THE LIGHT OF THE DARK: DARK MATTER, ASTRONOMY, AND KNOWING THE UNOBSERVABLE

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ABSTRACT

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Dark matter in astrophysics offers a rare treat for philosophers of science. When they look at the contemporary science of dark matter, they see reports of a widely accepted theoretical posit indispensable to our best theories and models but without an accepted experimental confirmation of its existence. Nearly all astrophysicists and cosmologists believe that dark matter exists and makes up approximately a quarter of the mass-energy content of the universe. However, they seem to know almost nothing about its nature, cannot directly observe it, and have been unable to detect the products of any interactions with any of the candidate dark matter particles. This project addresses the apparent tension between the impressive knowledge taken to have been obtained in contemporary sciences of the cosmos and the methodological and theoretical limitations in obtaining such knowledge. To do so, this dissertation investigates the ways in which astronomers and astrophysicists are making progress by looking more closely at their experimental practices and actual theoretical commitments. More specifically, the goal is to determine how this bears on longstanding philosophical questions of scientific realism and the nature of scientific experimentation. Ultimately, I argue that astronomers do conduct traditional, interventionist experiments and that we can be realists about dark matter. These two views offer a way of thinking differently about how scientists can and do obtain knowledge about inaccessible and unobservable targets systems.

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Dark matter in astrophysics offers a rare treat for philosophers of science. When they look at the contemporary science of dark matter, they see reports of a widely accepted theoretical posit indispensable to our best theories and models but without an accepted experimental confirmation of its existence. Nearly all astrophysicists and cosmologists believe that dark matter exists and makes up approximately a quarter of the mass-energy content of the universe.[1] However, they seem to know almost nothing about its nature, cannot directly observe it, and have been unable to detect the products of any interactions with any of the candidate dark matter particles.

Beyond just dark matter, astrophysicists and cosmologists have developed a diverse array of methodologies that have yielded an impressive amount of knowledge and understanding about the nature, structure, and evolution of the Universe as a whole. This includes good evidence of what transpired just *millionths* of a second after the Big Bang up until our current moment approximately 13.8 billion years later. Ever-improving technologies, including images from the most powerful telescope ever constructed – the James Webb Space Telescope (JWST), in operation since 2022 – have allowed for observations of objects just a few hundred million years after the Big Bang. To put this in perspective, JWST can see so far back

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[1] Baryonic matter – ordinary visible matter that makes up stars, gas, and everything we see on Earth – makes up just 4% of everything in the universe. Dark energy accounts for 72%.

that, temporally speaking, it is only missing access to the first 1-2% of the Universe's existence. These successes have bolstered increasing consensus in the standard model of cosmology – the Lambda Cold Dark Matter (ΛCDM) model, which has itself achieved impressive results. ΛCDM is not only consistent with most observational data but also extremely good at generating the large-scale structure observed in the universe via advanced computer simulation.

From the philosophical perspective, all these accomplishments come despite two major challenges: (1) purported methodological limitations in investigating the cosmos beyond Earth, and (2) reliance on mysterious forms of matter and energy that play outsized roles in the success of contemporary astrophysics and cosmology. For (1), the most glaring methodological constraint is the apparent inability to directly experiment on target systems of interest. For (2), the impressive success of ΛCDM indispensably relies on dark matter. And yet, nobody seems to know exactly what dark matter is.[2]

For philosophers of science, historically so preoccupied with questions of scientific realism, surprisingly little has been said about the possibility of scientific realism about either dark matter or astrophysics more broadly. Regarding the possibility of realism about dark matter, the very few philosophical engagements have suggested that such realism is untenable (Allzén 2021; Martens 2022). For a broader concern with realism about astrophysics, one must go all the way back to Ian Hacking (1989) and his view that we must be antirealists about the entire discipline. Perhaps the methodological and theoretical worries just mentioned have

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[2] There are at least half a dozen kinds of dark matter particle candidates currently under consideration.

preemptively convinced philosophers that it is unlikely to avoid such conclusions. This dissertation seeks to reconsider these questions regarding realism and experiment in astrophysics by taking inspiration from Hacking himself and by digging deeper into contemporary scientific practice in astrophysics.

The three chapters below are motivated by an initial consideration of Hacking's (1983) entity realism and the broader insights of the New Experimentalist movement in philosophy of science going back to the 1980s. As a way into my project, this introduction provides a brief look at these philosophical considerations and how they have shaped my work. Although I am not yet able to resolve the issues of entity realism itself, I hope that the progress made in this dissertation provides the first steps to doing so moving forward. At the very least, I believe that we should rethink some of our assumptions about experimentation and how this should affect our views about sciences like astronomy, astrophysics, and cosmology. I also think we should look more closely at these fields in helping to resolve some longstanding questions in philosophy of science.

2. The New Experimentalists and Entity Realism

Ian Hacking's *Representing and Intervening* is a sort of *locus classicus* of the New Experimentalist movement in philosophy of science.[3] The New Experimentalist moniker reflects a shift by some

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[3] The shift itself was dubbed "the new experimentalism" by Robert Ackermann (1989) and its proponents as the "New Experimentalists" by Deborah Mayo (1994). The foundational New Experimentalists are epitomized by the work of Ian Hacking, Nancy Cartwright, Allan Franklin, Peter Galison, and Ronald Giere.

notable philosophers away from a positivist conception of philosophy of science focused on theory confirmation and inductive logic to a focus instead on the practice of scientific experimentation itself. As Hacking (1983) lamented:

> "Philosophers of science constantly discuss theories and representation of reality, but say almost nothing about experiment, technology, or the use of knowledge to alter the world…Philosophy of science has so much become philosophy of theory that the very existence of pre-theoretical observations or experiments has been denied. I hope the following chapters might initiate a Back-to-Bacon movement, in which we attend more seriously to experimental science" (149-150).

I do not intend to go into historical exposition about this experimental turn in the philosophy of science here.[4] Suffice it to say that the core and most relevant insight for my purposes is the realization that close attention to the details of experimentation and the practice of science can yield insights and make progress on important questions in philosophy of science. One way or another, each of the below chapters takes this insight seriously.

In addition to a focus on scientific experiment and its products, Hacking also proposed a new way to resolve the longstanding debate about scientific realism. Traditionally construed, the question of scientific realism is a question about the truth and accuracy of scientific theories (Chakravartty, 2017). Realists claim that, roughly, we should believe in the approximate truth of our successful scientific theories and models, as well as in the real existence of both the

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[4] Hacking's (1983) own introduction provides one such historical perspective. Potters & Simons (2023) provide a recent and more complicated picture of the relevant historical facts. It may also be worth noting that a "practice turn" had already developed in the decade prior to Hacking, focused on the experimental, technical, and material aspects of science (Simons & Vagelli, 2021).

observable and unobservable aspects of the world that such theories describe. Anti-realists reject commitments to truth and existence and instead see our best theories and models as providing a useful, adequate, or otherwise sufficiently effective way of describing the world.

Entity realism carves out an option for those, like me, who want to believe in the real existence of some unobservable entities without a commitment to the truth of the theories that postulate such entities. To borrow a quip from Anjan Chakravartty (2007), "as in life generally, so too in science: do not believe everything you are told" (29). This shift away from concern with the truth of theories transformed the longstanding debate about scientific realism (Nanay, 2019). Both Hacking (1983) and Nancy Cartwright (1983) deserve major credit for opening up this space of possibilities. In his initial formulation of entity realism, Hacking (1983), summarizes the idea as follows:

> "One can believe in some entities without believing in any particular theory in which they are embedded. One can even hold that no general deep theory about the entities could possibly be true for there is no such truth" (p. 29).

One possible intuition behind this shift from a realism about theories to one about entities might arise from the observation that while most (all?) theories are eventually determined to be, strictly speaking, false, many unobservable entities posited by these theories nonetheless persist. Even some of our most successful theories to date seem unlikely to survive in the long term. For example, despite their major respective successes, the theories of General Relativity and Quantum Mechanics are known to be incompatible. Whether one or the other is discarded, or whether they are both replaced via some sort of grand unification, theoretical change is extremely likely. The lesson I take from the traditional scientific realism debate is to avoid getting entirely bogged down in theory. We should look to navigate between the Scylla of the no-miracles argument for theory realism and the Charybdis of pessimistic meta-induction for anti-realism.

For any scientific realist, whether entity realist or otherwise, a key burden is to explain how it is that entities persist through time despite the change in theories and models that we use to describe the world (Psillos, 1999; 2012). Psillos (2012) calls this the 'tracking requirement': the ability to retain specific unobservable entities throughout the development and evolution of scientific theories and models that posit and rely on them. Even if a discovery of new physics and new models of particle interactions replaces quantum mechanics in its current form, the realist expects that electrons, quarks, and other fundamental particles will remain in the replacement theories, with essentially the same properties that past theories conceived them to possess.

What does entity realism claim? Entity realism as conceived by Hacking (1983) proposes a manipulationist condition for belief in the reality of unobservable entities. On Hacking's view, if we can manipulate an entity in a way that would create observable phenomena or effects that could be used in some other domain, then we are justified to be realists about that entity. The idea is that we should be convinced in the reality of unobservable entity if we can build an apparatus that can exploit the causal properties of the entity in service as a tool to explore or interfere with other parts of nature. Taking the case of electrons – specifically as produced by the polarizing electron gun (PEGGY) and used in many particle accelerator experiments – Hacking (1983) famously sloganized the view of entity realism with his quip: “if we can spray them, then they are real” (23).

Despite the appeal of this kernel idea of entity realism, the view is quite controversial (Nanay, 2019). Criticisms home in on the view’s two central claims: (a) that successful manipulation of an unobservable entity in the service of other efforts is sufficient to justify the existence of such entities, and (b) that realism about such unobservable entities can be achieved with such an extremely limited commitment to any specific theoretical framework. Against (a), critics have argued that: Hacking begs the question about what is to be inferred about the manipulated entity (e.g., van Fraassen, 1985); that the belief in a specific entity considering the causal powers used in a single experiment is unjustified (Barwich & Bschir, 2017); and that one can appear to successfully manipulate objects known to be illusory (Gelfert, 2003). Against (b), critics have attempted in a variety of ways to show that Hacking’s argument either cannot avoid committing to the approximate truth of theories that posit the entities of interest (e.g., Morrison, 1990; Resnik, 1994; Musgrave, 1996; Psillos, 1999; Massimi, 2004) or that experiments themselves rely on much more theory than Hacking permits (Resnik, 1994). Moreover, philosophers have also argued that Hacking, despite his explicit disavowals, nonetheless relies on inferential reasoning such as Inference to the Best Explanation (e.g., Resnik, 1994; Reiner & Pierson, 1995;

Sankey, 2012). It is no surprise then that defenses of entity realism in recent decades have been limited.[5]

As mentioned, this dissertation does not propose a solution or reconceptualization of entity realism to rescue it from its myriad apparent problems. There is much to overcome if an overarching entity realism is to be vindicated. Perhaps in future, the progress made here may light the path to doing so. Nonetheless, entity realism as typically conceived raises a major problem for astrophysics right off the bat, one that led Hacking to conclude that scientific realism about astrophysics is simply not possible. I turn to this issue now, as it forms the basis for the scope of this dissertation.

3. Entity Realism and Astronomy

Even if entity realism is right, alarm bells should go off for scientists and philosophers concerned with the universe beyond the Earth's exosphere. After all, astronomers and cosmologists have no direct access to their systems of interest. They cannot visit these systems, cannot move some objects out of the way to get a better look at others, cannot manipulate objects or bring them into the laboratory, and so on. Astronomy is considered an observational science; traditional interventionist experimentation seems impossible. Jared Diamond and James Robinson (2010) put the point starkly: "the cruel reality is that manipulative experiments

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[5] Nonetheless, a handful of intrepid philosophers have sought to develop improved versions of entity realism, including Matthias Egg's (2012, 2014, 2016) causal realism, Markus Eronen's (2015, 2017) robust realism, Bence Nanay's (2019) singularist semirealism, and most recently Mahdi Khalili's (2023) criterion for the reality of property-tokens as a narrower conception of a kind of entity realism.

are impossible in many fields widely admitted to be sciences. That impossibility holds for any science concerned with the past, such as evolutionary biology, paleontology, epidemiology, historical geology, and astronomy; one cannot manipulate the past" (1). Hacking (1989) himself famously ridiculed the possibility of experiments in astronomy: "galactic experimentation is science fiction, while extragalactic experimentation is a bad joke" (p. 559). If manipulative experiments are in fact impossible, then objects in astronomy cannot be exploited or deployed toward other ends in scientific practice, and thus entity realism for astronomy cannot get off the ground.

To Hacking's credit, he follows through with the commitments implied by his view. For him, realism is only possible for terrestrial objects, those able to be brought into the laboratory and deployed by scientists in their various investigations.

> "We believe in the reality of many entities postulated by theory because we can construct devices that use those entities in order to interfere in other aspects of nature, and to investigate the inner constitution of matter (my 1983, chap. 16). People, it has been said, are tool-making animals. When we use entities as tools, as instruments of inquiry, we are entitled to regard them as real. *But we cannot do that with the objects of astrophysics. Astrophysics is almost the only human domain where we have profound, intricate knowledge, and in which we can be no more than what van Fraassen calls constructive empiricists.*" (1989, p. 578, emphasis mine)

Although Hacking's astronomical antirealism is indeed a natural implication of his entity realism, it is wholly unsatisfying for those of us who find the core of entity realism appealing but do not want to relegate sciences like astronomy and cosmology, and their objects of interest, to a special status not on a par with the experimental sciences. Is it really the case that realism about unobservable objects beyond Earth is categorically precluded? Is it really the case that astronomers do not conduct experiments? Moreover, if experiments in astronomy are impossible, then what is there to learn about those sciences from the perspective of the new experimentalism? That is, even if we did discard entity realism, what can attentiveness to the practice of astronomy tell us? Are we resigned to focus on the methods of inference and reasoning in astronomy in a way that attends only to the notion of observation?

Hacking's line in the sand between realism for the terrestrial laboratory and antirealism for the rest of the cosmos received pushback from a handful of philosophers, including Dudley Shapere (1993), Jutta Rockmann (1998), and Michelle Sandell (2010). Shapere and Rockmann both seek to deny Hacking's main claim that we must be antirealists about gravitational lenses – massive celestial bodies such as galaxy clusters that cause a sufficient curvature of spacetime for the path of light around it to be visibly bent. I do not review these arguments here other than to say that neither Rockmann nor Shapere fully investigate the question of experimentation in astronomy. Rockmann focuses on the notion of observation and its role in inferences to realism. Her point is ultimately that manipulability cannot be a necessary condition for entity realism. Shapere also doesn't probe whether or how astronomers might conduct experiments. His overall point is rather that Hacking simply has an improper view of science, one that restricts legitimate scientific inquiry to methods that solely involve interfering with the world in order to understand it. Shapere also holds Hacking's feet to the fire on the latter's ambiguous uses of terms like ‘interfere’, ‘use’, and ‘experiment on’, though again sees this as a general problem for Hacking’s views that is not specific to astrophysics. Sandell offers an incisive criticism of Hacking’s conclusions about astronomy and objects like black holes, stars, and planets. Her paper is unique in that it proposes that even by Hacking’s own lights we should think that astronomers do conduct experiments. However, there is no discussion of how we should think about what counts as an experiment and whether the examples of interest qualify as such. Sandell identifies two examples of plausible experiments in astronomy – the discovery of the cosmic microwave background radiation and the detection of interstellar CH (methylidyne radical) – but does not offer a positive account for why these should qualify as experiments.

Aside from these insights, there has been no virtually targeted effort to investigate whether and how the work of astrophysicists connects to traditional notions of experimentation in the spirit of the New Experimentalists. Furthermore, it is often just taken for granted that, whatever astronomers and astrophysicists are doing, it is not quite what laboratory scientists are doing. Defenders of astronomy and astrophysics have tended to be less concerned with experimentation *per se* and instead more concerned with defending the justification for scientific knowledge obtained in these fields. These efforts have largely sought to show that the methods of astrophysicists and astronomers are justified *despite* their methodological limitations. For example, Carol Cleland’s (2002) excellent work to vindicate astronomy and other historical sciences as respectable scientific enterprises argues *not* that such sciences conduct experiments but rather that we should vindicate their work by properly articulating the type of evidential reasoning they *do* employ. As she says, "Historical researchers investigating particular past events cannot test their hypotheses by performing controlled experiments. But this doesn't mean that they cannot procure empirical evidence for them" (p. 490).[6] I, on the other hand, am more interested in the experimental nature of the methods themselves, and whether we have missed something about *experiment* as opposed to missing something about justifications for knowledge.

4. Dissertation Chapters: Overview

Given the above state of affairs for realism about dark matter and astrophysics, this dissertation begins not with the challenges facing entity realism in general but rather with some core features of scientific practice in astronomy and astrophysics, with a significant focus on investigations of dark matter. The three chapters below reflect an initial effort at investigating the ways in which astronomers and astrophysicists might be making progress by looking more closely on their practices and the commitments that matter to their work. The goal is to see what the various lessons drawn should tell us about the flavor of philosophical views, especially those around scientific realism and experimentation, we might want to pursue in future work.

In Chapter 1, I investigate analogies between scientific inquiry into dark matter and the investigation of atoms and molecular theories of the 19th and early 20th centuries. My view is that dark matter does not present a target of inquiry that is so exceptional we cannot draw

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[6] In a personal conversation in 2022, Cleland reiterated to me her conviction that astronomers do not conduct experiments in the traditional interventionist sense.

direct lessons from work on past unobservable entities. In particular, I want to show that there are important lessons to be drawn from Jean Perrin's Brownian motion experiments and applied to contemporary work on dark matter. Most important of these is the structure of experiments on Brownian motion and the way in which Perrin created an object to stand in for the theoretical atoms themselves. By doing so he was able to intervene on an analog of his target in a way that facilitated an inference to the actual unobservable entity. Similarly in the case of dark matter, experimental access to the unobservable can be obtained via a proper connection to an observable object. This may potentially be done in the form of computer simulations or other methodological strategies.

In Chapter 2, I argue that traditional, interventionist experiments in astrophysics are indeed possible. The standard view relegates astrophysics as an observational science relying on passive, non-experimental methods that limit the field's epistemic status. I argue that genuine astrophysicists can and do conduct experiments on a par with laboratory experiments and use some case studies to show how they are instantiated. My paradigm example is the Eddington expedition during the 1919 solar eclipse to measure the bending of starlight around the Sun as a crucial test of Einstein's theory of General Relativity. I show how the expedition's methodology should be understood as an interventionist experiment. In particular, the expedition was able to use knowledge of stable features that allowed the comparison of only the change in apparent position of these stars due to the light bending around the Sun. I argue that this is not an idiosyncratic part of astrophysics but rather is reflected in a number of ways, especially in their use of gravitational lensing to investigate all sorts of cosmic phenomena. If interventionist experiments in astrophysics are possible, then contra Hacking, the door to a possible entity realism is open for this field.

