extend a good explanatory model beyond its original domain of application. Justifying the extension of a model to a new domain beyond the one it was originally constructed for requires assessing uncertainty in the target system and commitment to the claim that a model has good explanatory fit, which includes a claim about the relations in the model capturing actual dependencies of the system. This suggests that a model with a strong theoretical component will likely be successful at making predictions. Even if the model was constructed with a descriptive purpose in mind, it will allow one to make claims about future and past states of the system. While a fundamental theory is meant to apply in any domain, it likely will not be universally useful. Approximations and idealizations are made when constructing a model for a domain that differs from the standard domain of the theory. These approximations and idealizations may build in a domain dependence for the model that may not exist for the theory itself. What this also demonstrates is the consequences of taking ΛCDM seriously as a model rather than extension of theory.

By approaching the debate this way, one can see that when one thinks of a model as having good explanatory fit, it is because of the way the representational relation is accounted for in the model. It is endorsing the idea that the dynamics in the model represent explanatory relations. If one thinks they have a model with good explanatory fit, what they think they have is a model that has good similarity to the target system, and to the real dynamical or counterfactual dependencies that exist in the world. Models with good explanatory fit make very strong commitments to what there is in the world, and this is the reason why it is natural to think they can be extended to new domains. A model that accurately captures explanatory dependencies in one domain will likely apply at other domains because the dependencies are actually present in the target system. As such, one can generate new models based on having a good explanatory understanding of a phenomenon.

This cannot necessarily be done with a model that offers only good predictions. One might construct a model that ends up always predicting future states of the system correctly, but nonetheless the modeler may not be able to say why it is those predictions and not others. Thus, when the model is extended to a new domain, a predictive model may still offer adequate predictions, but may not be able to say why the model's predictions still hold. Explanatory models commit to more, namely, to the existence of these relations. Where the ΛCDM and MOND models run into trouble is when they attempt to move beyond their original domains, and attempt to extend their claims about the model's explanatory adequacy. Both are adequate for prediction and description in their original domains. But what they disagree about is what they are committed to existing in the target system. That is to say, they disagree about the dynamical relations and features of the system that are causing the system to behave in a certain way.

Even though neither the MOND or ΛCDM model was explicitly developed with the purpose of explanation in mind, they both have come to be regarded as offering explanations in their respective domain of applicability. This is perhaps why cosmologists have considered it justifiable to extending them to other domains. However, each model fails to correctly predict in the extension to the new domain. This shows that there must be some problematic representational dependences of the original target system in the original domain and for the purpose for which it was originally constructed.

The reader might notice that I have not attempted to adjudicate which model, ΛCDM or MOND, is right or wrong. Focusing on this verdict misses the more subtle point I wish to make regarding how one might more productively go about making that assessment. To make that kind of assessment one must acknowledge that it also requires making at least some choices about what the modeler wants to represent in the model, some of which may be scale relative, and only apply in a particular domain. These representational choices might be simply related to the scale, but it might also be related to the construction of the model for some original purpose (for example, providing predictions). Therefore, the fact that the ΛCDM or MOND models are not successfully extendable means that either they are not successfully providing the complete explanation in their original domain, or are not completely representing the causal dependences in their original scales.

The model-focused interpretation also provides further nuance to understanding the failure of extendibility. The failure of ΛCDM and MOND to be extended to the new domains could in part be tied to the gravitational theory used. But there may be more to it than theory. The failure to extend is possibly the result from idealizations and approximations made during the construction of the model, or assumptions made about the real-world target system. This demonstrates the need to be able think there is a separation between models and theories. This is what permits proponents of GR to make sense of ΛCDM even though there is this "failure" to extend. The most likely juncture for the introduction of this issue is in the introduction of idealizations or approximations in the construction of the model. The final question then, is whether models that contain idealizations can give good explanations, even in their original domain. And the answer should be yes.[21] But it is the assumptions that are made when introducing idealizations or approximations that are scale relative. The modeler is making idealizations, they very well may be idealizing away some of the real true dependences, but nonetheless the models can still offer good explanations. What is important is that the explanation has scale relativity, which comes from the idealizations, and so it may only preserve a good explanation at a particular scale—so when idealizations are made that eliminate some of the causal dependencies, this is where the domain relativeness comes from.

