Synthese (2024) 204:82
https://doi.org/10.1007/s11229-024-04728-3

ORIGINAL RESEARCH

Realism and the detection of dark matter

Eugene Vaynberg[1]

Received: 19 July 2023 / Accepted: 26 July 2024

Abstract
A number of philosophers 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.

Keywords Philosophy of science · Realism · Dark matter · Cosmology

1 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” (Allzén, 2021, p. 155). Evidence for its existence is indirect, based on observations of other astrophysical phenomena (Jacquart, 2021a). 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 (Allzén, 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

---

✉ Eugene Vaynberg
eugenev@sas.upenn.edu

[1] Department of Philosophy, University of Pennsylvania, Claudia Cohen Hall, Room 433, 249 S. 36th Street, Philadelphia, PA 19104-6304, USA

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). Such a detection has yet to occur.

Although empirical detection of dark matter would indeed provide justification 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 (Merritt, 2021), we should instead look to see whether this non-particle concept has been empirically detected. Assessed in this way, detections of dark matter via gravitational lensing provide empirical confirmation. Thus, realism about dark matter does not rely solely on explanatory successes of ΛCDM and such a detection should be seen as sufficient to justify a realist attitude toward dark matter.

This paper proceed as follows. In Sect. 2, I describe the challenges in attempting to obtain confirmation of dark matter and conclude that realism about dark matter requires an empirical detection of dark matter. In Sect. 3, I use Psillos's (1999) causal-descriptive theory of scientific reference to obtain a minimal concept of dark matter that identifies the properties of dark matter that do need to be detected. In Sect. 4, I argue that the experiment by (Clowe et al., 2006) on the Bullet Cluster collision of galaxy clusters achieves a detection of these properties and thus provides the necessary empirical detection of dark matter to justify realism about it. I make concluding remarks in Sect. 5.

2 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 (Jacquart, 2021a; Massimi, 2018). 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%.[1]

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

---

[1] 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).

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.[2] 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 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 (Merritt, 2021).[3] 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.[4] 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. 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 of GR.

Attempts at empirically testing the accuracy of GR on large scales is problematic because it 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

---

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

[3] 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.

[4] There are studies that provide evidence in favor of the accuracy of GR at large scales (e.g., Collett et al., 2018; Reyes et al., 2010). 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.

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 qualify as an empirical detection of dark matter.

Because of this, the argument for the existence of dark matter is instead 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 in the sense that there is no detection of dark matter itself. 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 via detection of the entity in question. For the purposes of this paper, I assume that we require 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 standard GR-mediated empirical detection can provide evidence that is strong enough for an empirical confirmation of dark matter. The alternative is thus to turn to detecting 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 & Green, 2010). Evidence obtained without the invocation of gravity would be taken to provide an independent, and presumably more convincing, path to realism about dark matter.

Ultimately, the consequence of all this appears to be that if gravity-mediated detection is insufficient, then it leaves us no choice but to look for particles. 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 of dark matter. 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. To sum up: we need a detection of dark matter, but not via detecting a dark matter particle. How this is to be done is discussed next.

3 Realism about dark matter

So far, I have said that empirical detection of dark matter is a necessary condition for a plausible realism about it but denied that this 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's (1999) causal-descriptive theory of scientific reference for theoretical terms given its stature among contemporary theories of scientific reference (e.g., Allzén, 2021; Merritt, 2021).

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 particle (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. We can use these constraints to articulate a core causal description. Note that this description will neither specify mass nor velocity. Mass is not specified since ΛCDM only provides a *total* proportion of the cosmos’s mass purported to be constituted by dark matter. This would not tell us about any local case of dark matter. Velocity will not be specified because different possible types of dark matter differ in their theoretical velocities, none of which undermines the causal role dark matter uniquely plays in the phenomena of interest. 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, this provides a way to articulate the relevant kind-constitutive properties that currently form the core causal description associated with the term ‘dark matter’: (a) non-baryonic and electromagnetically neutral, (b) interacts gravitationally (acts like a collisionless fluid).