Finally, in Chapter 3 I argue in favor of dark matter realism on the basis of experimental detection via the Bullet Cluster collision. The few philosophers who have engaged this debate claim that realism about dark matter in cosmology is unwarranted because there has been no empirical confirmation of a dark matter particle. This demand is misguided. I argue that we should take the theoretical concept of dark matter as described in our best cosmological model (ΛCDM) at face value. Since there is no theoretical or nomological requirement that dark matter be a particle, we should better assess the implications of dark matter detection via gravitational lensing. The result is that realism about dark matter is a viable position.

CHAPTER 2: DARK MATTER AND UNOBSERVABILITY

> *Nature reveals the same wide grandeur in the atom and the nebula, and each new aid to knowledge shows her vaster and more diverse, more fruitful and more unexpected, and, above all, unfathomably immense.*
>
> - Jean Perrin, *Atoms* (1913)

Introduction

Dark matter is not the first entity posited by a scientific theory prior to any direct observational evidence. Atoms, phlogiston, Neptune, and Vulcan are just a few examples of entities posited to explain some phenomenon or to solve some otherwise intractable scientific problem. Some of these entities ultimately found permanent places in our ontology (atoms, Neptune) whereas others serve as cautionary tales about theories gone wrong (phlogiston, Vulcan). Unlike the entities just mentioned, dark matter *prima facie* presents a unique problem. One the one hand, nearly all astrophysicists and cosmologists accept that dark matter exists and makes up approximately 24% of the mass-energy content of the universe.[7] The Standard Model of cosmology (SMC), which is not only consistent with most observational data but also extremely good at generating the large-scale structure observed in the universe via simulation, centrally relies on the posit of dark matter. And, despite many ongoing attempts, no existing alternative model has been able to achieve the observed distribution and structure of

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[7] Baryonic matter - ordinary visible matter that makes up stars, gas, and everything we see on Earth - makes up just 4% of everything in the universe. Dark energy accounts for 72%. Although dark energy deserves just as much attention as dark matter, I do not focus on it here for sake of simplicity.

astronomical objects by excluding dark matter.[8] On the other hand, we know almost nothing about dark matter's nature, cannot directly observe it, and have been unable to detect the products of any interactions with any of the candidate dark matter particles. To put it in simple terms: we have a model that is very consistent with the vast majority of observational data but centrally relies on an entity that is impossible to observe directly and may never be possible to detect.

Given some outstanding problems that the SMC has been unable to solve, discrepancies between the model and some of the astronomical observations, and the failure of particle physics to produce evidence of any dark matter particles, some scientists have begun to worry that this state of affairs is indicative of a crisis (Bull et al., 2016). For philosophers, there are related worries. Are cosmologists simply fine-tuning their models and coming up with ad-hoc solutions until they fit with observational data? Even if they are, is such fine-tuning methodologically problematic? How can we be sure that mysterious entities like dark matter exist if we have no direct experimental evidence and if there is no good indication that such evidence will be forthcoming? Along these lines, more skeptical scientists and philosophers claim that detecting dark matter particles is a necessary condition for obtaining sufficient epistemic warrant for their existence. Without confirmed instances of detection, skeptics claim that we are not justified in accepting the posits of the SMC. Talk of crisis is overblown, but these

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[8] Some models like Modified Newtonian Dynamics (MOND) have found some success at certain narrow astronomical scales but fail to achieve consistency with the full spectrum of available observations without incorporating dark matter.

sentiments express something important. Namely, there is more general tendency to emphasize observability or detectability for substantiating the existence of a posited entity.[9] Because of the mysterious nature of dark matter, there may also be a tendency to think that we have stepped into a realm of scientific inquiry that is somehow entirely unique compared to historical cases of unobservable entities posited to solve their own intractable problems.

My contention is that these concerns about observability or detectability are misplaced when it comes to dark matter. To see why, I suggest that we revisit the posit of atoms and the scientific inquiry into their existence in the 19th and early 20th centuries. Sufficient epistemic warrant for atoms was achieved not on the basis of direct observation or detection but thanks to a combination of overdetermining the value of Avogadro's constant N and structural features of Jean Perrin's experiments on Brownian motion. Inquiry into dark matter is relevantly analogous. I believe that epistemic warrant for dark matter via the SMC depends on similar criteria: overdetermination of certain cosmological parameters and the extent to which the simulations cosmologists rely on can be taken to have appropriate epistemic standing. Observability or detectability should be of little concern to substantiating the entities posited by our best theories if they fulfill some other criteria.

The goal of this paper is two-fold. First, I want to show that scientific inquiry into dark matter is indeed analogous to the investigation of atoms and molecular theories of the 19th and early 20th centuries. The point here is that at its core, dark matter does not present a target of

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[9] I clarify this terminology of 'observability' and 'detectability' in the next section.

inquiry that is so exceptional we cannot draw direct lessons from work on past unobservable entities. Second, I want to show that there are at least three important lessons to be drawn from Jean Perrin's Brownian motion experiments and applied to contemporary work on dark matter. First is the importance of over-determining parameters central to theorized properties of the unobservable entities. Just as the convergence of Perrin's calculation of Avogadro's constant *N* with many other independent results is taken to have provided convincing evidence for the existence of atoms, overdetermination of the parameters used in the SMC would provide the best reason for accepting it. Second is the relationship between the structure of experiments and/or simulations used to investigate the entity of interest. Specifically, experimental access to the unobservable can be obtained via a proper connection to an observable object. Third, I want to deny the importance of observability or detectability. Just as it did not require the observation or detection of actual atoms to substantiate their existence, the unobservability and potential undetectability of dark matter should not affect our epistemic warrant for its existence and function. I conclude with some considerations about the epistemic burden on simulations in cosmology, developed in separate work.

1. Setting the Stage – Detecting Dark Matter

The Standard Model of cosmology (SMC) is currently best represented by the Lambda Cold Dark Matter (ΛCDM) model. The relevant aspect for this paper is the 'CDM' portion of the model – cold dark matter is posited to resolve the discrepancy between the total amount of mass observed in the universe and the amount that should be necessary to account for various astrophysical phenomena and the universe’s large-scale structure (discussed in more detail in Section 3). Although the underlying features of the SMC are largely accepted by the scientific community, there are two different kinds of competing alternatives to be distinguished. The first are the various models operating under the core assumptions of the SMC. As Butterfield (2014) notes, although ΛCDM is the current best fit model, the SMC is underdetermined because there are other models that fit well but differ in important ways. Still, it is the cosmological models that are underdetermined, not the theories that underpin them. Despite their differences, these competing models nonetheless all assume General Relativity (GR), make assumptions about homogeneity and isotropy, and posit dark matter (although some of them do *not* posit dark energy).

The second kind of alternative is one that seeks to match the same astronomical observations without the posit of a mysterious entity like dark matter – these do not fall under the auspices of the SMC. Alternatives like Modified Newtonian Dynamics (MOND) do not assume GR and work by modifying the laws of gravity at small scales (Milgrom, 2001; 2014). These modifications are compelling to some because they have been able to achieve a very close match to the observed behavior of galaxies (Famaey & McGaugh, 2012). However, this approach is much more controversial because there is no evidence to suggest that Newtonian dynamics should fail at these scales.[10] Still, because MOND does very well at matching galaxy-

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[10] This is not to suggest that GR is incontrovertibly true. Physicists know that it is unlikely to work at all scales and is likely to be superseded by a theory of quantum gravity (Smeenk, 2013). However, there does not appear to be good evidence to suggest that Newton’s laws won’t work at the scale at which MOND is

level observations, and because ΛCDM struggles at this scale, proponents of alternative gravitational theories suggest that we are more justified in modifying laws of gravity than in positing mysterious entities like dark matter (see Massimi, 2018 for a review of these 'tyranny of scales' challenges in cosmology). Proponents of alternatives like MOND are then unmoved by more and more evidence accrued in favor of ΛCDM at large scales.

Whereas new and improved astronomical observations in the coming years will hopefully be able to break the underdetermination between the various models under the SMC and resolve the first problem, the story is different when it comes to the debate between ΛCDM and MOND. Since MOND fares exceptionally well at the galactic scale, proponents place the burden for vindicating ΛCDM on detecting dark matter particles, not on the successes of models and simulations in matching observations. It is common for MOND proponents to suggest either that (a) vindicating dark matter's existence will require detecting dark matter particles (e.g. Kroupa 2012; McGaugh, 2015; Merritt, 2020) or (b) that the lack of detection so far should cast doubt on the veracity of the models that posit its existence (e.g. Baldi et al., 2014; Bull et al., 2016; Merritt, 2021). The overarching philosophical question raised by these authors is twofold. First, how much epistemic warrant can we possibly have for some (initially)

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supposed to work. The fundamental claim made by MOND is that Newton's law of gravity differs at low accelerations. This offers a possible test for MOND. Although testing MOND on Earth is extremely difficult (if not virtually impossible), experimental methods for overcoming the relevant challenges have been developed by Ignatiev (2007; 2008) and others (e.g. De Lorenci et al. (2009); Das & Patitsas (2013); and Pereira, 2017). Subsequent tests have been conducted using some of these methods. Current results, although not conclusive, do not bode well for MOND. Gundlach et al. (2007), Meyer et al. (2012), and Little & Little (2014) find no deviations from the predictions of Newton's laws down to accelerations as small as 5×10^{-14} m/s^2, well-within the range MOND suggests acceleration values should deviate.

theoretical entity prior to its detection? Second, to what extent can a model's success be undermined by an inability to detect the underlying theoretical entity? Baldi et al. (2014), for example, claim that even though the standard ΛCDM model continues to match almost all observational data with increasing accuracy, the fact that no dark matter particles have yet to be detected suggests that the model's theoretical foundations are "poorly motivated" (p. 75). They suggest that even if a model matches a large number of independent observations with increasing levels of accuracy over time, such progress does not provide any *additional* epistemic warrant in favor of the theoretical entity central to the model's success. Others like McGaugh (2015) claim that in the face of competing models, "convincing laboratory detection of appropriate dark matter particles" (p. 255) is a necessary condition for justifying commitment to ΛCDM. It is these claims that this paper will challenge.

At first glance these positions may not seem so unreasonable. Surely we might want to actually detect an entity before we accept it into our ontology. Particle physicists are not shy about positing new and exotic particles. Take for example the neutralino – a theoretical particle posited by the Minimal Supersymmetric Standard Model (MSSM) that attempts to solve some of the problems long known to exist with the Standard Model (SM) of particle physics (Terning, 2006). No matter how theoretically compelling or convenient the existence of the neutralino might be, scientists are obligated to go through great experimental lengths to actually find it. Detecting such a particle through an experimental apparatus like the Large Hadron Collider (LHC) is likely a necessary condition for accepting that the neutralino exists. The posit of dark matter may then seem surprising because most cosmologists *do* claim that dark matter exists even though it has never been detected. Many of them maintain this view while simultaneously acknowledging that we may never detect dark matter particles. And they do so despite the fact that there are alternative models that plausibly cohere with astronomical observations without positing any dark matter at all. For all the evidence to which adherents to the dominant ΛCDM model appeal, their opponents point to alternative models or unresolved problems that ΛCDM has struggled to solve. For the proponent of MOND, on the other hand, there is good reason for the failure to detect dark matter particles – they don't exist. Thus, if one is disposed to agree with the majority of today's cosmologists in accepting dark matter, one must go beyond detection to provide criteria that is achieved for dark matter but not for the neutralino, or at the very least explain why detection is not a necessary condition.

Before moving on, I must clarify some important terminological distinctions. All of the skeptical claims discussed above rely on some notion of 'detection' or 'observation' as a criterion for justifying our commitment to some initially theoretical entity. For the purposes of this paper, detection and observation are largely interchangeable. I am not making the philosophical distinction between 'observable' and 'unobservable' (e.g. van Fraassen, 1980; 2005), where 'observable' entities are typically taken to be things that can be perceived using unaided human senses and 'unobservable' entities are those that cannot be so perceived (note that this distinction has been problematized). On van Fraassen's view, all particles – including purported dark matter particles – are unobservable. Observability on this definition is independent of detection since scientists have experimentally detected many unobservable entities. However, as Shapere (1982) pointed out, practicing scientists tend not to use the term ‘observable’ in this way. For them, something counts as (directly) observable if “(1) information is received (can be received) by an appropriate receptor; and (2) that information is (can be) transmitted directly, i.e without interference, to the receptor from the entity x (which is the source of the information)” (p. 492). For the scientist, if something is detected by an appropriate experimental apparatus then it is taken to have been observed.[11]

The observable/unobservable distinction may be relevant for debates about scientific realism but does not affect the arguments to be advanced here. Scientists in general take successful detection to provide sufficient evidence to establish the existence of an (philosophically) unobservable entity. In particle physics, neutrons and neutrinos are taken to exist because they have been experimentally detected/observed, whereas neutralinos do not (yet) exist because they are theoretical posits that have not (yet) been similarly detected/observed. Importantly, nothing hinges on the precise use of the term ‘exist’. If one is only willing to go as far as to say that the experimental detection of a neutron or neutrino only achieved some threshold of empirical adequacy, so be it. The point is that both a realist and anti-realist should commit to a neutron or neutrino in some fashion. As far as I am aware, there is no philosophical or scientific debate about whether the neutron or neutrino ‘exists’ in this

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[11] Searches for dark matter particles also involve ‘indirect’ experiments – those that would not fit under Shapere’s definition of being scientifically observable. These are discussed in Section 4. Whether or not these pose special problems for the kind of epistemic warrant we might want for unobservable entities is unclear. Chakravartty (2003), for one, suggests that such distinctions are not epistemically significant.

broad sense. That is, within the domains of particle physics or philosophy of science there are no alternative posits that take the place of the neutron or neutrino either as adequate empirical constructs or as genuine entities in the realist's ontology. All I care about is the kind of epistemic warrant that would justify accepting dark matter and rejecting alternative theories of gravity. Thus, I am interested just in the minimum of detection (or what scientists would accept as an observation) because any debate about the *reality* or *existence* of some entity should at least agree on the entity's indispensability in our best theories and models.

Going back to the question of dark matter's existence, my strategy is to suggest that we need not reinvent the wheel when it comes to assessing the MOND proponent's claim about the necessity of detecting dark matter particles as the proper criterion for establishing sufficient epistemic warrant for its existence. We can instead find good precedent in the history of atomism and what led to the scientific community's commitment to the existence of atoms. I then propose to apply these criteria to the case of dark matter. Whether these criteria are successfully satisfied will ultimately depend on issues related to computer simulations in cosmology. For the purposes of this paper the upshot is that scientists can be justified in claiming that they have sufficient epistemic warrant for the existence of dark matter despite the fact that (a) dark matter particles have never been detected and (b) that it is possible that dark matter particles will never be detected in the future.

2. Atoms

It is generally agreed that acceptance of the existence of atoms was achieved thanks to the experimental work of Jean Perrin on Brownian motion and his independent determination of Avogadro's constant *N* (Nye 1972). *N* specifies the number of molecules in a chemical substance whose mass in grams equal its atomic mass, with a value of approximately 6.02×10^{23}. Perrin's papers in 1908 and 1909, along with his 1913 book *Atoms* did not just report his experimental methods and results, but explicitly argued for the existence of atoms as "objectively real" and the molecular theory as "experimentally established" (2013, p. 554).

This scientific episode is philosophically rich and many have sought to reconstruct the argument Perrin uses to arrive at this conclusion.[12] My goal here is not to engage this literature directly, but rather to articulate certain important assumptions and features of the scientific inquiry itself within the context of previous measurements to determine *N*.[13] The goal is to answer the following two questions: (1) Why was Perrin's determination of *N* so persuasive given the fact that it had been previously calculated via a number of independent methods and

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[12] E.g. Cartwright (1983), Salmon (1984), Mayo (1986), Miller (1987), and Achinstein (2001).

[13] I take this approach for two reasons. First, it is unclear whether existing reconstructions are appropriately sensitive to Perrin's actual arguments. As Coko (2020) suggests, this literature is an instance of what Ernan McMullin pointed out many years ago – that philosophers "often use the historical material to illustrate or offer support for their pre-established conceptions" (p. 13). The second reason is that irrespective of which argument reconstruction is correct, Perrin explicitly appeals to the role of multiple determinations of *N*. Some (e.g. Mayo, 1986) deny that Perrin is making a multiple determination argument. For my purposes, I simply take seriously the idea that multiple determinations of *N* played an important role in Perrin's work.

converged on roughly the right value? (2) Did it matter whether atoms were in-principle directly observable?

Before addressing these questions directly, I first provide some background on the posit of atoms by the kinetic theory of gases and its development prior to Perrin's experiments. I will then discuss the role of overdetermination and the nature of Perrin's experiments to answer (1) and suggest that observability is of no importance in response to (2). The answers to these questions can explain why epistemic warrant for atoms was achieved in light of Perrin's experiments despite a lack of observation or detection.

2.1 Kinetic Theory of Gases

Prior to Perrin's experiments on Brownian motion, the kinetic theory of gases provided the most compelling support for the existence of atoms and molecules.[14] The theory was initially developed in the 17th Century to explain the observed behavior of gases. By the mid-19th Century, the theory was able to explain a large variety of phenomena and predicted novel results that were then empirically confirmed (see Chalmers, 2019). This included the ideal gas law; Avogadro's law that equal volumes of gases at the same temperature and pressure have the same number of molecules; laws of diffusion; and Gay Lussac's law that for a gas at some constant volume the pressure varies directly with its absolute temperature. This latter result

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[14] The kinetic theory of gases already made a distinction between gas molecules and the various atoms that might compose those molecules.

allowed for calculating atomic weights and articulating chemical formulas that matched independent results from organic chemistry. It also predicted the ways in which the behavior of real gases should diverge from the ideal behavior stipulated by the various gas laws, yielding the Van der Waals equation and its empirical confirmation. All of these results relied on the claim that the behavior of gases was due to movement and interaction of their constituent molecules.

It is important to note the extent of the ontological claims made by the kinetic theory. For one, it posited the existence of atoms to explain the behavior of gases at the macroscopic level. It did not make claims about the inner structure of these posited atoms. It also did not assign extensive properties to atoms beyond some basic mechanical properties. These properties were that the motion of the molecules was governed by mechanical laws, that their structure allowed for elastic collisions, and that their size was (obviously) very small, but not small enough that they could avoid regular collisions (Chalmers, 2019). It was also recognized that these properties were not exhaustive of atoms and that atoms were not fundamental particles. Perrin himself does not attribute any properties to atoms beyond those already posited by the kinetic theory. He claims that molecules are in motion and engage in elastic collisions. He also suggests that although we don’t know the shapes of different molecules (they are posited to differ depending on the chemical element they constitute) we can effectively treat them as spherical and analogize their behavior to colliding billiard balls. And he claims that molecules can hold interior electric charges.