### 4.3 Implications for Massimi's Analysis.

Finally, I would like to return to Massimi's claims regarding what is philosophically at stake in the ΛCDM–MOND debate. Similar to Massimi, my analysis of the ΛCDM–MOND debate through a model-focused lens highlights that ΛCDM and MOND, respectively, work best at a specific scale (large scale for ΛCDM, meso or galactic scale for MOND). Each model faces challenges when modelling across more than one scale. The ΛCDM faces problems going down from large scale structure formation to the meso scale of individual galaxies—she calls this the "downscaling problem". MOND faces problems going up from the meso scale of individual galaxies to the large scale of clusters and structure formation—she calls this the "upscaling problem".

With respect to Massimi's first two claims: in a model-focused interpretation, her first claim is not contentious. ΛCDM is the best existing model for large scale, and MOND models are best for the meso-galactic scale of individual galaxies. This is because the model's success can be defined or understood as serving a specific purpose of modeling well at these scales. On a model-focused interpretation, there is nothing problematic or puzzling about a model having a specific domain of applicability. And so her second claim, on a model-focused conception, is likewise as unproblematic. Each model faces challenges when the model is extended to a new domain of application, what she calls modelling across more than one scale. The ΛCDM model extension from large-scale structures to meso-scale individual galaxies faces a downscaling problem. MOND model extension faces an upscaling problem when extended from meso-scales of individual galaxies to large-scale structure.

Her third claim however, states that philosophically, the downscaling problem and upscaling problem are different in nature. The downscaling problem for ΛCDM is a problem about the explanatory power of ΛCDM. The upscaling problem for MOND is a problem of consistency: "how to consistently extend MOND to large scale where general relativity (GR) applies (and most of the larger scale phenomena and even experimental techniques, such as gravitational lensing, rely on and presuppose the validity of GR)". I have argued that the upscaling and downscaling problem are not different in nature. Rather, both are about the explanatory power of the models, and their ability to extend their explanations to their different scales. And, they are both about consistency with respect to consistently extending the explanations embedded in them.

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[21] This is in fact the original target of Bokulich's account of explanation I have drawn on in this paper. She provides an account for how models, even if they include fictitious entities or behaviors, can still be regarded as explanatory.

## 5. Conclusion

I have provided an account for how ΛCDM and MOND models can both be understood as highly successful and through this model-focused interpretation, a different way to make sense of such success claims. ΛCDM fits well with respect to describing and predicting the large-scale structure of the universe. However, in order to maintain general relativity as its fundamental explanatory basis, it has to include a stipulation that dark matter is a feature of the target system. MOND fits well for describing and predicting the meso-scale structure of single galaxy rotations. However, in order to provide this accurate description, general relativity as the underlying theory is abandoned in favor of modified Newtonian dynamics. Both can be evaluated as successful, even if based on fundamentally different theories. Within their original domains, the models are successful in offering accurate description and predictions that fit with observations. The key in making sense of the conflict lies in the ability to identify the third dimension on which we can assess a model's fit: explanation. This third aspect of evaluation allows one to separate out the issue that each model includes what might be potentially problematic explanatory structures.