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 unique 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.[5] 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).[6] 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.

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

---

[5] It would also be consistent with non-cold versions of dark matter, since any type of dark matter would have to satisfy the above kind-constitutive properties.

[6] 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.

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 & 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.[7]

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

---

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

of possessing a set of kind-constitutive properties—those properties that collectively make an entity belong to a kind.[8]

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).[9] 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 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, p. 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.[10]

---

[8] I follow Psillos (1999, p. 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.

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

[10] It is true that most scientists believe that dark matter is of a particle nature. It may thus still seem odd to suggest that one can be a realist about an entity where, on the one hand, most agree that it has some property and, on the other hand, the specification of this property is irrelevant to substantiate its existence. However, it is important to distinguish between what is minimally necessary to confirm that some entity exists and that what is necessary to confirm that the entity is of a certain type. The former does not require

If the suggested causal description of dark matter is of a legitimate Goldilocks variety, it is an important step 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.[11] 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.

4 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 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.

Footnote 10 continued
as robust of a description of the entity as the latter. If the realist is correct, the existence of dark matter will persist independently of whether it ultimately turns out to be a particle—I take this to be a welcome result. I thank an anonymous reviewer for pressing me on this issue.

[11] 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.

Gravitational lensing is a phenomenon that arises because of the deflection of light by large masses.[12] 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.[13] 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 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, Kosso's claim is that dark matter detection in these cases relies solely on the Einstein equivalence principle (EEP) and its central role in all metric theories of gravity. Any theory of gravity that includes the EEP is a metric theory (Will, 1993). 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. And, since *any* viable theory of gravity requires that EEP be true (Kosso, 2013; Vanderburgh, 2014), we are justified in taking these results at face value.[14]

The fact that the path of light is affected by massive objects 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 light. If, as both Kosso (2013) and Vanderbugh (2014) agree, the results of

---

[12] 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).

[13] 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).

[14] A good technical overview of EEP, including details of its empirical tests, is in Will (1993). I do not go into extra detail on the EEP here because the relevant results—that theories of gravity must be metric theories, is sufficient to obtain the results I am looking for. For the necessity of the EEP, I defer to the claims established by Kosso (2013) and Vanderburgh (2014).

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 et al., 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.[15] 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, p. 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, p. 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 the mass that would be necessary for the observed light distortions is located elsewhere. Kosso (2013) offers a helpful analogy to describe this:

---

[15] 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.

> “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 match is correct, 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 an objection from Sus (2014). Sus’s main argument is that it does not follow from a commitment to EEP that the Bullet Cluster demonstrates a location populated by dark matter. He argues instead that since *in principle* there could be such a metric that matches the Bullet Cluster observations without requiring dark matter, we cannot infer that *all* proposed metric theories will require dark matter in roughly the same location as identified by GR. Alternative theories of gravity to GR, using different metrics, could theoretically replicate the observations. While perhaps technically true, in practice the story is not so promising. There are several alternative theories of gravity to GR developed to avoid the posit of dark matter. The most prominent is Modified Newtonian Dynamics (MOND) originally developed by Mordehai Milgrom (1983). MOND was designed specifically to account for the apparent missing mass in galaxies as determined by GR via an adjustment in Newton’s acceleration law (Massimi, 2018). Sus (2014) tentatively endorses the Tensor-vector-scalar theory of gravity (TeVeS), a more recent and more promising theory that builds on MOND. However, as Vanderburgh (2014) points out, there is no compelling alternative view, including TeVeS, that has been able to get around relying on some sort of dark matter in the case of the Bullet Cluster. Vanderburgh (2014) suggests that Sus is overreaching in his suggestion that alternatives like TeVeS 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 is intended to replace standard conceptions of dark matter but is ultimately not in principle a way of avoiding the central problem.[16] This is because even if it was the case that such dark fields did exist, it could still be a vindication of dark matter. Since, as has been central to my arguments, 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 in the traditional sense 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 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 et al., 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

---

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

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.