Despite the theoretical and empirical successes generated by the kinetic theory, important theoretical problems, competition from rival theories, and philosophical opposition to the positing of unobservable entities prevented a wholesale commitment to the existence of atoms. Kinetic theory faced two major theoretical problems worth noting. First, experimentally determined values of the ratio of the two specific heats of gases deviated from the theory's predictions. This problem could be overcome by constraining the degrees of freedom for molecular motion. However, such a solution would be unable to explain how molecules emit and absorb radiation. Second, the theory seemed to undermine the second law of thermodynamics. According to the second law, and corroborated by all experimental observations, entropy cannot decrease with time. Heat only flows from hot regions to cold regions and separate gases mix together whereas mixed gases do not separate. Kinetic theory cannot explain this since it allows for the time inverse of any process. To account for the observed irreversibility, one can interpret the second law of thermodynamics as only being statistically true such that time irreversible events are just extremely unlikely as opposed to impossible. However, undermining the absoluteness of the second law was extremely controversial and had no independent empirical support.

Solving these outstanding problems turned out to be largely irrelevant to convincing almost all scientists of the existence of atoms. In fact these problems were not, and could not, be solved by Perrin's experiments. For example, the problem of spectra and specific heats is a quantum effect and was not resolved until the development of quantum theory later in the 20th

Century. Despite this, Perrin's independent calculation of Avogadro's constant *N* was taken to provide compelling evidence in favor of atomism. To the extent that overdetermination of *N* does contribute to epistemic warrant for atoms, it is not obvious as to why Perrin's calculation was taken to be so conclusive given that it was just another in a line of many prior instances of determining *N* within appropriate experimental thresholds (Brush, 1968). Something more must be said about why Perrin's work was seen as so conclusive and, by extension, the conditions under which overdetermination is most compelling.

2.2 Overdetermination and Experiment

In the concluding section of his book *Atoms*, Perrin provides a list of known values for Avogadro's constant *N* as determined by a variety of prior independent methods, including work on blackbody radiation, motion of ions in gases, radioactivity, and the Tyndall effect that explained why the sky is blue. It also includes his own experiments on Brownian motion for comparison. He concludes:

> "Our wonder is aroused at the very remarkable agreement found between values derived from the consideration of such widely different phenomena. Seeing that not only is the same magnitude obtained by each method when the conditions under which it is applied are varied as much as possible, but that the numbers thus established also agree among themselves, without discrepancy, for all the methods employed, the real existence of the molecule is given a probability bordering on certainty" (p. 206-207).

Here Perrin is invoking a multiple determination or no-coincidence argument.[15] The idea behind such arguments is that it would be extraordinarily unlikely for many independent investigations using different methodologies to converge on a single value for a parameter in question if the underlying theory's relevant assumptions were false. In the case of atoms, the agreement on the value of *N* across the 13 different procedures listed by Perrin would be a wildly improbable coincidence if molecules did not exist. What makes this sort of overdetermination especially compelling is that the sources of possible error for each method used to quantify the parameter are independent of each other. The possibilities of measurement error in Perrin's Brownian motion experiments do not have analogues in the other methods used to obtain *N*. It is also important to note that there was no alternative to the kinetic theory of gases that predicted the same value for *N*. Had such a rival theory existed, the multiple determination argument would obviously lose its force. However, values for *N* were already well-established by the 1870s using the other independent methods and approaches cited by Perrin. But, if multiple determination arguments are persuasive, why were the existing values for *N* insufficient? Why should Perrin's calculations provide such a convincing reason for accepting the existence of atoms? The answer is twofold: (1) Perrin's method of doing science and (2) the structure and assumptions in Perrin's experiment. I discuss each in turn.

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[15] See Wimsatt (1981), Hacking (1983), Culp (1994), and Stegenga (2009) for some treatments of this approach. Note again that whether or not Perrin's argument is in fact properly understood as one of multiple determination is not too important. Rather, I am interested in this emphasis on multiple determination in the process of substantiating his claims.

For Perrin, Brownian motion presented a unique opportunity for exploring molecular theory because he could apply a method different from the one used to develop the kinetic theory of gases. First identified by Robert Brown in 1828, Brownian motion is the constant random movement of very small particles suspended in a liquid. Experimental work in the late 19th Century had conclusively established that the Brownian particle's motion was completely independent of any external influences. It was not caused by convection current, light from the microscope used in examining the effect, dust particles, or any other element external to the liquid. Eliminating these possibilities elevated the status of Brownian motion as an important problem to be solved because now the contentious atoms of kinetic theory were being offered as a possible cause.

Perrin correctly thought that the movement occurs due to regular collisions between the observed particle and the fluid's constituent molecules. Getting to this conclusion required a different kind of scientific approach than the one used to develop the kinetic theory of gases. The kinetic theory used a *deductive* approach. It posited molecules *a priori* as a plausible entity that could explain the observed behavior of gases and chemical interactions. The subsequent theory could then deductively predict other phenomena that could be empirically confirmed. Its plausibility relied on experimental work on the predicted observations, though it could never be conclusive if a rival theory could provide an alternative explanation. Thermodynamics was just such a rival, with an experimental program that did not require positing unobservable entities or determining the underlying structure or properties of matter (Chalmers, 2019).

Perrin’s approach to Brownian motion is instead one of “logical induction” (Coko, 2020) – his version of a sort of eliminative induction. Instead of positing the unobservable entity, one looks at the observed characteristics of Brownian motion and eliminates all the possibilities that cannot explain it. As mentioned, external causes had already been discarded. Certain internal causes were also eliminated: the effect was shown to be independent of the chemical nature of the particles or the liquid in which it was suspended. The remaining possibility was that the motion is caused by something internal to the liquid agitating the particle. The observed random constant motion also required that matter was discontinuous – that it consisted of entities that moved constantly in all possible directions and were able to engage in elastic collisions. The importance of Brownian motion to scientific inquiry into the existence of atoms is that Brownian motion provides an opportunity to conduct an experiment on a system for which one has identified a single plausible explanation.

Perrin’s subsequent experimental work relied on a crucial assumption about how to treat and interpret the behavior of Brownian particles. Since molecules are not observable, Perrin’s strategy was to extend the known gas laws to liquids of a certain type (homogeneous emulsions), suspend Brownian granules within the emulsion, and treat the granules as if they themselves were large molecules behaving just like invisible gas molecules (Achinstein, 2001; Coko, 2020). The key was to provide justification for the claim that one could treat the Brownian particle as if it were governed by the same mechanisms that kinetic theory attributed to gas molecules. For this Perrin appealed to the equipartition theorem, which states that all molecules of any fluid at the same temperature have the same mean translational kinetic energy. Perrin then calculated the mean kinetic energy of Brownian particles and found them to agree with the values for liquid particles obtained via the kinetic theory. This gave him license to treat the suspended Brownian particles as if they were visible molecules. Having previously derived an equation that related *N* to the number of Brownian particles in the emulsion and their mass, Perrin could thus determine *N.* I highlight Perrin's own statement on this (1916, p. 105, emphasis mine):

> "The objective reality of the molecules therefore becomes hard to deny. At the same time, molecular movement has not been made visible. The Brownian movement is a faithful reflection of it, or, better, *it is a molecular movement in itself*, in the same sense that the infra-red is still light. From the point of view of agitation, there is no distinction between nitrogen molecules and the visible molecules realised in the grains of an emulsion, which have a gramme molecule of the order of 100,000 tons. Thus, as we might have supposed, an emulsion is actually a miniature ponderable atmosphere; or, rather, it is an atmosphere of colossal molecules, which are actually visible."

The license for Perrin's conclusion relies on showing that one is allowed to treat the experimental Brownian particle using the same theory that describes the invisible liquid and gas molecules. In the end, Perrin could determine the value of *N* by measuring the particles he could actually observe as a stand in for the particles he could not observe.

We can now see more clearly the answer to question (1) above. The question asked: Why was Perrin's determination of *N* so persuasive given the fact that it had been previously calculated via a number of independent methods and converged on roughly the right value? First, Perrin's determination of *N* was achieved by pursuing an inductive approach that converged with the determination of *N* used by the deductive approach of the kinetic theory. The deductive approach posited the existence of atoms and then calculated values of *N* based on the theory. The inductive approach eliminated all but one possible cause for Brownian motion and calculated *N* in light of it. Second, Perrin's actual experiment was such that there was a proper relationship between the object of experimentation (the Brownian particle) and the ultimate target of inquiry (molecules in the liquid). Specifically, one could treat the Brownian particle as an analogue of the molecules constituting the liquid.

2.3 The Importance of Observability/Detectability (or lack thereof)

Perrin himself does seem to place some emphasis on the observability of the entity of interest. Before engaging in his experiments on Brownian motion, Perrin made clear that he took the molecules postulated by the atomists and the kinetic theory of gases to be in principle observable. Perrin conceded that "science should not base itself on atomism if that meant simply reducing the visible to the invisible or unknowable" (Brush, 1968, p. 30). For Perrin, treating seriously a hypothesis about unobservable entities like atoms requires that one believe that future technology would allow for their "sensation" in the same way that one might observe a microbe with a microscope. Perrin analogizes this assumption to the germ theory of disease. It is plausible that the development and successful medical application of Pasteur's germ theory could have occurred without ever seeing the germs through a microscope. Thus, it is possible that we can obtain knowledge of germs without first observing them directly. The key is that we posit an entity that we expect to be able to observe in future experiments. It is for this reason that Perrin rejected alternative theories to atomism like Wilhelm Ostwald's 'energetics', which sought to describe all scientific phenomena in terms of laws of energy (Ostwald, 1907).[16] In Perrin's own words: "A time may perhaps come when atoms, directly perceptible at last, will be as easy to observe as are microbes today. The true spirit of the atomists will then be found in those who have inherited the power to divine another universal structure lying hidden behind a vaster experimental reality than ours" (1916, vii).

Perrin's view notwithstanding, *future* observability (in van Fraassen's sense) cannot be a criterion for epistemic warrant. Criteria for accepting the existence of some posited entity must be achieved in light of the evidence available, not in light of plausible future evidence. Electrons, for example, will never be directly perceived by our senses (though they are detected). This does not undermine all of the reasons we have for their existence. In comparing scientific inquiry into atoms to their inquiry into dark matter galaxies, Weisberg et al. (2018) suggest that although Perrin's work provided epistemic warrant for a pre-quantum conception of atoms at the time, our current warrant for their existence comes from our ability to detect them spectroscopically and observe them via scanning electron microscopes. It is certainly true that IBM's use of this microscope to arrange 35 xenon atoms such that they spelled out "IBM" provides incredible direct evidence of atoms.[17] But surely this evidence was not necessary for

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[16] Ostwald himself later accepted the existence of atoms based on Perrin's experimental results.

[17] https://www.nytimes.com/1990/04/05/us/2-researchers-spell-ibm-atom-by-atom.html

accepting their existence. Given that the microscope works by exploiting the known properties of atoms, their existence was never in doubt. Although in principle 'sensibility' is clearly not a necessary criterion for establishing sufficient epistemic warrant for some posited entity, what about detectability? Here it is enough to note that sufficient evidence for the existence of atoms was obtained without detection either. Instead, the important factors are the convergence of independent methods on parameters predicted by the posit of the theoretical entity and the extent to which our experimental approach can give us access to the features of the entity we are trying to understand.

2.3 Lessons Learned

Perrin's experiments on Brownian motion and his persuasive arguments in favor of atomism reveal three key lessons for scientific inquiry into unobservable and undetected entities.

1. *Overdetermination:* multiple, independent quantifications of theoretical parameters central to the unobservable entity are crucial for establishing sufficient epistemic warrant. However, overdetermination may not be sufficient unless there are both deductive and inductive reasons to posit an unobservable entity.
2. *Experimental access:* scientific inquiries typically rely on direct experiments or their analogs (e.g. models and simulations). When the target of inquiry is a theoretical object, scientists may develop a way to investigate the unobservable entity by instead

intervening on its observable analog. They key is to establish the legitimacy of the analogy by showing that the properties and laws governing the target are appropriately reflected in the observable object.

3. *Observability/Detectability*: there is no requirement to demand that an entity will one day be directly observed nor that the entity can be experimentally detected. The burden instead lies on the first two lessons described above.

In Section 3 I will revisit these lessons and show how they apply to the case of dark matter.

3. Dark Matter

My view is that scientific inquiry into unobservable entities looks very similar irrespective of the kind of entity one is interested in. If scientific work on atoms and dark matter is indeed sufficiently similar, then I think it is appropriate to apply the lessons from Perrin to contemporary cosmology. To get to this point, this section describes the nature and current status of scientific inquiry into dark matter and then demonstrates its similarity to the work on atoms.

3.1 Astronomical observation and the evidence for dark matter

Astrophysics faces major methodological challenges (for extensive discussion see Anderl [2016]). It relies primarily on observational data and cannot experimentally manipulate its targets of inquiry. The observational data that is available presents its own challenges. The astronomical objects being observed are extremely far away (from tens of thousands to billions of light years) and extremely large (galaxies may be upwards of 1 million light years in diameter and contain billions of stars). The events we observe now thus occurred in the deep past. They also happen over vast timeframes. A single 'event' like the collision between two galaxies takes place over the course of one million years. One cannot observe any such event in its entirety. Because of this, astrophysicists rely extensively on computer simulations to model the evolution and dynamics of objects in the universe and inform theories of astronomical phenomena (Jacquart, 2020).

As with many other unobserved entities across the sciences, dark matter was originally posited to account for observations that could not be explained by accepted theory. Initially, it was introduced as a way to account for a discrepancy between the observed mass of the Coma galaxy cluster and the mass theoretically necessary to hold it together gravitationally (Zwicky, 1933; 1937). Starting in the 1960s, astronomers began to find systematic discrepancies between the observed rotational velocity of stars in a galaxy and the velocity that theory predicts based on a star's distance from the galaxy's center (e.g. Rubin et al., 1980). For a typical galaxy with mass concentrated in the center, velocity should decrease as one moves further out. However, astronomical observations across many galaxies found that stars at the edges of the galaxy had much higher velocities than would be possible based on the observed mass distribution. The only solution consistent with General Relativity is for there to exist a halo of mass surrounding the galaxy.[18] Since no such halo is directly observed, the matter that must constitute it is "dark" - its nature is such that it cannot be observed at any electromagnetic wavelength.

Contemporary cosmology now has many additional types of evidence to support the existence of dark matter. Since dark matter cannot be directly observed, cosmologists rely on models and simulations to investigate the evolution of galaxies and other structures in the universe and the dynamics of their interactions and collisions. The Lambda Cold Dark Matter model (ΛCDM) is currently accepted as the best model of large-scale structure of the universe. It relies on just six parameters and is largely accepted to be in agreement with the vast majority of observational evidence. The determination of these parameters is a crucial issue for cosmologists and is discussed further in Section 4. The observational data includes sky surveys that create 3D maps of large-scale structures in the universe (e.g. Sloan Digital Sky Survey), measurements of the cosmic microwave background radiation (CMB), and measurements of radiation emissions and gravitational lensing from colliding galaxies (Jacquart, forthcoming). Measurements from the CMB currently provide the most compelling evidence (Scott, 2018). The CMB is a faint electromagnetic radiation that is a remnant of an extremely early stage of the Universe shortly after the Big Bang (~half a million years). Roughly, the CMB is the residual heat left over from the Big Bang. There are fluctuations in the CMB due to acoustic oscillations – a result of interactions between gravitational forces and pressure caused by photons in the

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[18] General Relativity (GR) is one of science's most successful theories. It has passed every test thrown at it so far and has successfully predicted novel phenomena. Whether there is good reason to modify it is outside the scope of this paper. Here it suffices to note that consistency with GR is taken to be extremely important.

plasma of the early universe. These oscillations can be characterized by a power spectrum that relates the size of the fluctuations as a function of angular scale. The peaks of the power spectrum reflect matter density. Recent measurements of the CMB power spectrum obtained by the Planck satellite closely matched predictions made under ΛCDM (Ade et al., 2013). In fact, the only known models that can fit the observed power spectra rely on incorporating dark matter (Scott, 2018).

The above provides compelling evidence for dark matter. However, although the existence of dark matter is accepted by nearly all cosmologists, we know very little about its nature. We know that it does not interact electromagnetically and that it must be relatively slow-moving. Beyond this, many possibilities for dark matter particles are currently viable. Worse, all attempts at detecting a purported dark matter particle have thus far failed. It is increasingly possible that dark matter particles will never be detected because they only interact gravitationally.

3.2 Analogies between inquiry into atoms and dark matter

The convergence between our best model (ΛCDM) and the vast majority of available observational data can be seen as basically analogous with the kinetic theory of gases and Perrin's experiments on Brownian motion. Consider the following key similarities:

- Just as the kinetic theory was able to achieve significant theoretical success in explaining the macroscopic behavior of gases and the results of organic chemistry, ΛCDM has achieved success in explaining the universe's evolution and observed large-scale structure. More importantly, each predicted novel phenomena that would be empirically confirmed and provided explanations for existing phenomena that could not be satisfactorily addressed by alternative theories.

- Both theories (to the extent that we may call ΛCDM a theory) are able to achieve agreement with empirical observation while attributing minimal properties to the unobservable entity they posit. The kinetic theory did not require an extensive understanding of the actual nature of atoms to be able to develop successful predictions about phenomena that relied on atoms. Similarly, ΛCDM has made significant progress though it does not, and cannot, attribute more than a few basic properties to dark matter.
- Perrin's experiments to determine the value of N relied on translating between the unobservable entity of interest and the observable Brownian particle. Said differently, determining value that has to do with atoms was achieved by determining a value for a separate object. Similarly, ΛCDM simulations rely on translating between unobservable dark matter and the observable particles in N-body computer simulations.

While these similarities may seem overly general or even superficial, they reflect the idea that scientific investigations into any unobservable entity will rely on some basic considerations. Namely, how well does the theory continue to match empirical observations?

What are the minimal properties we must attribute to the theoretical entity? Trying to attribute too many properties prior to sufficient development of a theory or model may impose undue constraints on the inquiry's progress. Finally, are there ways to conduct experiments on observable entities that can serve as appropriate analogs for the entities we are positing? If so, what are the criteria for achieving the proper relation?