I hope this model-focused interpretation of the ΛCDM–MOND debate lays bare some commitments that might shed light on other dimensions to the debate. In particular, one should pay careful attention to which of these conceptions—model-based or theory-based—are the terms in which they are thinking of the debate. Additionally, that a source of conflict is that models evaluated as having high explanatory fit make the most commitments to features in the target system (this is why it is natural to think they can be extended to new domains). The puzzle stems from failing to recognize the implicit commitments embedded when extending the model to a new domain. Approaching the debate this way puts the focus back where I think it properly belongs: re-examining the construction of the model, its original intended purpose, and what was considered to be the important features in the target system that the model should capture. ΛCDM has, as far as our current knowledge of our target system goes, the stronger representational relation because the dynamics in the model for gravitational attraction in the model comes from our current best theory. The questionable attributes that it includes (namely, dark matter and dark energy) are not *theoretically* problematic according to general relativity. What may be needed is not evidence for the theory per se, but rather evidence for claims about certain features, attributes or mechanism, of the model being part of the target system.

My goal in this paper was not to make the stronger claim about which of these models is the right or wrong model. I instead want to draw attention to the need for more careful consideration and analysis of the extension of models beyond their original domains. When one extends a model to a new domain, there are explanatory commitments at play, and the reasoning for a claim about justified extension contains an implicit premise related to the explanatory aspects of the model. My goal has been to make a subtler point: the reason that is given for the claim that the extensions of both models are justified is connected to explanatory claims. By analyzing this issue through the lens of modeling, we see this disagreement is also connected to the various justificatory steps made in the construction of the model (via idealization and approximations), and concerns regarding commitments to what exists in the target system.

What this sort of analysis allows for is a richer understanding of how it could be possible for two models with fundamentally different physics to both be good fits in their domains for their purposes. This approach more precisely formulates where disagreement stems from: the models aim to be successful for description, prediction, *and* explanation. The models conflict when they are extended, and one is only justified in extending a model beyond their original domain if the model is considered to be a good explanatory model. If one thinks it is a good explanatory model, they are committed to the features in the models standing in some representational relation to features in the actual target system. More broadly, the important point that must be acknowledged is what these models commit us to when claims move beyond the model itself. It is when we attempt to make inferences from our models to the real world that we must reflect on what the model commits us to.

## References


Batterman, R. (2013). The tyranny of scales. In The Oxford handbook of philosophy of physics. OUP.

Begeman, K. et al. "Extended rotation curves of spiral galaxies: Dark haloes and modified dynamics." *Monthly Notices of the Royal Astronomical Society* 249, no. 3 (1991): 523-537.

Bokulich, A. (2011). How scientific models can explain. *Synthese 180*(1), 33–45.

Bokulich, A. (2013). Explanatory models versus predictive models: reduced complexity modeling in geomorphology. In *EPSA11 Perspectives and Foundational Problems in Philosophy of Science*, pp. 115–128. Springer

Bokulich, A. (2018). Representing and explaining: The eikonic conception of scientific explanation. *Philosophy of Science*, *85*(5), 793-805.

Boylan-Kolchin, M. et al. "Resolving cosmic structure formation with the Millennium-II Simulation." *Monthly Notices of the Royal Astronomical Society* 398, no. 3 (2009): 1150-1164.

Boylan-Kolchin, M., J. S. Bullock, and M. Kaplinghat (2011). Too big to fail? the puzzling darkness of massive Milky Way subhaloes. *Monthly Notices of the Royal Astronomical Society: Letters 415*(1), L40–L44.

Boylan-Kolchin, M., J. S. Bullock, and M. Kaplinghat (2012). The Milky Way's bright satellites as an apparent failure of Λ CDM. *Monthly Notices of the Royal Astronomical Society 422*(2), 1203–1218.

Boylan-Kolchin, M., V. Springel, S. D. White, A. Jenkins, and G. Lemson (2009). Resolving cosmic structure formation with the Millennium-II simulation. *Monthly Notices of the Royal Astronomical Society 398*(3), 1150–1164.

Carnap, R. (1937). *Logical Syntax of Language*, Volume 4. Psychology Press.

Cartwright, N. (1983). *How the Laws of Physics Lie*. Oxford: Oxford University Press.