5 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. My claim is that 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, will depend on whether the referent of the term 'dark matter' retains its core identifying properties throughout the ongoing process of scientific investigation and theory development.

Why should we think this will be the case? 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 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.[17] 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 I am right about the reality of dark matter, then this has one additional major upshot. The existence of dark matter might help to make progress on an ongoing debate in astrophysics and cosmology. As mentioned, the most prominent alternative

---

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

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). Despite limited supporters in the scientific community, MOND continues to enjoy significant consideration in the philosophical literature (e.g., McGaugh, 2015; Massimi, 2018; Merritt, 2020). The persistence of MOND as a viable alternative is based on these galaxy scale successes and on the claim that there is no dark matter enveloping those galaxies. If dark matter has indeed been detected, then MOND must be responsive to this fact. It puts extra pressure on MOND to explain how its explanation of phenomena at the scale of galaxies can be justified given the detection of dark matter in galaxy cluster collisions. This demand on MOND is independent of whether in general some other alternative theory of gravity at large scales will eventually turn out to be correct. Debates about ΛCDM and the possibility of alternative gravity will continue, but the existence of dark matter seems to me to seriously undermines the viability of standard versions of MOND and its role in contemporary debate.

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.

Acknowledgements I am grateful to Michael Weisberg for his insights and comments on multiple drafts of this paper. I also thank Douglas Clowe, Barry Madore, Quayshawn Spencer, Lisa Titus, and three anonymous reviewers for their helpful comments, questions, and suggestions.

Funding No funding was received to assist with the preparation of this manuscript.

Declarations

Conflict of interest The author has no competing interests to declare that are relevant to the content of this article.

References

Abuter, R., Amorim, A., Bauböck, M., Berger, J. P., Bonnet, H., Brandner, W., Cardoso, V., Clénet, Y., de Zeeuw, P. T., Dexter, J., Eckart, A., Eisenhauer, F., Förster Schreiber, N. M., Garcia, P., Gao, F., Gendron, E., Genzel, R., Gillessen, S., Habibi, M., … Zins, G. (2020). Detection of the Schwarzschild precession in the orbit of the star S2 near the galactic centre massive black hole. *Astronomy & Astrophysics, 636*, L5.

Allzén, S. (2021). Scientific realism and empirical confirmation: a puzzle. *Studies in History and Philosophy of Science Part A, 90*, 153–159.

Anderl, S. (2018). Simplicity and simplification in astrophysical modeling. *Philosophy of Science, 5*, 819–831.

Bertone, G., & Hooper, D. (2018). History of dark matter. *Reviews of Modern Physics, 90*(4), 045002.

Bertone, G., Hooper, D., & Silk, J. (2005). Particle dark matter: evidence, candidates and constraints. *Physics Reports, 405*(5–6), 279–390.

Boyd, R. N. (1983). On the current status of the issue of scientific realism. *Erkenntnis, 19*(1), 45–90.

Cerdeño, D. G., & Green, A. M. (2010). Direct detection of WIMPs. In G. Bertone & D. Hooper (Eds.), *Particle dark matter: observations, models and searches* (pp. 347–369). Cambridge: Cambridge University Press.

Chakravartty, A. (2017). Scientific realism. In: *The Stanford encyclopedia of philosophy,* Edward Zalta (ed). https://plato.stanford.edu/archives/sum2017/entries/scientific-realism.

Clowe, D., Bradač, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., & Zaritsky, D. (2006). A direct empirical proof of the existence of dark matter. *The Astrophysical Journal, 648*(2), L109.

Collett, T. E., Oldham, L. J., Smith, R. J., Auger, M. W., Westfall, K. B., Bacon, D., Nichol, R. C., Masters, K. L., Koyama, K., & van den Bosch, R. (2018). A precise extragalactic test of general relativity. *Science, 360*(6395), 1342–1346.