4. Applying the Lessons to Dark Matter

In Section 2, I articulated the key features of Perrin's experiments on Brownian motion and drew three lessons regarding scientific inquiry into unobservable entities. In Section 3, I described the state of cosmological research into dark matter and suggested that it is appropriately analogous to work on atoms. If the analogy holds and my claims about the general features of scientific into unobservable entities are reasonable, then the same lessons can apply to dark matter research. I discuss each of the lesson with respect to dark matter, highlighting areas in which the two already converge and places where these lessons can inform future work.

1. Overdetermination

The importance of overdetermining the parameters used in the ΛCDM model of cosmology is already acknowledged by both scientists and some philosophers (e.g. Smeenk, 2017; Ade et al., 2013; Peebles et al., 2009). The European Space Agency's Planck Collaboration, for example, was devised precisely to obtain additional and more precise evidence for the model's parameters. This process is still ongoing, as there is still an insufficient diversity of parameter measurements and discrepancies that need to be solved. Nonetheless, most accept that (a) a high level of precision has already been achieved in matching model parameters to observational data, and (b) continued work will obtain increasingly precise convergence on the values for the model's parameters. The evidence available thus far suggests that scientists have achieved a level of overdetermination that should justify epistemic warrant in the posit of dark matter.

Some concerns are yet to be resolved, though it is not quite clear how serious they are. Merritt (2017) argues that the convergence arguments made by cosmologists in support of ΛCDM are not as strong as those made by Perrin. First, Perrin was trying to determine a single parameter – Avogadro's constant *N* – instead of the six parameters needed for ΛCDM. *All* of the experiments cited by Perrin were trying to determine *N*. Whereas for ΛCDM there is "degeneracy" between certain parameters – choosing a value for one parameter constrains the choice for another. One can therefore only determine that a *set* of parameters fits the observational data but cannot confirm any single parameter on its own. Attempts to determine these parameters independent of others often finds values that differ from those obtained when they are dealt with co-dependently. Merritt's claim is that if overdetermination arguments are to be successful, they must find a way to justify the independent parameter values in spite of the degeneracies. However, it is not clear that this degeneracy problem threatens the posit of dark matter itself. Degeneracies exist between different models that seek to accurately reflect the large-scale structure of the universe (Feng et al., 2000). This harkens to the kind of underdetermination highlighted by Butterfield (2014). However, as mentioned, this underdetermination is between *models* developed under the theoretical assumptions of the SCM, not underdetermination of the theory. Competing models, all of which posit some form of dark matter, may suffer from this degeneracy problem. But it is only models which rely on dark matter seem capable of matching the relevant observations and overdetermining the relevant parameters. In any case, it is clear that there is an appropriate emphasis on overdetermination of the parameters and the resolution of degeneracy problems.

2. *Experimental access and structure*

Despite the fact that we don't know much about the nature of dark matter and have not detected any particles, the ΛCDM model and simulations used based on its parameters are really good at generating the large-scale astronomical structure we can observe. In light of the methodological constraints in astrophysics and cosmology and the inability to directly manipulate or experimentally intervene on the system of interest, the epistemic burden is on computer simulations to connect theory to observation.

If there is anything unique about scientific inquiry into dark matter, it is the overwhelming reliance on computer simulations. And, as many have pointed out, the use of computer simulations raises distinct epistemological questions.[19] More importantly, I think that

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[19] See in particular Humphreys (2009).

it is crucial to the status of dark matter research to determine the proper relationship between simulation and experimentation.[20] This is because while experiments like Perrin's work on Brownian motion draws its cache from being able to obtain epistemic access to the actual phenomenon of interest, cosmological simulations are fraught with concerns about underdetermination, circularity, fine-tuning of parameter values, and sufficient robustness. By determining whether or not the kinds of simulations used in cosmology can be on a par with traditional direct experimentation, progress can be made on the epistemic fidelity of scientific inquiry that relies so predominantly on simulation.[21] If there is something that might be learned from Perrin's work on atoms in the broader context of the kinetic theory of gases, it is the power of experiments based on the inductive method.

3. *Observability/Detectability*

Although I claim that cosmologists need not require the detection of dark matter particles to achieve sufficient epistemic warrant for their existence, it is worth briefly canvassing detection experiments up to this point because of the effort dedicated thus far. It may be that skepticism about dark matter persists to some extent because of the sheer intellectual and financial effort committed to making a discovery (Jacquart, forthcoming). Lopez-Corredoira

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[20] Jacquart (2020) is also interested in determining the proper status of computer simulations in astrophysics. However, she is interested in "how the scientists actually use these tools" and not "how these computer simulations do or do not meet the epistemic standards philosophers have endorsed" (p. 5-6).

[21] An attempt to elucidate the proper relationship is the focus of a subsequent chapter.

(2014) suggests that commitment to ΛCDM can be explained from a sociological perspective and not by assessing philosophical issues around theory choice.

We know that dark matter particles do not interact electromagnetically and thus cannot be observed or detected by telescopes. Instead, there are three other possible methods of detection: direct detection, indirect detection, and production experiments.[22] Direct detection experiments look for interactions between dark matter particles and standard baryonic matter as the former pass through the Earth. This first requires theoretically specifying the possible interactions between a purported dark matter particle and known particles in the Standard Model of particle physics and predicting the recoil energy generated in a collision. This energy can then be detected and matched to predicted values. Bertone et. al. (2005) report more than 20 direct dark matter detection experiments worldwide. Even as of this writing, none of these have obtained a verified positive result.

Indirect experiments seek to observe theorized radiation produced by dark matter annihilations. This involves choosing regions in space with purported high densities of dark matter, called *amplifiers*, and looking for predicted radiation that results from particle interactions within these areas. Such radiation includes gamma rays, X-rays, charged cosmic rays, micro-waves, radio waves, and neutrinos, all of which can be detected using Earth-based instruments (Leane, 2020). The main difficulty here is to distinguish any observed radiation that

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[22] 'Direct' and 'indirect' are scientific and not philosophical terms. 'Direct' does not mean that a dark matter particle is directly observed, but rather that a result of an interaction with a dark matter particle is detected.

may be theoretically consistent with dark matter particle annihilation from other possible sources. Similar to direct detection experiments, no confirmed results have yet been obtained from indirect experiments.

Production experiments use particle accelerators like the Large Hadron Collider (LHC) to collide protons in the hopes of producing a dark matter particle. These experiments cannot detect a dark matter particle. Instead, they rely on finding ways in which there might arise discrepancies between collision data and predicted calculations of properties like momentum and spin. By controlling the environment of the collisions, one can look for differences between the total momentum measured for colliding particles and the value predicted by calculation. Missing momentum may suggest the presence of a dark matter particle. No accelerator production attempts have yet to yield data suggesting the presence of dark matter.

Given that there is very little known about the nature of dark matter, there is no shortage of candidate particles. Bertone et al. (2005) examine 10 prominent possibilities in some detail and list 9 others that have been suggested beyond these. Worse than the sheer number of prospects is that there is no reason yet to think that dark matter must be composed of a single kind of particle. Successfully detecting one candidate does not foreclose the possibility of others. Proposals and searches proliferate as long as there is a plausible candidate, search space, or experimental technique that has not been sufficiently probed or exploited. Some have more theoretical appeal than others, but given the lack of any discoveries, it is not clear how to assess all of the available options.

Although scientists tend to strike an optimistic tone, there is frustration with the lack of detection via any of the above approaches. Here one may be reminded of the search for the planet Vulcan. The astronomer Urbain Le Verrier posited its existence to explain perturbations in Mercury's perihelion. Despite successfully hypothesizing the existence of Neptune to explain the anomalous perihelion of Uranus, the same theoretical approach did not work for Vulcan. After 60 years of failed attempts at observation, it turned out that the eventual explanation for the phenomenon required the development of an entirely new theory – General Relativity (Lahav & Massimi, 2014).

Unlike Vulcan, however, one of my central points has been to say that failing to detect dark matter does not provide good inference to the claim that physicists' best theory requires reconsideration or that the existence of the entity itself is on shaky epistemic footing. For one, the possible nature of dark matter particles is so underdetermined that new proposals and experimental techniques are regularly developed. We may yet detect a dark matter particle in upcoming experiments. Second, it may simply be the case that dark matter particles are just in-principle undetectable because they interact solely via gravity. If these are legitimate possibilities, then we must have other criteria for achieving sufficient epistemic warrant. Third, and most importantly, the case of atoms and the kinetic theory shows that we already have precedent for properly accepting some theoretical posit without first achieving any detection. Similarly, the search for dark matter particles goes beyond what is necessary to achieve sufficient epistemic warrant for dark matter. The importance of particle detection has sometimes been conflated with the importance of evidence provided by our best cosmological models and increasingly better observational evidence. We must take care to distinguish the two when deciding what precisely a lack of particle detection might mean for the future of dark matter research.

5. Conclusion

The goal of this chapter was to articulate some important similarities between any scientific inquiry into unobservable entities and to draw a few lessons that should inform how we approach astrophysical and cosmological research on dark matter. Most importantly, I have tried to provide good reason to reject observation or detection as a necessary condition for establishing sufficient epistemic warrant for dark matter. Toward this end, I tried to show that scientific inquiry into dark matter is sufficiently analogous to the investigation of atoms and molecular theory of the 19th and early 20th centuries. The central theories in the respective cases were able to consistently match empirical observations, make successful novel predictions, and explain phenomena that other theories could not. They were also able to do this while attributing minimal properties to the theoretical entity they posited. The overarching point is not that atoms and dark matter are identical kinds of targets, but rather that features of scientific inquiry into an unobservable entity are likely to be shared and lessons from one can be applied to the other. The indispensability of computer simulation to cosmological research does distinguish this scientific program from most others. Nonetheless, dark matter as a theoretical entity is not exceptional. Second, I articulated three key lessons for dark matter research, drawn from Jean Perrin's experiments on Brownian motion. These lessons include the importance and utility of overdetermining parameters central to the theorized entities; the importance to cosmology of articulating the proper relationship between simulation and experiment; and the limited importance of observability or detectability of the entity in question. Each of these considerations raises important philosophical questions that require much more attention.

CHAPTER 3: EXPERIMENTS IN ASTROPHYSICS

Introduction

It is standard to claim that astrophysicists do not conduct traditional experiments. The targets of astrophysical inquiry – stars, galaxies, galaxy clusters, nebula, etc. – cannot be brought into the laboratory nor can scientists probe them directly via controlled interventions. Instead, astrophysicists seem relegated to observational studies of these objects. Whereas observations are typically seen as passive activities, experiments require directly manipulating or intervening on systems of interest. This presents a prima facie challenge for astrophysics because experiments have a special and privileged status in science. Traditional experiments are often seen as epistemically superior to other knowledge seeking methods. If active intervention via material experiment is important for obtaining knowledge about a system, then sciences like astrophysics may have certain epistemic limitations.

In this paper I deny the above claims. I argue that genuine experiments on a par with laboratory experiments are in fact possible in astrophysics and use some case studies to show how they are instantiated. Specifically, I use Woodward's (2003) non-anthropocentric definition of what counts as an experimental intervention to show how astrophysicists can conduct intervention-based experiments. To do so, I show how astrophysicists can achieve the kind of 'control' necessary to count as an experiment.

The key idea is that astrophysicists systematically capture and archive ongoing snapshots of different parts of the Universe to compare the features as they change through time. They can thus determine those features that have a certain kind of stability and those that are undergoing regularly observable change. Using this information, they can use stable features to create a contrast set of observations that accounts for variables to be held constant (obtaining the necessary 'control') while measuring just the single aspect that has changed. My paradigm example is the Eddington expedition during the 1919 solar eclipse to measure the bending of starlight around the Sun as a crucial test of Einstein's theory of General Relativity. I show how the expedition was able to take photographs of the Hyades star cluster both with the Sun present and without, and how knowledge of stable features allowed the comparison of only the change in apparent position of these stars due to the light bending around the Sun. I claim that this counts as a genuine interventionist experiment. Furthermore, this is not an idiosyncratic part of astrophysics but rather is reflected in a number of ways throughout the science, especially in its use of gravitational lensing to investigate all sorts of cosmic phenomena.

1. Experimentation in Astrophysics

It is standard to claim that astrophysicists do not conduct traditional experiments (Boyd, 2023). Melissa Jacquart (2020) goes further and claims that, "astrophysicists cannot perform experiments on stars and galaxies *in any way*" (1210, emphasis mine). Sybille Anderl (2016) agrees that it is not possible to perform traditional experiments in astrophysics that require "directly interacting, manipulating, or constraining" their target systems (Anderl, 2016, 653).[23] Not to put too fine a point on it, Ian Hacking (1989) famously quipped that, "galactic experimentation is science fiction, while extragalactic experimentation is a bad joke" (p. 559). In this paper I will deny these claims. It will turn out, if I am right, that truth is stranger than such fiction.

The intuitive reason for these claims is due to the types of objects and processes investigated by astrophysics and the field's related status as an observational science with respect to these targets. The target systems and objects of interest to astrophysicists are so far spatially and temporally removed from investigating scientists. Astrophysicists are interested in objects like stars and galaxies, their constitution, how they work, how they evolve, and how they give rise to other observable phenomena. But, the claims goes, stars and galaxies and their related phenomena cannot be brought into the laboratory nor can scientists probe them directly via controlled interventions like in the traditional laboratory arrangement. Instead, astrophysicists are largely relegated to observational studies of these objects. Whereas observations are typically seen as passive activities, experiments require directly manipulating or intervening on systems of interest.[24] As Carnap (1966) suggested, "we make

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[23] Following Anderl (2016), I will use the terms *astronomy* and *astrophysics* interchangeably. Jacquart (2020) distinguishes *astronomy* as an observational science and *astrophysics* as applying laws of physics and other analytical tools to interpret and model these observations, though I don't believe much hinges on this here.

[24] This distinction between observation and experiment has more recently been problematized (e.g. Morgan 2013; Bromham 2016; O'Malley, 2016; Malik, 2017; Perovic, 2021). I do not pursue this debate here. Even if I am right that astrophysicists conduct experiments, it is not because of any failures in this distinction.

experiments…we *do* something that will produce better observational results than those we find by merely looking at nature" (40, emphasis in original).

This presents a *prima facie* challenge for astrophysics and astronomy because experiments have a special and privileged status in science (Currie & Levy, 2018; Boyd, 2023; Desjardins, Oswick & Fox, 2023). Traditional experiments are often seen as epistemically superior to other knowledge seeking methods in science and, "commonly held up as the paradigm of successful (a.k.a. good) science" (Cleland, 2002, 474). If active intervention via material experiment is important for obtaining knowledge about a system, then sciences that are paradigmatically assumed to be investigating objects and processes without the ability to stage real experiments may have certain epistemic limitations.

The extent to which this is problematic depends on how one evaluates the other methodological resources available to astrophysicists. Some of these same philosophers who deny the possibility of experiments in astrophysics nonetheless hold that the field has other, epistemically robust resources to obtain knowledge. For example, Jacquart (2020) and Morrison (2015) both argue that computer simulations provide sufficient replacement for the lack of traditional experiments. Cleland (2002; 2013) argues that astrophysicists do well by relying on different modes of evidential reasoning.

Other philosophers argue that astrophysicists do conduct experiments *of some sort*, just not the kinds typically thought to be on a par with experiments that require interventions. For example, Anderl (2016) considers the possibility that astrophysicists conduct natural experiments or quasi-experiments. Desjardins, Oswick & Fox (2023) agree that, "Much of astrophysics fits well with a conception of 'natural experiment,' where one can observe a large ensemble of appropriately similar systems and exercise experimental control by treating or selecting systems with certain initial or environmental conditions" (p. 142). Michelle Sandell (2010) argues that astronomers might be seen as conducting experiments in virtue of understanding the causal forces that are involved in a given phenomenon. Although she does not provide an explicit account, she gestures toward the idea that astrophysicists utilize these causal powers in their investigations and, "build devices that work with those causal forces to produce stable effects" (256). In all of these cases, the epistemic power of experiments is still limited, often by the respective authors' own admission, compared to the robust forms of laboratory investigations.

In a separate vein, Nora Boyd (2023) argues that astrophysicists do conduct terrestrial laboratory experiments whose data and results allow for inferences about the systems of interest beyond the Earth. Insofar as these terrestrial experiments are laboratory experiments and a part of the normal scientific practice of astrophysics, then astrophysicists conduct experiments. However, these are not laboratory experiments conducted *on* the systems themselves, and so are limited to some extent by the connection between what is possible to investigate in a terrestrial laboratory and the ability to infer about the actual target systems.

There is one view in the literature on experiment in astrophysics that does explicitly argue that traditional intervention-based experiments are in fact possible. Leconte-Chevillard (2021) argues that astrophysicists do conduct traditional experiments by appealing to Woodward's (2003) non-anthropocentric definition of what counts as an intervention. However, his account fails to successfully explain how his examples of astrophysical experiments actually meet Woodward's criteria. Furthermore, he does not make clear what counts as an experiment as opposed to what justifies the claim that an entity's causal nexus can be deployed in investigating some other system. I will focus on this account and its problems in some detail in Section 4 below before offering my own view. First, however, I want to review the notion of experiment and set a framework for thinking about scientific experimentation.

2. What is an Experiment?

The philosophical literature on scientific experiments is fairly extensive.[25] There are many different kinds of experiments (Steinle, 2003), but here I will focus specifically on those used to confirm theoretical hypotheses. In these cases, experiments are generally seen as controlled manipulations of natural phenomena to test whether some hypothesis is true (Currie & Levy, 2018). The contemporary literature tends to converge on the necessary condition that

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[25] E.g. Hacking (1983), Morrison (1998), Steinle (2003), Radder (2009), and Franklin (2010) to highlight just a few overarching works.

conducting such experiments thus requires that one be able to *intervene* on it (e.g. Parker, 2009; Radder, 2009; Beisbart, 2018).[26] What counts as an intervention needs clarification. Parker (2009) claims that, "an intervention is, roughly, an action intended to put a system into a particular state, and that does put the system into a particular state, though perhaps not the one intended" (487). But what is necessary for *putting* a system into a particular state is not spelled out. Parker presumably is thinking that a scientist conducts an action to try to achieve a particular state. Radder (2009) states the intervention must be such that there is, "a measure of control of the experimental system and its environment" (3). These notions of control and isolation persist in the literature, and I focus on them below. As we will see, however, there is an alternative, non-anthropocentric notion of intervention that does not require the kind of artificial, i.e. human, intervention (Woodward, 2003). I will turn to this in Section 4.