Elliott-Graves, Alkistis (2020). What is a Target System? *Biology and Philosophy* 35 (2):1-22.

Famaey, B, and S. McGaugh. "Modified Newtonian dynamics (MOND): observational phenomenology and relativistic extensions." *Living Reviews in Relativity* 15, no. 1 (2012): 10.

Giere, R. N. (1996). Visual Models and Scientific Judgment. *Picturing knowledge: Historical and philosophical problems concerning the use of art in science*, 269.

Giere, Ronald N. (1999). *Science Without Laws*. University of Chicago Press.

Giere, R. (2004). How models are used to represent reality. *Philosophy of Science 71*(5), 742–752.

Giere, R. (2006). *Scientific Perspectivism*. University of Chicago Press.

Giere, R. (2009). Why scientific models should not be regarded as works of fiction. In M. Suárez (Ed.), *Fictions in Science: Philosophical Essays on Modeling and Idealization*, pp. 248–258. Routledge.

Giere, R. (2010). An agent-based conception of models and scientific representation. *Synthese* 172(2), 269–281.

Hamilton, J-Ch. "What have we learned from observational cosmology?." *Studies in History and Philosophy of Modern Physics* 46 (2014): 70-85.

Hempel, C. G. (1965). *Aspects of scientific explanation*. New York: The Free Press.

Le Bihan, Soazig. "Defending the semantic view: What it takes." *European Journal for Philosophy of Science* 2, no. 3 (2012): 249-274.

López-Corredoira, M. "Non-standard models and the sociology of cosmology." *Studies in History and Philosophy of Modern Physics* 46 (2014): 86-96.

Massimi, M. (2018). Three problems about multi-scale modelling in cosmology. *Studies in the History and Philosophy of Modern Physics*, *64*, 26-38.

Massimi, M. and J Peacock. "What are dark matter and dark energy?" In M. Massimi (Ed.), *Philosophy and the Sciences for Everyone*, Chapter 3, pp. 33–51. Routledge, (2014).

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. (2001). MOND–a pedagogical review. *arXiv preprint* astro-ph/0112069.

Milgrom, M. (2002). MOND's theoretical aspects. *New Astronomy Reviews 46*(12), 741–753.

Milgrom, M. (2009). MOND: Time for a change of mind? *arXiv preprint* arXiv:0908.3842 .

Misner, C. W., K. S. Thorne, and J. A. Wheeler (1973). *Gravitation*. Macmillan.

Mo, H., F. Van den Bosch, and S. White (2010). *Galaxy Formation and Evolution*. Cambridge University Press.

Morgan, M. S. and M. Morrison (1999). *Models as Mediators: Perspectives on Natural and Social Science*, Volume 52. Cambridge University Press.

Parker, W. (2009). “Confirmation and adequacy-for-purpose in climate modelling”. *Aristotelian Society Supplementary Volume 83*(1), 233–249.

Parker, W. (2010). “Scientific models and adequacy-for-purpose”. *The Modern Schoolman 87*(3/4), 285–293.

Parker, W. (2015). “Getting serious about similarity”. *Biology and Philosophy 30*(2), 267–276.

Parker, W. (2020). "Model Evaluation: An Adequacy-for-Purpose View". *Philosophy of Science*

Sellwood, J., and S. McGaugh. "The compression of dark matter halos by baryonic infall." The Astrophysical Journal 634, no. 1 (2005): 70.

Springel, V. et al. "The large-scale structure of the Universe." *Nature* 440, no. 7088 (2006): 1137

Suppe, F. (1989). *The Semantic Conception of Theories and Scientific Realism*. Chicago: University of Illinois Press.

Suppes, P. (2002). *Representation and Invariance of Scientific Structures*. CSLI publications Stanford.

Van Fraassen, B. (1980). *The Scientific Image*. Oxford: Oxford University Press.

Weisberg, M. *Simulation and similarity: Using models to understand the world*. Oxford University Press, 2012.