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

De Sitter, W. (1913). The secular variations of the elements of the four inner planets. *Observatory, 36*, 296–303.

De Swart, J. G., Bertone, G., & van Dongen, J. (2017). How dark matter came to matter. *Nature Astronomy, 1*(3), 0059.

Dellsén, F. (2019). Should scientific realists embrace theoretical conservatism? *Studies in History and Philosophy of Science Part A, 76*, 30–38.

Earman, J., Janssen, M., & Norton, J. D. (Eds.). (1993). *The attraction of gravitation: new studies in the history of general relativity* (Vol. 5). Berlin: Springer.

Ellis, R. S. (2010). Gravitational lensing: a unique probe of dark matter and dark energy. *Philosophical Transactions of the Royal Society a: Mathematical, Physical and Engineering Sciences, 368*(1914), 967–987.

Gates, E. (2010). *Einstein's telescope: the hunt for dark matter and dark energy in the universe*. WW Norton & Company.

Hall, A. (1894). A suggestion in the theory of Mercury. *The Astronomical Journal, 14*(7), 49–51.

Hamilton, J. C. (2014). What have we learned from observational cosmology? *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 46*, 70–85.

Jacquart, M. (2021a). Dark matter and dark energy. In E. Knox & A. Wilson (Eds.), *Routledge companion to philosophy of physics.* New York: Routledge.

Jacquart, M. (2021b). ΛCDM and MOND: a debate about models or theory? *Studies in History and Philosophy of Science Part A, 89*, 226–234.

Kosso, P. (2013). Evidence of dark matter, and the interpretive role of general relativity. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 44*(2), 143–147.

Martens, N. C. M. (2022). Dark matter realism. *Foundations of Physics, 52*(1), 1–19.

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

McGaugh, S. S. (2015). A tale of two paradigms: the mutual incommensurability of ΛCDM and MOND. *Canadian Journal of Physics, 93*(2), 250–259.

Merritt, D. (2020). *A philosophical approach to MOND: assessing the milgromian research program in cosmology*. Cambridge University Press.

Merritt, D. (2021). Cosmological realism. *Studies in History and Philosophy of Science Part A, 88*, 193–208.

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

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

Mo, H., Van den Bosch, F., & White, S. D. (2010). *Galaxy formation and evolution*. Cambridge University Press.

Newcomb, S. (1895). *The elements of the four inner planets and the fundamental constants of astronomy*. U.S. Govt. Printing Office.

Psillos, S. (1999). *Scientific realism: how science tracks truth*. Routledge.

Psillos, S. (2012). Causal descriptivism and the reference of theoretical terms. In A. Raftopoulos & P. K. Machamer (Eds.), *Perception, realism, and the problem of reference* (pp. 212–238). Cambridge: Cambridge University Press.

Reyes, R., Mandelbaum, R., Seljak, U., Baldauf, T., Gunn, J. E., Lombriser, L., & Smith, R. E. (2010). "Confirmation of general relativity on large scales from weak lensing and galaxy velocities. *Nature, 464*(7286), 256–258.

Skordis, C. (2009). The tensor-vector-scalar theory and its cosmology. *Classical and Quantum Gravity, 26*(14), 143001.

Smeenk, C. (2013). Philosophy of cosmology. In R. Batterman (Ed.), *The Oxford handbook of philosophy of physics* (pp. 607–652). Oxford: Oxford University Press.

Sus, A. (2014). Dark matter, the equivalence principle and modified gravity. *Studies in History and Philosophy of Science Part b: Studies in History and Philosophy of Modern Physics, 45*, 66–71.

Vanderburgh, W. L. (2003). The dark matter double bind: astrophysical aspects of the evidential warrant for general relativity. *Philosophy of Science, 70*(4), 812–832.

Vanderburgh, W. L. (2014). On the interpretive role of theories of gravity and 'Ugly' solutions to the total evidence for dark matter. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 47*, 62–67.

Will, C. M. (1993). *Theory and experiment in gravitational physics*. Cambridge University Press.