Currie & Levy (2018) provide the most precise recent account of experimentation that captures the conditions highlighted above and I will rely on their conception here. They specifically focus on hypothesis-driven experiments and their role in confirmation; i.e. those, "aiming to test theoretical hypotheses against the world" (p. 1067). On their account, there are two key features of bona-fide experiments: *control* and *specimen*. The concept of control is supposed to capture the testing of just the features thought to be responsible for the scope of the hypothesis. For example, suppose one seeks to determine whether female scorpion flies select

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[26] Following Beisbart (2018), I treat similar words like 'manipulate' or 'interfere' as synonymous and will use them interchangeably.

mates based on their pheromone secretion or forewing asymmetry.[27] In order to answer this question, one must be able to test solely the effect of pheromones on mate selection and then separately test solely the effect of forewing asymmetry on mate selection. One can then compare the effects of each possible cause separately. This requires constructing an experimental setup where such tests are possible. In this case, experimenters physically manipulated male scorpion flies' forewing asymmetry while covering the pheromone dispersal gland with glue to conduct the first test. In the second test, they kept forewing asymmetry constant by physically manipulating the wings while allowing pheromone levels to vary.

Currie & Levy describe this sort of experimental control via three features. First, the object of study must be *isolated*. According to them, this means that the object is 'severed' from its causal connections to the environment so that the properties central to the experimenter's aim are undisturbed. In the case of the scorpion fly, males and females are brought out of their natural environment and into the laboratory so that they can be investigated separately from the "'raw' empirical world". The laboratory thus allows for the properties of forewing asymmetry and pheromone secretion to be investigated without having them be potentially disturbed by unknown variables in the natural environment.

The second feature of control according to Currie & Levy is that the object of study must be *manipulated*. This involves "causally interacting with the relevant properties of the object, while holding other factors fixed" (p. 1070). Experimenters held the male flies' forewing

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[27] This example is taken from Woodward (2003, p. 98-99) in his discussion of experiments.

asymmetry fixed across all individuals while varying pheromone levels and allowing for females to choose among the available range. They then held pheromone levels fixed while allowing females to choose among a range of forewing asymmetries. Third, experiments must be *repeatable*. Any lab sufficiently expert and equipped to investigate mate selection among scorpion flies should be able to obtain quality data that must be taken into consideration when seeking to evaluate the hypothesis.

The notion of control is indeed important in experimental science and will be a central focus in the rest of this paper. If we are interested in determining whether some variable X is a cause of Y, we must be able to account for other potentially concurrent influences on Y in the phenomena of interest. However, although the notion of manipulation is central to experimental control, there are problems with the demand for *isolation* as another necessary feature. First, isolation can be detrimental to certain types of scientific investigations (Desjardins, Oswick & Fox, 2023). For example, songbirds severed from their natural environments will behave differently in terms of their song preferences than conspecifics investigated in their natural environments (West & King, 2008). Similarly, human agent behavior will vary if it is examined in a controlled laboratory setting as opposed to typical social environments (Reis & Gosling, 2010). These are issues associated with what is known as *ecological validity*: "whether an effect has been demonstrated to occur under conditions that are typical for the population at large" (Brewer & Crano, 2000, p. 21). Sometimes the artificial nature of the laboratory environment prevents processes that would be found in nature to appropriately manifest themselves. Many areas of scientific research may have to contend with these issues. That isolating a target object would get the wrong experimental result in cases throughout various sciences suggests that isolation should not be a necessary criterion as part of experimental control.

Second, to the extent that one wants to ensure that the target properties are not acted upon by confounding factors, it is not clear why laboratory isolation is always necessary to achieve this nor why we can be sure that it does in fact achieve this. There are some properties that we confidently assume to be independent of relevant confounders even if we cannot bring the target object or system into the laboratory. In his discussion of experiments, Carnap (1966) notes that experiments seek to "determine the relevant factors involved in the phenomenon we wish to investigate" (p. 42). This means that some factors contributing to a phenomenon must be "left aside as irrelevant". The canonical example is the disregarding of friction in experiments in physical mechanics. We know that friction contributes to an object's kinematics but believe that its influence is too small to justify a more complicated experimental design. More importantly, bringing an experiment into the laboratory does not get rid of friction. In many cases, the experimentalist merely ignores the friction that continues to exert an effect on the experimental apparatus. Relatedly, suppose we are interested in testing whether a particular genetically modified crop strain will produce more yield than a conventional variety. If we plant both varieties side by side in a field and then compare the resulting yield, it is reasonable to think that we have run an appropriately controlled experiment. If the field as a whole is relatively homogenous in its nutrient composition, receives the same amount of sunlight and irrigation, and is subject to the same sets of environmental threats, it is reasonable to conclude that confounders have been appropriately dealt with. It is not immediately clear why one should run this experiment in a controlled greenhouse laboratory instead.[28] The ultimate point here is that isolation should not be a necessary condition of achieving experimental control.

If so, we can focus on what is necessary to achieve the 'manipulation' condition. Manipulation is typically construed as requiring human intervention – that one must have direct causal contact with the object or system of interest. Margaret Morrison (2015), for example, claims that precisely what makes astrophysicists rely on computer simulations is their inability to conduct "materially based experiments" (p. 214) that allow for such direct contact. Radder (2012) also explicitly argues for an anthropocentric account of manipulation. He endorses Von Wright's (1971) claim that a necessary condition for experiments is that an experimental system must be 'closed' to causal influences from outside of it. To obtain such a system, Radder requires that scientists must actively intervene to produce it – what he calls 'artificial intervention" (60) to contrast it from natural processes occurring outside the experimental setup. This requires human involvement to achieve a kind of isolation of the experimental system from confounding external influences and to control the evolution of the

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[28] In both cases, it may turn out that either the supposedly irrelevant factor or some unexpected factor does in fact confound the experiment. For example, perhaps researchers notice that the crop's most common pest seems to prefer one variety over the other. Or perhaps it seems like friction plays more of a confounding role than previously thought. In these cases, a new experiment must be designed to take this into account.

system throughout the experimental process. Human intervention is indeed a very good way to achieve the criteria for controlled experiments. But it is not clear why human intervention is *necessary* for this achievement. If I can provide a compelling view to show how the relevant experimental control can be achieved without traditional human intervention, then this will still achieve the demands of scientific experimentation.[29]

3. Experimentation in the Cosmic Laboratory

As mentioned above, Leconte-Chevillard (2021) offers an initial account of how astrophysicists might conduct experiments on objects beyond the Earth. To do so, he uses Woodward's (2003) non-anthropocentric definition of intervention. Although I am sympathetic to the spirit of his account, I believe it falls short of providing adequate justification for why his proposed cases of astrophysical experiments meet Woodward's definition and why they should count as proper interventions.

Woodward's (2003) definition of intervention IN is as follows (p. 91):

> "(IN) An intervention I on X with respect to Y (for the purposes of determining whether X causes Y) is an exogenous causal process that completely determines the values of X in

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[29] Here one might think that 'natural experiments' provide a plausible way to construe some of the activities of astrophysicists as experiments. The basic idea of a natural experiment is one where a discerning scientist identifies a system that has arranged itself in a way that mimics the features of a genuine intervention. According to Woodward (2003) a natural experiment is: "the occurrence of processes in nature that have the characteristics of an intervention but do not involve human action or at least are not brought about by deliberate human design" (94). Despite the resemblance to actual interventions, natural experiments are not seen as genuine experiments (Anderl, 2016; Beisbart, 2018; Currie & Levy, 2018). Even if it turns out that astrophysicists do conduct natural experiments in a certain sense, it still does not capture the kind of interventionist experiment I argue for here.

> such a way that if any change occurs in the value of *Y* it occurs only in virtue of *Y*'s relationship to *X* and not in any other way. This means, among other things, that *I* is not correlated with any other variable that also causes *Y* and does not lie on the causal route (if such a route exists) from *I* to *X* to *Y* and that *I* does not cause *Y* via a route that does not go through *X*."

The basic idea behind this definition is that we want to determine whether some feature X causes some effect Y by testing solely the proposed causal connection between X and Y. For Woodward, this definition of intervention characterizes an "appropriately designed experimental manipulation" or "ideal manipulation" to determine whether X causes Y (91). Woodward imagines a researcher who observes a correlation between two variables X and Y, rules out the possibility that Y causes X and also the possibility that the correlation is coincidental, but is unsure as to whether X truly causes Y or whether the observed correlation is instead due to some *other* cause or set of causes Z.[30] To determine whether X in fact causes Y, one must intervene on the system by isolating the proposed causal connection from X to Y from other possible causes Z. One can then see whether a change in X results in a change in Y. To put this in the language of hypothesis testing, we can say that we are testing the hypothesis that X causes Y.

On Woodward's definition, an intervention need not be conducted by a human being since all that is necessary is that some external cause produces a system that isolates a possible

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[30] Woodward notes that his notion of cause is "partial" rather than "total", where what is needed to say that X causes Y is just that "changes in the value of X will result in changes in the value of some other variable Y" and not that Y is caused solely thanks to X and is not affected by any other factors (91-92). That is, an intervention is intended to establish that X is *a* cause of Y and not that X is the *only* cause of Y.

causal relationship between two variables of interest. In traditional laboratory cases this requirement is fulfilled by the actions of the scientist themselves. In non-laboratory conditions, one can plausibly seek to identify systems where it just so happens that the necessary exogenous process has occurred independent of any human action.[31]

It is straightforward to see why a traditional laboratory experiment fulfills IN. Recall the example of scorpion flies from above. Researchers noticed that females prefer males with high levels of pheromone secretion R and low levels of wing asymmetry W. But which of these variables R or W is what causally influences the mate selection? Since R and W are correlated, the answer cannot be obtained solely from observations of mating behavior. To determine which of R or W are causally influential, researchers intervene in a way that fulfills IN. They arrange the system such that only R can influence mate selection F without the effects of W and, in a separate test, such that only W can influence mate selection F without the effects of R.

In traditional laboratory experiments like this, possible causal links of interest are typically isolated by physically severing other causal factors or by keeping correlative variables constant. When researchers looked to test only the effect of forewing asymmetry W, they had to physically block the flies' ability to release pheromones using glue. If pressed on how they were

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[31] Woodward suggests that this is an instance of 'natural experiment', which he calls a "neglected category" of scientific work, though he does not pursue it as a specific topic of further consideration. I discussed natural experiments above and will not get into a deeper discussion about exactly how to define or disambiguate the potentially different kinds of natural experiments across scientific practices. For my purposes moving forward, we can simply distinguish those cases where the causal process is instantiated by a human agent to create a particular experimental arrangement and those cases where the causal process is exogenous.

sure that this particular intervention isolated the possible causal link between W and mate selection F, researchers would point to the fact that pheromones R were prevented from entering into the experimental process. Similar justification is given in the case of keeping W constant while allowing R to vary. The intervention I on R is an ideal manipulation where the connection between W and R is broken. Thus, if F changes when R is manipulated, it can only be because R causally influences F and not due to W.

The general lesson here is that In order to claim that an intervention fulfills the definition of IN, one must be able to *justify* how the arrangement ensures the stated relationship between X and Y, specifically that the values of one are affected by the value of the other and *not in any other way*. In the scorpion fly case, one must defend the claim the intervention *I* on forewing asymmetry [*X]* with respect to mate selection [*Y*] is such that if any change occurs in mate selection [Y] it occurs only in virtue of the relationship between mate selection [*Y*] and forewing asymmetry [*X]* and *not in any other way*. This emphasis is crucial. It reflects the kind of control any experimenter must seek to achieve. It does not mean that the experimenter is sure, beyond any doubt, that all confounding causal influences have been accounted for. In this sense, even the paradigm laboratory experiment faces similar challenges to the astrophysicist. Rather, one must provide justification for why one has sufficiently good reason to think that the most likely confounders have been considered.

Lectone-Chevillard (2021) readily admits that it is difficult to perform interventions in astrophysics that meet Woodward's definition precisely, "because it is difficult to be sure that no undetected change of any uncontrolled variable Z” (268). His attempt at avoiding this challenge is lacking, however, because he does not provide any robust justification for why any of his proposed examples of astrophysical interventions achieve Woodward’s demands. I will not go in depth into each of Leconte-Chevillard’s examples, but want to provide a general diagnosis of why they lack the appropriate justification to meet the criteria of intervention and experiment. I will then offer my own central example of what I take to be a paradigmatic astronomical experiment in the next section and then provide a few additional, more concise examples.

Leconte-Chevillard’s examples of astrophysical experiments all revolve around the use of gravitational lenses to investigate other phenomena, including: the measurement of the Hubble constant, the testing of competing gravitational models, and the detection of exoplanets. Gravitational lenses can be any large amount of matter (e.g. clusters of galaxies) that create a gravitational field that distorts the light from distant objects that are behind it but in the same line of sight. By analyzing the systematic distortion of light, scientists have obtained incredible insights into understanding fundamental aspects of the structure and evolution of the Universe and its constituents. The use of gravitational lensing is not idiosyncratic. It is one of the most powerful investigational tools in contemporary astronomy (Ellis, 2010). It is thus a good candidate for thinking about experimental interventions in the field.

I suggest that the shortcomings of Leconte-Chevillard’s accounts are twofold. First, he does not explain what the intended intervention is supposed to be testing. Second, and partially because of the first issue, he does not offer justification for how a scientist tries to ensure that the causal link between two variables of interest has been isolated. Again, by 'isolated' I do not mean in the sense of Currie & Levy (2018), who define isolation as a severing of an object or system of interest from its natural environment. Instead, I simply mean it in the sense of blocking off possible other causes or correlated variables from the relationship of interest. I will focus on one particular example, which I think generalizes to the other cases. Although the details are technical, I have simplified them to show these main issues at play.

One of Leconte-Chevillard's examples of experimental intervention is an analysis of a collision between galaxy clusters. Galaxy clusters are groups of hundreds or thousands of galaxies that can pass by each other that result in interesting effects. In this case, scientists were interested in mapping the purported dark matter within these clusters following their collision. To do so, astronomers rely on the phenomenon of weak gravitational lensing, where the principal signal is a small distortion in the shape of a background galaxy because of the way that light is distorted as it passes sufficiently close to other large masses on its path to the Earth. It is well known that there is a relationship between the variable κ (how much the image of the galaxy has been distorted by the lens) and the variable Σ (the surface density of the lens). This relationship is true for any weakly lensed object and is applied to investigate particular instances of weak lensing. It is not particular to cases of galaxy cluster collisions.

In describing the work of Clowe et al (2006) to detect dark matter by investigating the effects of a collision between galaxy clusters, Leconte-Chevillard claims that the instance fits Woodward's definition of IN because:

> "This experimental intervention can be described as follows: an exogenous causal process (the collision of the two galaxies) determines the value of the variable κ (the gravitational shear) in such a way that any change in the variable Σ (the surface density of the cluster) occurs only in virtue of κ relation to Σ" (269).

The relationship between κ and Σ identified here is trivially true. The experiment is not seeking to confirm this relationship, but is rather seeking to apply this known relationship to a test of a different hypothesis about the mass composition of the colliding galaxy clusters. In this experiment, scientists were able to use analysis of weak lensing (via the relationship between gravitational shear and surface density) to map the mass distribution of the colliding galaxy clusters. Scientists were looking to see whether the luminous mass after the collision aligned with the total mass of the cluster system as determined via lensing. Given the goals and specific hypothesis of the experiment, the relevant causal factors here are not the gravitational shear of the galaxy clusters and the surface density of the lens. As just noted, this relationship (K to sigma) is true for any mass that is weakly lensed. The relevant causal factor is instead the location of the mass doing the lensing. The problem is that since Leconte-Chevillard does not specify what hypothesis is being tested, he misses identifying the relevant variables.

Since the relationship between κ and Σ is already known, one can use the phenomenon of weak lensing to reconstruct the masses of any desired source. That is, there is nothing special about the case of galaxy cluster collisions from the perspective of the above equation that relates these variables. Leconte-Chevillard's claim that it is specifically the collision of two galaxies that determines the variable κ in a way that only depends on Σ is not quite right. What might make the case of galaxy cluster collisions count as an experiment is that there is a *comparison* between cases where the κ and Σ relationship is obtained on a regular galaxy cluster and cases where the same galaxy clusters have undergone a collision. Since we cannot ensure that we have accounted for all confounding factors in the single target instance of the colliding cluster of galaxies, we must compare our desired feature of the collisions with a stable contrast that does not include the collision. Only in this way can the collision serve as an exogenous causal process that differentiates between two otherwise identical states of affairs. First we trace the mass of a galaxy cluster as a solitary entity and then also once it has undergone a collision with a different cluster. In this way, we have the same object except for one difference and we confirm that the κ and Σ relationship obtains differential measurements in both cases.

4. The Structure of Experiments in Astrophysics

I will take on board Woodward's notion of intervention. Recall that the relevant bit is that an intervention I on X with respect to Y is an exogenous causal process that completely determines the values of X in such a way that if any change occurs in the value of Y it occurs only in virtue of Y's relationship to X and *not in any other way*. One insight from traditional laboratory experiments will help build the case for astrophysical interventions. In a typical laboratory setting, ensuring that potential confounding factors are 'controlled' often requires monitoring in the form of ongoing measurements that take place throughout the experimental process. For example, to be sure that unexpected temperature changes from external sources are not confounding an experiment, a scientist can measure the temperature of the system throughout the experimental process and check that the temperature remains static throughout. This mirrors what Radder (2012) describes as the need for human intervention to ensure that an experimental system proceeds from an initial state e_i to a final state e_f in the proper way.

Implicit in this kind of monitoring to protect against confounding factors is the notion of a contrast between initial and final states. An experiment begins with a system in state e_i and attains a final state e_f. The transition from e_i to e_f is supposed to occur solely in virtue of the interaction between two variables or features, X and Y. The result of the experiment is the comparison between the initial values of X and Y in state e_i and the final values of X and Y in state e_f. The intervention includes a monitoring of confounding factors to ensure their stability and thus non-influence. Thus, an appropriate comparison between e_i and e_f relies on the claim that every non-X and non-Y feature of the experiment remained (roughly) the same between e_i and e_f.

In cases where such direct control of the system is not possible, like in astrophysics, the scientist must provide a related argument that every non-X and non-Y feature of the experiment remained the same between e_i and e_f. This cannot be done simply by appealing to the mathematical description of the system but must rather be done by offering an actual comparison between e_i and e_f to provide evidence that all relevant non-X and non-Y features remained the same. This is where Leconte-Chevillard's (2021) account fails. A more successful account, which I hope to provide below, needs to explain how the relevant notion of control is achieved without direct intervention into the experimental system. My claim is that to do this, one must have the relevant contrast set of observations. A contrast set is a set of observations of the same target system except with a single change - the intervention. The key then is to explain how one can be sure that the feature of interest has changed solely because of this one difference and not because of anything else.

If I am interested in what happens when two astronomical objects interact with regard to some particular factor, I must be able to explain how I can be sure that the intervention (moving object A into proximity with object B, say) allows for measurement of just the factor of interest. Luckily, something implicitly similar already occurs in traditional experiments. In addition to configuring an experiment so that possible confounding variables are prevented from affecting the causal relationship of interest, determining whether or not a causal relationship exists *at all* requires observations or measurements before *and* after the intervention or manipulation. This is necessary because the value measured after the intervention needs to be compared with the initial value to determine that the causal relationship exists. If one is interested in knowing whether changing the pressure of a gas affects its volume, one must first measure the volume before conducting the intervention that changes the pressure. In the case of non-anthropocentric intervention, one must similarly compare the system both before and after the intervention. The trick for the astrophysical case is to justify why the comparison only differs with respect to the single factor of interest. Luckily, in astrophysics we have good reason to believe that many of our objects and systems of interest, when viewed repeatedly from the same perspective through time, remain relevantly stable with respect to all other relevant features.

A basic version of this idea is touched upon by Weisberg et al (2018) in their paper on dark galaxies. They note that astronomers "systematically record the sky over the course of many nights, then create a catalog or database of these observations" (1208). Attempts to map features like the locations of specific stars have been ongoing since the attempts of ancient Chinese, Mesopotamian, Egyptian, and Greek astronomers (Gysembergh et al, 2022). Star maps tracked the relative positions of stars in the observable Universe and allowed for predictions of stars and other easily observable phenomena at different times throughout the year. Ancient star maps were of course limited in the features they could distinguish, but the core idea is the same. A catalogue of observations through time can discern specific features that change in contrast to those that stay the same.

In contemporary work, astronomers conduct ongoing sky surveys such as the Sloan Digital Sky Survey (SDSS) for similar reasons. By capturing and archiving ongoing snapshots of different parts of the Universe, one can compare the features as they change through time using knowledge about those that have certain kinds of stability and those that are undergoing change. In this way, astronomers can rely on the stability of features over time that allows them to distinguish changes that occur in any two different observations. Additionally, astronomers have identified other stable or predictable features that has generated usable relationships between variables that can be applied to other phenomena. For example, astronomers seeking to measure the Hubble constant (the rate of the expansion of the Universe) use the idea of a standard candle. Standard candles are astronomical objects that have a known luminosity. Standard candles are Cepheid Variables, stars whose luminosity brightens and dims over a regular period. Thanks to Leavitt's Law – the relationship between a Cepheid's luminosity and pulsation rate – the luminosity is thus well known and this stability can ultimately determine the distance to the Cepheid star (Freedman & Madore, 2010). In the next section, I show how this method can serve as a model for achieving the necessary 'control' in astrophysical experiments.

One final point to revisit up front is Carnap's claim that in setting up an experiment, one seeks to determine the relevant factors in the phenomenon of interest and to set aside or ignore those deemed irrelevant. There is nothing special for non-laboratory experiments in this regard. Of course, controlled laboratory settings might claim or appeal to more certainty in their ability to account for certain factors. But this is only a question of degree. For example, astrophysicists interested in collisions of galaxy clusters believe they are justified in largely ignoring any interactions between galaxies themselves, since they are believed to account for a very small portion of the overall mass (see my other chapter). X-Ray and lensing data suggest that scientists are justified in setting these factors aside as irrelevant. One might claim that without the sort of material control afforded by laboratory interventions, such assumptions are insufficiently justified. However, this is not a question of whether *any* such assumptions are justified but rather a choice of thresholds between what falls into the realm of the irrelevant.

Furthermore, as Boyd (2023) points out, it is also not the case that traditional laboratory experiments avoid the need to make inferences about target systems in virtue of the fact that they are material interventions conducted on an actual object of interest. She is not the first to point this out, but articulates it well:

> "If one is unwilling to countenance these [terrestrial] experiments as astrophysical experiments, then one should also be unwilling to countenance most laboratory experiments as intervening on their targets in the relevant sense since in virtue of being conducted in the laboratory, laboratory experiments do not intervene on instances of their targets in the wild, but rather on instances of the relevant type located in the laboratory…Of course, arguments do need to be furnished to support the crucial claim that the instances in the laboratory belong to the relevant type, and these arguments are not always successful. This is a general challenge for scientific research however, not a specific handicap of astrophysics" (18).

Thus, although laboratory experiments might have some advantages in terms of their ability to access their experimental objects, they do not avoid the fact that (a) they must still make claims about relevant and irrelevant features of the phenomena, and (b) infer from the experiment to the target system in the real world.

5. The Eddington Experiment

The phenomenon of gravitational lensing - the bending of the trajectory of light by large masses - was proposed by Isaac Newton in 1704 and calculated for the first time using Newton's theory by Henry Cavendish in 1794 (Ellis, 2010). In 1915, using his theory of General Relativity (GR), Einstein calculated the precise amount of light bending that should occur due to the Sun. The famous expedition by Arthur Eddington and other astronomers in 1919 sought to test Einstein's prediction by taking photographs during that May's solar eclipse. In this section I describe this expedition and argue that it should be construed, relying on Woodward's IN, as a genuine experiment.

In the case of the eclipse, Eddington and his collaborators sought to measure the degree that starlight is bent as it passes by the sun.[32] Einstein proposed the test of bending starlight as one of the three *experimentum crucis* of his theory (in addition to the measurement of the advance of the perihelion of Mercury and redshift…). If such an experiment could be designed by astronomers, they would arrange an experimental system with a source of light, an extremely massive object, and an apparatus to capture the light. Of course, such setups are not possible given the necessary sizes and distances involved, but just as in a traditional construal of a natural experiment, one can find a natural arrangement that facilitates just such arrangement.

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[32] Some might recall the controversy launched by Earman and Glymour that questioned the integrity of Eddington's results and the more recent work by Kennefick to vindicate the original 1919 expedition. Ultimately, we need not be concerned with the results of the experiment nor whether it appropriately confirms GR. The point here is solely about the construction and nature of the experiment itself.

5.1 The experimental apparatus

The goal of the Eddington expedition was to measure precisely how much light is bent by the gravity of the sun. How can this be done? The basic strategy is to compare the positions of the same stars when the sun is between them and Earth and when the sun is absent (at night). If the trajectory of light from these stars is bent by the Sun, their apparent positions will differ in both cases. Using straightforward geometrical optics, one can use the measured differences between these positions to calculate the amount of light bending and compare it to the theoretical prediction.

The problem is that the Sun is too bright - stars are not visible during the day and so their positions cannot be observed. The solution is to wait for a solar eclipse, where the sun is sufficiently blocked by the moon and thus allows for observation of light from very bright stars whose light is passing very close to the sun. Luckily, the total solar eclipse of May 29, 1919 would occur right when the sun was passing the location of the very bright Hyades star cluster. The darkness afforded by the eclipse would be enough to observe these stars in the same locations as they would appear at night. This would provide accurate measurements of their positions both without the Sun's presence and their apparent positions due to the gravitational effects of the Sun.

The method of comparison is literally to compare the position of stars on photographic plates taken of identical star fields. The astronomer in Eddington's expedition took photographs through telescopes set in locations chosen based on their helpful orientations to the eclipse. The same stars are identified in photographs both prior to, during, and even after the eclipse. The small differences in relative position of each star image can be precisely analyzed to determine changes in scale and orientation between the two photographs, and any systematic effect caused by gravitational light bending. Importantly, only the stars closest to the sun will reveal a shift in their apparent position. Stars further from the Sun do not change their positions by very much compared to the close-in target stars because the light does not pass sufficiently near the sun to cause a determinable bending. These distant stars will then serve as a frame of reference for the undisturbed geometry of space near the sun.

In summary, the Eddington expedition apparatus consists of the Hyades star cluster, sun, moon, and observational equipment on Earth. The positioning of the observational equipment to take photographs of the solar eclipse is intentionally arranged given the observable path of the eclipse on Earth such that photographs can be taken during “totality” - the moment at which the solar disc is completely covered by the Moon as it passes between Sun and Earth. The observational apparatus consists in telescopes that capture and magnify the light from the stars now visible thanks to the moment of totality and the photographic equipment designed to capture static images of this light. The apparatus here is, again, very intentionally arranged to take advantage of the relevant features or properties of the objects collectively composing it. The 1919 expeditions selected locations such that photographs could be taken given the arrangement of the various parts of the apparatus. In fact, the apparatus is achieved precisely because of the locations chosen to position the observational equipment. If equipment were not positioned in the path of the eclipse, we would say that the apparatus was poorly or insufficiently designed. Furthermore, the observational equipment captures only a single feature of the apparatus - light. The light is captured as different points in time: once at some point prior to the eclipse and once during the eclipse. The photographs of the eclipse were compared to photographs of the same light source captured previously. The light captured in these two instances differs in only a single meaningful respect: whether or not the light passed close to the Sun. No other known factor has changed.

5.2 The expedition as experiment

Recall Woodward's definition of intervention. The relevant bit is that an intervention I on X with respect to Y is an exogenous causal process that completely determines the values of X in such a way that if any change occurs in the value of Y it occurs only in virtue of Y's relationship to X and not in any other way. The exogenous causal process here is the motion of the Sun and Moon such that they arrange themselves into a particular alignment relative to the Hyades star cluster and the detection apparatus on Earth.[33] To see whether or not the Eddington apparatus constitutes a Woodwardian intervention, we can first look at the equation to determine starlight deflection:

$$\boxed{\boldsymbol{\theta}}\,(\textit{angle theta in radians}) = \boxed{\frac{4GM}{c^2R}}$$

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[33] It is worth noting that there is also a sense in which it is the intentional positioning of the detection apparatus on Earth that is the intervention, but whether this is the case is not pertinent here.

In this equation, we are looking to determine the angle $\boxed{\theta}$ between two different positions of the visible star's location. On the right side of the equation, *G* is an unchanging gravitational constant, *M* is the unchanging mass of the sun, and *c* is the unchanging speed of light. *R* is the only changing variable, defined as the distance between the light ray and the center of the sun. Thus, the determination of the angle $\boxed{\theta}$ at which the starlight is bent is essentially determined by the distance of the passing light from the sun. Since all other variables are known constants, the initial structure of Woodward's definition is a plausible consideration, since a change in the variable $\boxed{\theta}$ is brought about solely by a change in the variable R. The experimental apparatus is designed such that one ensures that all other variables are constant (in virtue of selecting objects whose features do not change meaningfully over time) and by collecting data in a way that isolates the two relevant variables.

So far, all this shows is that the apparent relationship between and R is such that it preliminarily meets Woodward's formal definition of intervention. However, the key justificatory challenge is to explain how we can be sure that the change in the variable is *only* caused by distance of the light ray to the Sun and not by any other potential cause. Perhaps R does contribute to the cause of the change in $\boxed{\theta}$ but is not the entire cause. Or perhaps R somehow obscures the actual cause of the change in $\boxed{\theta}$. Or, perhaps the change in R is only apparent but does not in fact reveal that in the world there truly is the relevant phenomenon at all. In the laboratory setting, one could potentially control for each of these possibilities. What can the astrophysicist say?

The answer is twofold. First, the positions of the target stars are contrasted with the positions of other stars in the same field. Since the deflection varies inversely as the angular distance of the star from the Sun, those stars much farther away in the field establish fixed reference points because their relative positions are largely unchanged compared with the stars whose light passes much closer to the sun (Will, 2015). Recall the earlier discussion of star charts. By regularly tracking the position of the stars over time, one can determine with some certainty that the positions of stars in any instance will be, for all intents and purposes, identical. If the apparent position of the Hyades changes (as expected) during the eclipse, it is inferred to be caused by the sole difference-maker between two instances: (a) the apparent position of the Hyades relative to other stars when the Sun is *not* present, and (b) the apparent position of the Hyades relative to other stars when the Sun *is* present. Given this background and the two contrast cases, the presence of the Sun can be taken to serve as the source of the exogenous intervention that facilitates the fulfillment of Woodward's IN. And if this is the case, the relationship between $\boxed{\theta}$ and R is established as being determined solely due to the intervening solar mass and not because of any other facts.

Second, as with any experiment there are sources of error and possibilities of confounding factors. In the Eddington case, for example, the Earth's atmosphere also causes distortion of starlight and so affects the precision of the necessary measurements. These distortions can be comparable in degree to the scale of the target light deflection and so are important to consider. In this particular case, scientists know that atmospheric deflections are random in nature and, assuming multiple photographs can be taken, these deflections can be averaged away to reveal the underlying, systematic deflection of light caused by the Sun (Will 2015).

Given Woodward's definition of intervention, we can say that the experiment intervened on the variable R relative to $\boxed{\theta}$. Scientists arranged the apparatus such that the moon could be placed between the earth and the Sun and that the Sun would appear in between the Hyades stars and the Earth. That scientists did not physically place the moon and the Sun in these positions is irrelevant. The end result of the moon as located in a position such that it can occlude the entire solar disc as observed from the telescope location is identical independently of how it arrived at this location. This is also true because only the moon's location is relevant, not any of its other properties.

5.3 Other cases

Other work in astronomy and astrophysics also likely meets the criteria for interventionist experiments. I will briefly review the case of exoplanet detection here, though much more can certainly be said about it. Gravitational lensing cases provide the most obvious examples for interventionist experiments. My view, however, is that this is not the only method that will eventually qualify as such. Future work will identify more cases and expand the methodological varieties that should count as experiments in this way.

At core, Eddington's experiment is an example of employing a gravitational lens. As mentioned, gravitational lenses are massive celestial bodies such as galaxy clusters that cause a sufficient curvature of spacetime for the path of light around it to be visibly bent. Advanced techniques are now able to detect extremely minimal amounts of lensing to provide insights into much smaller objects. Not all use of such lensing events might qualify for an interventionist experiment. Some uses of lensing are intended to measure properties of objects of interest or magnifying the desired image to get better observational data. Other work uses lensing to capture the collective distortion of millions of galaxies as a way of investigating the cosmic microwave background radiation or to try to measure the mysterious dark energy.

One particularly interesting use of gravitational lensing is to identify exoplanets orbiting around distant stars. Even though a single star has a much smaller effect on the bending of light, contemporary astrophysicists can nonetheless detect the subtle differences – the effect in such cases is a type of gravitational lensing known as microlensing. When one star passes the line of sight to another, more distant star, this causes the background star's light to appear brighter. This is because the light from the background star is focused by the lens in the same way that a magnifying glass can focus sunlight into a single bright spot. If the star in the foreground happens to have a planet in its orbit, this planet will affect the normal lensing event by creating a very brief spike in the brightness of the light as the planet contributes to the lensing. The foreground star itself might increase the perceived brightness of the background star for a period of a few weeks or a month, while the quickly passing planet will cause much more temporally limited spikes in brightness. These microlensing events thus reveal the exoplanet.

Similar to the Eddington experiment, detection of exoplanets using microlensing relies first on establishing a control – in this case it is the normal behavior of lensed light known not to change over certain periods due to the stability of the stars' position relative to each other. The brief brightening and dimming that occurs when an exoplanet passes by is the only factor that changes. Given the observed stability of the background stars and the normal lensing events, the presence of the exoplanet can be taken to serve as the source of the exogenous intervention that facilitates the fulfillment of Woodward's IN. And if this is the case, the relationship the exoplanet's presence and the brightness of the lensed light is established as being determined solely due to the intervening exoplanet and not because of any other facts.

6. Conclusion

The prevailing view about scientific work in astrophysics and astronomy claims that scientists rely on observational studies that do not qualify as traditional experiments. This paper rejects this view by arguing that astrophysicists can and do conduct genuine, interventionist experiments on a par with laboratory experiments. By using contrast classes of observations, typically in cases of gravitational lensing, astronomers and astrophysicists can achieve the kind of 'control' necessary to count as an experiment. On my view, the Eddington expedition during the 1919 solar eclipse to measure the bending of starlight around the Sun is a paradigm case of interventionist experimentation in astronomy. If this is correct, not only should this force us to reconsider our evaluation of astrophysical methodology and its status in comparison with other sciences, but also suggests that we rethink traditional views that promote the epistemic superiority of laboratory-based science.

CHAPTER 4: REALISM AND THE DETECTION OF DARK MATTER

Introduction

Can one justifiably be a scientific realist about dark matter? More specifically, does the theoretical term 'dark matter' in cosmology successfully refer to a real entity in the world? Answering these questions requires confronting a unique challenge. On the one hand, dark matter is taken to be "paradigmatically unconfirmed" (Allzen 2021, 155). Evidence for its existence is indirect, based on observations of other astrophysical phenomena. On the other hand, dark matter is an indispensable ingredient in ΛCDM (Lambda Cold Dark Matter) – the current 'standard model' of cosmology. This model is widely accepted by scientists and has proven extremely successful (Jacquart, 2021a; Dellsen, 2019). Given this, existing arguments for realism rely on appeal to the accuracy and explanatory virtues of ΛCDM (Allzen, 2021). However, ΛCDM itself relies on the accuracy of our best theory of gravity, General Relativity (GR), which lacks empirical confirmation at the relevant galactic scales. This lack of certainty about the right theory of gravity opens the door to alternative models that might seek to avoid the posit of dark matter entirely. Given these challenges, an empirical detection of dark matter can provide strong independent evidence in favor of its existence. More specifically, it is typical to suggest that resolving these questions requires a laboratory detection of a dark matter particle (Massimi, 2018; Vanderburgh, 2014). Such a detection has yet to occur. Detection may not guarantee realism but would provide a special kind of evidence beyond inferences solely from theoretical successes.

Although empirical detection would indeed provide a stronger foothold for dark matter realism, I disagree that it is a detection of a dark matter *particle* that must be obtained. A single previous claim that dark matter has been sufficiently empirically detected via the phenomenon of gravitational lensing (Kosso, 2013) has been denied or ignored precisely because it tells us nothing about the particle nature of dark matter. On this view, since analysis of gravitational lensing is independent of any specific particle, and since no dark matter particle has yet to be detected, such a path toward dark matter realism is so far off the table.

This demand for a particle detection, though understandably motivated, is misguided. I will argue that we should take the theoretical concept of dark matter as described in our best cosmological model at face value. Since there is no theoretical or nomological requirement that dark matter be a particle, we should instead look to see whether this non-particle concept has been empirically detected. Assessed in this way, detections via gravitational lensing provide plausible empirical confirmation. Thus, realism about dark matter does not rely solely on explanatory successes of ΛCDM and such a confirmation should be seen as sufficient to rule out alternative models that deny the existence of dark matter.

1. The Gravity of the Situation

Dark matter is an indispensable component in the current Standard Model of Cosmology, known as the 'Concordance Model' or 'ΛCDM' (Lambda Cold Dark Matter). This model describes the basic structure and evolution of the universe and has been extremely successful in matching all available observational data on the scale of galaxies and larger (Massimi 2018; Jacquart 2021a). According to ΛCDM, ordinary visible matter like stars, galaxies, gases, and dust only accounts for ~4% of the total mass-energy content of the universe. Dark matter accounts for ~24% and dark energy ~72%.[34]

Dark matter was initially posited to explain discrepancies between the observed masses of galaxies and galaxy clusters and the mass necessary to account for a variety of related observations. Since the pioneering studies of Vera Rubin and colleagues in the late 1970s, diverse evidence has continued to accumulate in support of dark matter. This includes, among other evidence, galaxy rotation curves, large-scale structure formation of the universe, features of the cosmic microwave background radiation, and gravitational lensing.[35] Despite this compelling evidence, very little is known about the nature of dark matter. It is electromagnetically neutral and so cannot be directly observed using any of our standard methods of detection. The presence of dark matter is instead typically inferred due to its effects on other objects that we can observe and from computer simulations of various cosmological

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[34] Good historical accounts of dark matter can be found in Bertone and Hooper (2018) and de Swart et al. (2017). A good overview of the philosophical issues related to dark matter and dark energy can be found in Jacquart (2021a).

[35] Good overviews of much of this evidence are provided by Hamilton (2014) and Massimi (2018).

phenomena. And, despite the posit of many particles candidates that might constitute dark matter, none of these particles have ever been detected.

As noted above, dark matter is paradigmatically unconfirmed. It is typically claimed that the only way to empirically confirm dark matter is to detect a dark matter particle because gravitationally mediated confirmations rely on unconfirmed theory (e.g., Jacquart 2021a; Vanderburgh 2014). Since a particle has not yet been detected, the conclusion is that there has been no empirical confirmation of dark matter's existence. However, ΛCDM's major theoretical success does not hinge on a specific particle concept of dark matter and there is no nomological reason why dark matter must be constituted by a particle.[36] Still, the demand for a particle detection is understandable because of confirmational issues that arise with General Relativity (GR), the current best theory of gravity and central to the success of ΛCDM. GR continues to be an overwhelmingly successful theory at the low energy, low curvature, and large length scales relevant to the astronomical systems of interest (Smeenk 2013). The problem is that there is no accepted way to empirically confirm GR at the large scales relevant to ΛCDM.[37] Instead, the accuracy of GR on these galactic and extragalactic scales is inferred from its success at the smaller terrestrial, planetary, and solar system scales for which there is empirical confirmation.

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[36] Although the term 'nomological' refers to laws as articulated in theories, my usage here is also meant to capture the requirements as set for by the Concordance Model. Although cosmologists do typically assume that dark matter consists of elementary particles (Merritt, 2021), the point is that the model's success does not necessitate this assumption.

[37] There are studies that provide evidence in favor of the accuracy of GR at large scales (e.g., Reyes et al. 2010; Collett et al. 2018). While these tests cannot rule out all alternative theories of gravity, it is worth noting that there is also no available data thus far to suggest that GR falters at these large scales. Recent work by the GRAVITY Collaboration (Abuter et al. 2020) highlights another impressive feather in the cap of GR.

As Jacquart (2021a) notes, “By and large, the astrophysical community has favored maintaining GR and ΛCDM, rather than abandoning them for alternatives” (738). There does not seem to be any obvious or motivated reason why the theory should not so hold. Of course, such an inference across scales does not qualify as confirmation.

Empirically testing the accuracy of GR on large scales first requires knowing the mass distribution of the relevant large-scale systems. However, we cannot know the mass distribution without first employing GR (or some other preferred theory of gravity). Thus, any investigation that relies on determining the mass of large-scale systems cannot get around assuming the accuracy of a theory that we have yet to confirm. This is what Vanderburgh (2003) calls the ‘dark matter double bind’. The need for dark matter arises from a discrepancy between the observed mass distribution in a system and the amount of mass necessary to account for its observed gravitational behavior. But the discovery of this discrepancy relies on the accuracy of GR. If a theory is taken to be insufficiently confirmed, then any evidence relying on this theory is of weaker quality. Therefore, without a confirmation of GR on large scales it is thought that gravity-mediated data from large-scale systems cannot qualifies as an empirical detection of dark matter.

Instead, the argument for the existence of dark matter is made using robustness arguments (Smeenk 2013) or proceeds along explanationist lines (Allzén 2021). Current evidence in favor of dark matter comes from several independent lines of inquiry, each relying on distinct modes of investigation and with different sources of systematic error. One strategy is to argue that it would be highly unlikely for each of these independent contributions to be fundamentally mistaken. On the explanationist view, one should be a realist about unobservable entities that are indispensable to our best scientific theories (Chakravartty 2017). Even if one does not want to assent to full-fledged realism, one should think that explanationist success justifies a higher epistemic credence toward the existence of a theoretical entity. Since dark matter is indispensable to the success of ΛCDM, it is a paradigm case. As Allzén (2021) points out, models relying on dark matter hit all the right explanationist criteria: "it's sufficiently mature, it's predictively successful, it has explanatory breadth and depth, and it satisfies the theoretical virtues of IBE [inference to the best explanation]" (153). Using the inferential justification provided by IBE, the best explanation for the indispensability of dark matter in the ΛCDM model is that dark matter really exists. Given also that there are no empirically equivalent alternative models without dark matter that achieve the same explanationist success, this line of reasoning might be taken to justify some sort of realist stance about dark matter.

Despite the convergence across the various lines of evidence and the explanationist successes of ΛCDM, these arguments result in a precarious realism because they leave us committed to the existence of an empirically unconfirmed entity. Even if one is willing to bite this bullet, the bigger problem with cases like dark matter is that this severely undermines the significance of empirical confirmation via future experimental detection. As Allzén (2021) nicely summarizes:

> "In the context of dark matter, selective confirmation via indispensability and the application of IBE generates a truth-statement about dark matter, effectively implying that the possible empirical confirmation of dark matter *would contribute no justification to the belief that dark matter is real*" (155, emphasis mine).

I will not debate the merits of Allzén's argument here nor the merits of arguments for realism that do not require empirical confirmation. For the purposes of this paper, I assume that we should demand an empirical detection of dark matter and take at face value the problems that arise without one. Considering these issues and the problems of confirmation surrounding GR, one can understand the motivation behind the claim that no gravity-mediated empirical detection can provide evidence that is strong enough for a confirmation of dark matter.

The alternative is to detect dark matter particles because the experimental methods for particle detection are independent of gravitational theory (Jacquart 2021a). Detection of particles would be achieved via predicted effects due to some non-gravitational force. For example, in the case of the most popular theoretical posit for a dark matter particle – the WIMP (Weakly Interacting Massive Particle) – a direct detection requires an apparatus to detect and measure the theorized nuclear recoil that would occur in the event of an interaction with a quark (Cerdeno and Green 2010). Evidence obtained without the invocation of gravity would be taken to provide an independent, and presumably more convincing, path to establishing the existence of dark matter.

Even in light of the best arguments in favor of a gravity-mediated detection – cases where the above confirmational issues related to GR are plausibly circumvented – the response has still been to set a threshold of a particle detection as a necessary condition for an empirical confirmation of dark matter. As will be discussed in the case of the Bullet Cluster and gravitational lensing in Section 4 below, even though Vanderburgh (2014) agrees that such arguments show that the *location* of dark matter has indeed been detected, he argues that this is insufficient to justify confirmation and a realist attitude:

> "…the point is not to 'detect' or 'locate' the dark matter…What is at stake is determining the nature as well as the existence of the dark matter, since understanding its nature is the likely route to devising potential direct detections of dark matter that would confirm its reality" (64).

Ultimately, the consequence of all this is that *any* gravity-mediated detection is considered insufficient. However, it seems to me that an unintended result is that once the commitment to the need for a particle detection was made, it obscured the fact that there is no theoretical requirement for dark matter to be a particle. Even if it is highly likely to be a particle, it does not follow that a particle detection is necessary for confirmation. As I discuss in the next section, the criteria for what it is that needs to be detected should align with what the theory or model tells us about the properties necessary for their success.

2. Realism About Dark Matter

So far, I have said that empirical confirmation is a necessary condition for a plausible realism about dark matter but denied that ΛCDM requires a particle concept. But if not a particle, what should we be seeking to detect? We should look to see what our best theory or model says about the properties possessed by the entity. On a standard realist account, theoretical terms in scientific theories have factual reference to entities in the world (Boyd 1983; Psillos 1999). If we want to develop a plausible account of realism about dark matter, then we need to stipulate a theory of reference, articulate the concept of the theoretical entity as provided by the theory or model, and show that the identifying properties have been empirically detected. I will rely on Psillos' (1999) causal-descriptive theory of scientific reference for theoretical terms given its stature among contemporary theories of scientific reference and its prominent role in recent debates about dark matter realism (e.g., Allzén 2021; Martens 2022).

Psillos's (1999) causal-descriptive theory of scientific reference for theoretical terms provides the following criteria for successful reference (296):

1. A term t refers to an entity x if and only if x satisfies the core causal description associated with t.
2. Two terms t' and t denote the same entity if and only if (a) their putative referents play the same causal role with respect to a network of phenomena; and (b) the core causal

description *t′* takes up the kind-constitutive properties of the core causal description associated with *t*.

For criteria (1), the core causal description is a description of the properties that the theoretical entity possesses in virtue of which it is causally connected to the phenomena that it is posited to explain. The burden of reference is carried by this set of identifying properties, which Psillos calls "kind-constitutive properties" (294-95). Kind-constitutive properties are the fundamental properties the entity must possess if it's going to play the necessary causal role and single out the entity as being a distinct kind. Criteria (2) is intended to ensure that any two instances of references are in fact tracking the same entity.

The source of this set of identifying kind-constitutive properties is the conceptual description of the entity provided by theory. As Psillos (1999) notes, "Only theories can tell us in virtue of what internal properties or mechanisms, as well as in virtue of what nomological conditions, a certain substance possesses the properties and displays the behaviour that it does" (288). Thus, we should look to our best theory or model for the relevant descriptive profile of dark matter. Any attempt at confirmation via an empirical detection should be tied to these properties. After all, it is these properties that underpin the success of the model and tell us what dark matter is supposed to be if it is to play its causal role. If, on the other hand, one demands a particle concept of dark matter then this should be because the theory or model specifies or requires such a concept. However, there is no such demand – the success of ΛCDM does not depend on specifying a concept of particle dark matter and therefore empirical confirmation of dark matter does not require detecting a particle.

What do theories and models tell us about dark matter? From the perspective of the Standard Model of Cosmology (ΛCDM), which describes the large-scale structure and evolution of the universe, the specifics of a possible particle nature of dark matter are irrelevant. The explanatory success of ΛCDM in fact requires relatively little to be specified about dark matter's nature or properties, with no obligation to provide a description of a specific particles (Merritt 2021). Of course, if one is later interested in investigating possible particle options then one can use evidence from ΛCDM to constrain the possibility space or rule out certain types of particle candidates. Still, the permissible range of particle properties that would satisfy the model is vast.

ΛCDM's constraints on dark matter only relate to its collective behavior – its total contribution to the universe's mass budget, its slow velocity (hence the 'cold' in 'cold dark matter'), and its mode of gravitational interaction. The mode of gravitational interaction tells us that we should expect dark matter to interact like a collisionless fluid. This provides some expected behavior when it comes to interactions between galactic entities believed to possess dark matter. This also means that dark matter must be nonbaryonic since it only interacts gravitationally and not via electromagnetism. Together, these are the relevant kind-constitutive properties that currently form the core causal description associated with the term 'dark matter'.

This is not an exhaustive description of dark matter and its properties, nor does it provide strong constraints on certain other properties (e.g., mass) that are more specific to particles. But it does not need to be exhaustive, nor does it need to be especially detailed. The kind-constitutive properties specified in the above description provide a stable set of identifying properties upon which a more robust and fuller characterization can be developed in light of ongoing scientific investigation (Psillos 2012). The sufficiency of the core causal description of dark matter provided by ΛCDM is achieved because these properties compose a set of kind-constitutive properties that collectively make an entity belong to a kind. Since there is not an already existing, empirically confirmed entity that satisfies the kind-constitutive properties associated with the core causal description, whatever satisfies the reference of 'dark matter' will belong to this kind. This set of identifying properties will be consistent with future discoveries of dark matter particles no matter how many different types of these particles are found. As far as *cosmological* models go, the term 'dark matter' refers to anything that satisfies the set of properties as generally outlined here (and whatever else cosmologists tell us is required for a successful model).[38] Cosmological models do not distinguish between different particle candidates for dark matter and so from their perspective it would be strange to demand that such models provide additional posits about the nature of dark matter beyond what is necessary for a model's empirical success.

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[38] I use the term 'model' because it aptly captures ΛCDM. But one can also think of this as a theory if they are so inclined and if it helps maintain consistency in how philosophers of science tend to think about the role that theories play in referential semantics. See Jacquart (2021b) on how it may be more productive to construe debates about ΛCDM and its competitors as being about models instead of theories.

This point has been overlooked or insufficiently considered. In a recent criticism, for example, Martens (2022) argues that there is no available causal description of dark matter that can justify realism. On his view, the available core concepts that we can be confident about are too semantically thin, while the thick concepts describe particles for which we have no empirical evidence. In contrast to Psillos, Martens believes that a plausible realism relies on a much more robust description of the posited entity. On his view, the following thin concept for dark matter is too thin to justify any sort of realism (4):

> **The Thin Common Core Concept of Mainstream Dark 'Matter':** A massive field with a contribution to the total cosmic mass-energy budget of 27%, thereby being responsible for certain gravity-mediated observables related to structure formation, clusters and galaxies. In case it is a particle, its mass is roughly between 10^{-22} and 10^{13} eV.

There are two problems with this conception. First, it does not articulate sufficient kind-constitutive properties. It does describe the causal role that dark matter is supposed to play vis-à-vis relevant astronomical phenomena, but it doesn't tell us in virtue of what properties it plays this role. Using Martens's concept, successful reference will be achieved by anything that provides sufficient mass to generate the necessary gravity-mediated observables. This means that baryonic matter would satisfy this concept as would many other non-unique kinds already known to exist. Without adding a description of properties, referential success can be achieved purely causally. But this runs into well-known issues for purely causal accounts of reference. It is not enough to say that the term ‘dark matter’ refers to whatever it is that causes the extra gravity to explain the phenomena of interest because this inappropriately guarantees successful reference. Since there is *something* that must play this causal role, the term ‘dark matter’ will just refer to whatever this happens to be. This is a problem because it would mean that two instances of dark matter reference are successful even if their respective causal descriptions have no shared properties.

This is a salient issue for the history of the term ‘dark matter’. To take one example, we know that the orbital velocity of stars in a galaxy depends on their distance from the galaxy’s center. However, in the 1930s (sixty years before the development of ΛCDM), Fritz Zwicky discovered that star velocities at the outer reaches of galaxies are too large and cannot be explained given just the total observed luminous mass (Bertone and Hooper, 2018). The entity ‘dark matter’ was posited to resolve this discrepancy by providing the missing mass needed to generate the amount of gravity that would account for the actual observed rotational behavior. Instead of some exotic entity, however, the missing mass was thought to be normal baryonic matter with such low luminosity that it could not be effectively detected. This included possibilities like extinguished stars and dark clouds. Such dark matter would only be ‘dark’ in the sense that it was too dim to be observed. It would not be ‘dark’ in the sense that it was a different kind of matter that does not engage in electromagnetic interactions.

Subsequent detection of baryonic dark objects showed that they are too few in number and too low in total mass to account for the discrepancy. Thus, dark matter must be non-baryonic – it is not like normal matter that is constituted by particles interacting via electromagnetism. But on a purely causal account of reference, the 'dark matter' reference to dark baryonic matter and the 'dark matter' reference to dark non-baryonic matter are both successful since both referents play the same causal role in the phenomena of interest. But since dark baryonic matter and dark non-baryonic matter are distinct kinds – they don't share any relevant properties – it cannot be that both cases of reference are successful. Without providing some description of the nature of the missing mass in the relevant astronomical phenomena, the existence of dark matter is trivially true. Moreover, no matter what we end up learning about the properties of dark matter in the future, our current models will be taken to have already successfully referred to whatever this concept turns out to be.[39]

What is needed in addition to a purely causal account is to employ a description of the theoretical entity such that the kind-constitutive properties identified by the theory play an essential role in fixing the reference. Our best theories and models tell us what properties the entity is supposed to have, the mechanisms at play, and the nomological conditions necessary for the system of interest to behave in the way that it does. In the astronomical systems of interest, dark matter plays the causal role that it does in virtue of possessing a set of kind-constitutive properties – those properties that collectively make an entity belong to a kind.[40]

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[39] This is the problem discussed above and is well-articulated by Allzén (2021).

[40] I follow Psillos (1999, 288) in appealing to the notion of natural kinds as a reasonable concept meant to capture the idea that entities consisting of a set of properties are distinct from entities that do not consist of this same set of properties. I will not argue for the existence of natural kinds.

If we ignore the insufficiency of kind-constitutive properties provided in the above thin concept, a more charitable interpretation is that Martens is essentially raising the "too little/too much" objection as articulated by Psillos (2012).[41] The problem is this. As already discussed, successful reference of the term 'dark matter' requires some descriptive elements that would uniquely pick out dark matter and not just whatever ends up playing the right causal role. However, merely having *some* core causal description is not enough. We need to know how thick the description of a theoretical term should be to ensure successful reference as well as referential continuity as the theory changes or evolves. If the causal description is too thick, it may be difficult to make sure that something in the world is successfully picked out and it will make referential continuity very challenging. If the causal description is too thin, there may be multiple entities that satisfy the reference and so no unique referent will be picked out. Psillos's answer is to have a Goldilocks causal description – one that is not too thin and not too thick. But how to make it just right? His suggestion is that we include just enough of a description such that there are "enough identifying markers of an entity (related to its causal role vis-à-vis phenomena Φ) to allow the stable use of the term in certain inductive and explanatory practices; but are not meant to asphyxiate the putative referent, that is, to leave no room for error, ignorance, or improvement" (224).

There are good reasons to think that the causal description provided by ΛCDM falls into the sweet spot between the extremes of thick and thin. First, as mentioned, the kind-constitutive

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[41] Martens (2022) does not cite Psillos (2012) or this objection. On my reading, however, this is essentially what his argument amounts to.

properties associated with dark matter pick out a distinct kind of entity. If so, this would ensure that the description is not too thin because irrespective of what particle or other entity is ultimately determined to be a more precise description of dark matter, such a particle would still be a member of the kind 'dark matter' as determined by the model and would build on the initial set of fundamental properties the model identifies. If the model tells us that the phenomena it accounts for can be fulfilled by any type of dark matter that has these properties, then we do seem to have enough identifying markers of the entity 'dark matter'. Second, since the model does not specify any particular particle, the causal description is not too thick. There exists a "non-baryonic candidate zoo" (Bertone et al. 2005, 305) of particles theoretically capable of fulfilling the causal description and so there is no reason to think that the description is liable to excessively prohibit progress in homing in on the individual or set of actual dark matter particles.

If this is all sufficiently compelling, it is an important point but does not yet get us to a plausible realism. All that this shows is that a commitment to a particle conception of dark matter is not reflected in the causal description of dark matter provided by the model itself. We should instead take the kind-constitutive properties identified by ΛCDM at face value and describe the concept of 'dark matter' as containing these core properties. The next step is to ask whether *this* concept of dark matter been detected. This still requires overcoming the issues related to GR articulated above since a gravity-mediated detection of *any* properties is subject to the objection that the theory being used is not sufficiently confirmed. However, this time we can assess proposed ways of getting around these gravitational issues with an eye toward the proper set of dark matter properties without holding the preemptive bias toward a particle detection. In the next section, I look at the 'new' evidence provided by the collision of two galaxy clusters known as the Bullet Cluster to see whether this is enough to meet the referential demands as required by the causal descriptive theory.[42] I will argue that Kosso's (2013) analysis of the empirical study by Clowe et al. (2006) shows that successful detection of this concept has indeed plausibly occurred. If so, then we have good evidence for empirical confirmation of the unique causal description of dark matter that is posited by the ΛCDM model.

3. The Bullet Cluster and Detection of Dark Matter

Now that we have determined the proper concept of dark matter as provided by our best cosmological model, we can see whether a detection of such an entity has occurred. Many cosmologists believe that gravitational lensing studies provide some of our best evidence for the existence of dark matter (Skordis 2009; Ellis 2010). Kosso (2013) provides the most robust argument that dark matter can be detected by exploiting gravitational lensing. Anderl (2018) also claims that gravitational lensing, "can and has been widely used for the detection of dark matter and for distance determinations" (657). However, per the above discussion, if it is true that no conclusive gravity-mediated detection of dark matter is sufficient for confirmation, the claims by Kosso (2013) and Anderl (2018) as stated can only provide weak evidence for the

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[42] Following Clowe et al. (2006), Kosso (2013) refers to the Bullet Cluster collision as providing a "new" kind of evidence in favor of dark matter. By "new" they mean that it does not rely on the same theoretical commitments used in explaining other large-scale phenomena.

existence of dark matter. However, Kosso (2013) argues that the gravitational lensing results in the Bullet Cluster collision of galaxy clusters (Clowe et al. 2006) do not rely on the entirety of GR and thus circumvent the issue of confirmation at large scales. If so, this allows us to investigate whether these results have detected the above concept of dark matter.

Gravitational lensing is a phenomenon that arises because of the deflection of light by large masses.[43] As light travels to Earth from distant galaxies it passes by other galaxies and galaxy clusters. According to any metric theory of gravity, such as GR, massive objects warp the underlying fabric of spacetime such that the path taken by the passing light will follow a curved path (null geodesic). When these masses are extremely large, the curvature of spacetime is more extreme and the path of light more significantly deflected. The myriad galaxies and galaxy clusters between Earth and the source of light are the gravitational lenses. In the phenomenon of weak gravitational lensing – the type of lensing relevant to this discussion – the masses warping spacetime on the path of light will cause the images observed on Earth to be systematically distorted.[44] Astronomers can measure the precise amount of distortion across the image and use this to determine the location and mass distribution of the intervening lenses. These calculations, relying on GR, have repeatedly demonstrated that the amount of mass

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[43] An accessible discussion of gravitational lensing is Gates (2010). A helpful overview of how gravitational lensing can be used to investigate dark matter can be found in Ellis (2010).

[44] There are three types of lensing: strong, weak, and microlensing. Weak lensing, which deforms images but does not result in multiple images, is the type used to calculate distributions of dark matter (Ellis 2010).

represented by the luminous matter is insufficient to cause the observed distortion. Models that include dark matter, on the other hand, can account for the lensing effects.

The collision of two galaxy clusters known as the Bullet Cluster (Clowe et al. 2006) provides a unique opportunity to circumvent the above gravitational issues when it comes to the detection of dark matter. For this reason, it is often cited as a major source of evidence (Jacquart 2021a). The strategy, as pursued by Kosso (2013), is to show that although it is true that GR *as a whole* is not confirmed at large scales, the detection of dark matter using gravitational lensing studies of galaxy cluster collisions does not depend on the entirety of GR. Instead, dark matter detection in these cases relies solely on the Einstein equivalence principle (EEP).[45] And, since *any* viable theory of gravity requires that EEP be true, we are justified in taking these results at face value.

Metric theories of gravity are those that are committed to the claim that masses shape the travel paths of particles (geodesics of the metric) by warping spacetime. The existence of this phenomenon has been known for some time. Even Newtonian gravity predicted that large masses would bend the path of light. Eddington's famous observations during the 1919 solar eclipse was not testing the truth of this claim but rather the extent to which GR correctly predicted the degree that light was bent by the mass of the sun. Although gravitational metrics differ in how they describe the relationship between mass and the warping of spacetime, *any* metric theory of gravity states that all mass, independent of its nature, systematically bends

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[45] A good technical overview of EEP, including details of its empirical tests, is in Will (1993).

light. If the results of empirical work rely solely on the accuracy of EEP and not on the truth of any specific comprehensive theory, then this will mitigate concerns of underdetermination. We can now look at what can be determined from the collision of galaxy clusters using just this feature of gravitational theory.

Collisions of galaxy clusters are revealing because the putative dark matter is not subject to interactions with baryons – the types of particles that make up ordinary observable matter. Instead, dark matter becomes spatially segregated from the colliding baryons. According to the Standard Model of Cosmology, the luminous parts of galaxies are made up of baryonic matter that are contained inside halos of dark matter. Anywhere from hundreds to thousands of galaxies make up galaxy clusters. The space between the galaxies that make up a cluster is filled with hot gas collectively known as the intergalactic medium (IGM). A crucial fact is that the IGM contains more baryonic material than the combined total of *all* the galaxies within the cluster. This gas thus constitutes the vast majority of non-dark mass and emits X-Ray radiation that can be detected by telescopes like NASA’s Chandra X-Ray Observatory (Mo, Van den Bosch, and White 2010).

Given a single galaxy cluster with thousands of galaxies and the IGM spread throughout, the purported dark matter and baryonic matter are normally ‘spatially coincident’. In this arrangement it is impossible to observationally disentangle different kinds of matter for the purposes of dark matter detection (Clowe et al. 2006). However, if two galaxy clusters collide, the dark matter is theorized to separate from the baryonic matter that exists largely in the IGM. This is because the gases in the IGM of each cluster interact as they travel past each other while the neutral dark matter passes uninterrupted.[46] As the gasses in the IGM of each cluster pass through each other, they slow down due to resistance from their electromagnetic interactions. However, the electrically neutral dark matter and its coincident galaxies continue moving uninterrupted. After some time, the dark matter will thus have traveled further while the baryonic matter remains more centrally clustered in the collision area. Following such a collision, the "observed baryons and the inferred dark matter are spatially segregated" (Clowe et al. 2006, L109). The center of mass of the baryonic matter is not located in the same location as the center of mass of the purported dark matter.

To show this, the Clowe et al. (2006) study mapped the X-Ray emissions from two colliding clusters and compared it to a map of their mass distribution as determined by an analysis of weak gravitational lensing – the distortion of light due to mass. These observations of light distortion showed that there must be a large gravitational potential that cannot be accounted for by the observed baryonic mass. The gravitational potential necessary to produce the visible distortion required more mass and, most importantly, a mass whose center "was significantly offset from the center of mass of the baryonic matter" (Kosso 2013, 146). Since, as mentioned, the IGM contains considerably more mass than the galaxies themselves, the center of the IGM is the approximate center of all the *observable* baryonic mass. Whereas the center of

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[46] The galaxies themselves are too far apart to interact directly with each other and, given the low proportion of the total mass for which they account, can be effectively ignored for these purposes.

the mass that would be necessary for the observed light distortions is located elsewhere. Kosso (2013) offers a helpful analogy to describe this:

> “Each of the colliding clusters acts as sieve for the other, separating dark matter, if there is any, from the normal baryonic matter, as an archeologist's sieve separates artifacts, if there are any, from the dirt. Gravitational lensing then looks indiscriminately for stuff, to see where it is, whether it's in the sieve or in the dirt. In the case of the bullet cluster, there is mass in the sieve” (146).

To reiterate, these results depend only on the accuracy of EEP, not on the truth of GR as a whole. To the extent that EEP is an established component for any viable theory of gravity, we have good reason to accept the results of studies like these that rely on EEP alone. We can grant that GR is unconfirmed while still agreeing on the minimal result that the *location* of some sort of dark matter has been detected. We still cannot confirm the precise amount of mass at this location because this would require a specific metric like GR. Nonetheless, we can say that there is necessarily some significant amount of mass located separate from the observable baryonic matter.

If Clowe et al. (2006) have indeed detected dark matter in virtue of *locating* it, what exactly is it that has been detected? Obviously, they have not detected a dark matter particle. Instead, they have detected an entity that interacts gravitationally, is electromagnetically neutral, non-baryonic, acts like a collisionless fluid, and plausibly slow-moving. We know that it is electromagnetically neutral and non-baryonic because our electromagnetic detector (X-Ray telescope) located the vast majority of baryonic mass separate from the location required to account for the observed gravitational lensing. We also know that this 'dark' matter must act like a collisionless fluid because if it did not it would have been prevented from traveling to the location responsible for the lensing. We now have an empirically determined description of the term 'dark matter' that matches the properties of the entity as provided by our best model. If this is right, then we have detected the entity described by the model and therefore have a plausible empirical confirmation of dark matter.

Before taking this fully on board, I need to consider the two available critical responses from Vanderburgh (2014) and Sus (2014). Vanderburgh (2014) largely concedes the point of detection in terms of location while arguing that this neither resolves his dark matter double bind nor is sufficient to establish the reality of dark matter. As he says, "the point is not to 'detect' or 'locate' dark matter…What is at stake is determining the *nature* as well as the existence of dark matter, since understanding its nature is the likely route to devising potential direct detections of dark matter that would confirm its reality" (164, emphasis in original). On the first point, Vanderburgh is right – the reliance on EEP certainly does not conclusively vindicate the entirety of GR. However, this is not the goal of detection and so is not relevant to my arguments here.

On the second point, Vanderburgh assumes, as described above, that a particle detection is the only route to confirming that dark matter exists whereas detections via gravitational lensing are insufficient. But this begs the question by presupposing that the only kind of viable confirmation is via particle detection. The important thing to note is that despite Vanderburgh's criticism he concedes the point of detecting dark matter in a limited sense. This limited sense is solely the location of the dark matter, since EEP on its own cannot establish how much dark matter there is. But if I am right then this is all we need to empirically confirm the entity in question. Establishing the location gets us the identifying markers that we can match to the kind-constitutive properties of dark matter as described by the model. If we do not presuppose the need for a specific particle and take the model's concept at face value, these properties are all we need.

For his part, Sus (2014) denies even the limited progress acknowledged by Vanderburgh. He argues that it does not follow from a commitment to EEP that the Bullet Cluster demonstrates a location populated by dark matter. He argues that since *in principle* there could be such a metric that matches the Bullet Cluster observations without requiring dark matter as determined by theories like GR, we cannot infer that *all* proposed metric theories will require dark matter in roughly the same location identified by GR. In practice, however, there is no compelling alternative view that has been able to get around relying on some sort of dark matter in the case of the Bullet Cluster. TeVeS – the most promising alternative theory at the time of Sus's publication (and the one Sus himself tentatively endorses) – is not currently seen as a viable option. Vanderburgh (2014) himself suggests that Sus is overreaching in his suggestion that alternatives without any dark matter are currently viable options, claiming that "it would seem imprudent to say that this is more than a mere possibility" and that Sus "seems to give too much credence to the MONDian possibility of dark fields" (65). Positing dark fields to replicate the phenomenon necessary to account for insufficient baryonic mass is also not in principle a way of avoiding the central problem.[47] Even if such dark fields did exist, this could still be a vindication of dark matter, depending on the properties of these fields. Since the astronomical definition of dark matter does not require it to be a particle, models that include dark fields or other sources of gravity distinct from baryons still would fit the necessary properties of dark matter. The fact that these possibilities are not matter is irrelevant.

Furthermore, even if TeVeS was sufficiently close to reproducing the Bullet Cluster results without dark matter, it would not follow that it is a viable theory. Sus argues that we need to determine whether *every* viable alternative to GR requires dark matter to produce the same results as Clowe et al. (2006). But this is not quite right – the demand on a proposed alternative theory of gravity is not just to reproduce localized results but also to match the observations of various independent phenomena that *any* viable theory of gravity must explain. The various MONDian alternatives thus far also fail in explaining the other large-scale phenomena any viable options would be on the hook to explain (Massimi 2018). This broader failure is more instructive than possible local successes. Finding an empirically adequate solution to some local scientific problem can often be achieved by contriving a theory that matches observations of the phenomenon in question. The ability to produce such locally viable

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[47] Thanks to Douglas Clowe for pointing this out to me.

solutions is on its own perhaps interesting and resourceful, but a theory's overall viability is borne out by how well it matches other independent observations reliant on the same theory and how well it makes predictions for novel phenomena.

For a related and notable example, Hall's hypothesis, proposed by Arthur Hall (1894), was a modification to Newton's law of gravity that sought to explain the anomalous perihelion of Mercury before Einstein's GR solved the problem. In Newton's law of universal gravitation, the force of gravity is proportional to the inverse square of the distance between two objects ($1/r^2$). Hall replaced this with $1/r^{(2+\delta)}$, where some very slight adjustment to the radius vector accounts for the advance of Mercury's perihelion. Hall's calculations (1894) and later Newcomb's (1895) found that however contrived, just barely tweaking the proportion by setting $\delta = 0.0000001574$ would do the trick. This was unattractive because most believed it to be highly unlikely that such an 'ugly law' could be true (Earman and Janssen 1993). More importantly, as noted by the astronomer Willem de Sitter (1913), the problem was that such an ad hoc modification for Mercury's orbit resulted in problems and contradictions elsewhere, including calculations for the motion of the Moon's perigee. De Sitter's resistance to accepting Hall's hypothesis was that although it may be a good *working* hypothesis to find a theory that accurately matches one prominent instance of observational data, accepting any theory requires investigating whether it can be applied beyond the initial scope for which it was developed. Even when a theory is confined to a certain scale, it must still be scrutinized with respect to the kinds of predictions it generates for other phenomena that would rely on the same theoretical foundation. Alternative theories of gravity fail at large scales not because they cannot be tweaked to account for some of the evidence, but because they systematically fail to account for the full diversity of observational evidence.

The upshot of all this is that if indeed we have detected the location of dark matter, what we have detected is a set of properties that sufficiently match the properties of dark matter as described by our best cosmological model. If a plausible realism about dark matter requires empirical confirmation, then I claim that this detection provides the necessary evidence.

4. Conclusion: The (Realistic) Future of Dark Matter

Optimism about a realist stance about dark matter is linked to what Psillos (2012) calls the ‘tracking requirement’: “a theoretical term *t* must track its referent” (226) throughout the development and evolution of scientific theories and models. As scientific investigation in astrophysics and cosmology progresses, reidentification of dark matter, acquisition of further information about dark matter, and a better understanding of how dark matter fits into our best theories and models all will build on the core identifying description provided for dark matter in our best current scientific account. Satisfaction of the tracking requirement, and therefore the possibility of realism, depends on whether the referent of the term ‘dark matter’ retains its core identifying properties throughout the ongoing process of scientific investigation and theory development.

Here I have argued that the combination of the extensive explanationist successes of ΛCDM and the plausible detection of dark matter via gravitational lensing should give make us confident in the core identifying properties of dark matter and the satisfaction of the tracking requirement. Concerns about the thinness of the core causal description are misplaced. Especially in the early stages of scientific inquiry, as theories and models are regularly being tweaked and improved in light of ongoing experimental and theoretical work, it is normal to have the core identifying properties provide a limited but nonetheless unique description. Uniqueness is established in the case of dark matter because none of the known entities in the relevant theories can account for the indispensable causal role the theoretical entity plays in the phenomena of interest.

It may of course turn out that the ΛCDM model is substantively changed in the future or that 'ugly solutions' – the need for both dark matter *and* modifications to GR – are necessary.[48] But the successful reference of the term 'dark matter' will not depend on the *overall* success of ΛCDM. ΛCDM already faces a number of well-known challenges that may well require important changes or additions to the model's key features (De Baerdemaeker and Boyd 2020). However, given today's evidence, we should expect that any future models will continue to include some form of dark matter as an indispensable component.

If this is right, then this has one additional major upshot. The existence of dark matter resolves a central and persistent debate in astrophysics and cosmology. The most prominent

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[48] On these "ugly solutions" see Vanderburgh (2003; 2014).

alternative to ΛCDM is called Modified Newtonian Dynamics (MOND). The standard version of MOND seeks to avoid the posit of dark matter by modifying Newton's acceleration law at the scale of galaxies (Milgrom 2020). This modification successfully avoids the mass discrepancy issue discovered in rotation curves as well as some other discrepancies at galactic scales (Massimi 2018). The persistence of MOND as a viable alternative is based on these galaxy scale successes. However, this success is only possible if there is no such thing as dark matter. If dark matter has indeed been detected, then MOND cannot be viable for the simple fact that its adjustments to Newton's laws only work if the mass of the relevant systems is fully accounted for by luminous objects. For now, MOND continues to enjoy significant consideration in the philosophical literature (e.g., McGaugh 2015; Massimi 2018; Merritt 2020). If dark matter exists, this should change. This will be the case even if turns out that some sort of alternative theory of gravity at large scales becomes necessary or viable, since even these models will have to incorporate dark matter. Debates about ΛCDM and the possibility of alternative gravity will continue, but the existence of dark matter seriously undermines the viability of standard versions of MOND.

My strategy in this paper has been to show that the available thin concept of dark matter provided by ΛCDM, and one that makes no claims about particles, is not too thin. In fact, it provides just enough meat on the conceptual bones to pick out a unique referent that plays the essential causal role in our best cosmological models. Furthermore, the properties picked out by *this* concept have been plausibly empirically detected via gravitational lensing analysis of galaxy cluster collisions (Clowe et al. 2006; Kosso 2013). Since standard accounts of scientific realism require empirical confirmation of theoretical entities, and since dark matter plays an indispensable role in the wildly successful ΛCDM model, realism about dark matter is a plausible view.

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