Studies in History and Philosophy of Modern Physics 47 (2014) 62–67

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

On the interpretive role of theories of gravity and ‘ugly’ solutions to the total evidence for dark matter

William L. Vanderburgh

Department of Philosophy, Wichita State University, Wichita, KS 67260-0097, USA

ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form
20 May 2014
Accepted 24 May 2014
Available online 19 June 2014

Keywords:
Dark matter
General relativity
Theory testing
Confirmation
Underdetermination

ABSTRACT

Peter Kosso (2013) discusses the weak gravitational lensing observations of the Bullet Cluster and argues that dark matter can be detected in this system solely through the equivalence principle without the need to specify a full theory of gravity. This paper argues that Kosso gets some of the details wrong in his analysis of the implications of the Bullet Cluster observations for the Dark Matter Double Bind and the possibility of constructing robust tests of theories of gravity at galactic and greater scales. Even the Bullet Cluster evidence is not sufficiently detailed to allow precision tests of General Relativity that would distinguish it from its rivals at galactic and greater scales. Taking into account the total evidence available, we cannot rule out “ugly” solutions to the dynamical discrepancy in astrophysics that involve *both* a large quantity of dark matter and a theory of gravity whose predictions differ significantly from those of General Relativity for interactions taking place at galactic and greater scales.

1. Introduction: Dark matter and philosophy of science

One of the most significant open problems in the contemporary physical sciences is commonly called “the dark matter problem” but can more accurately be referred to as “the dynamical discrepancy in astrophysics.” Multiple lines of evidence point to the conclusion that the observed motions within galaxies, clusters of galaxies and larger systems cannot be adequately accounted for by the combination of the visible matter within those systems plus the most widely accepted theory of gravity, General Relativity (GR). Looking just to the dynamical evidence derived from the motions within galaxies and clusters of galaxies (neglecting for present purposes strictly cosmological or any other reasons to hypothesize large quantities of matter in the universe in addition to what can be optically detected), scientists are faced with a stark choice: Either there is 10–100 times more mass present than is visible in these systems and it is in some hitherto-unknown type of matter, or it must be that an otherwise highly confirmed theory, GR, needs to be significantly overhauled.

On the first option for resolving the dynamical discrepancy, the exotic matter in question is called “dark” because one of the only things we know about it is that it neither emits nor absorbs electromagnetic radiation. This means it cannot be the ordinary baryonic matter (composed of protons and neutrons) with which we are familiar from all of our ordinary experience. Candidates proposed to be the dark matter have ranged from black holes to new fundamental particles. Almost all such candidates have been ruled out on empirical or theoretical grounds, and those that are as yet not eliminated have almost no positive empirical support despite nearly 40 years of serious efforts to describe and detect dark matter. The most popular open matter solutions involve Weakly Interacting Massive Particles (WIMPs)—that is, particles that interact with other matter only through gravity and the weak nuclear force.

Although the vast majority of physicists and astronomers prefer a matter solution to the dynamical discrepancy in galaxies and larger structures, to some it has seemed methodologically and metaphysically undesirable that we should—in an *ad hoc* response to a very significant and unexpected empirical discrepancy—hypothesize vast quantities of matter of an exotic, unknown and more or less unobservable type without any other independent theoretical or empirical motivation to do so. For this reason a few attempts have been made to describe alternative theories of gravity that are predictively equivalent to GR at roughly solar system and shorter scales, but which are able to account for the

E-mail address: william.vanderburgh@wichita.edu

http://dx.doi.org/10.1016/j.shpsb.2014.05.008
1355-2198/

observed motions in galaxies and clusters without the need for dark matter. Most notable among these attempts have been: the Modification of Newtonian Dynamics (MOND) developed by Milgrom (1983, 2010); MOND's relativistic version, namely Bekenstein's (2004, 2011) Tensor–Vector–Scalar gravity (TeVeS); and Mannheim's (2012) Conformal Theory of Gravity.

Since GR is highly confirmed for all systems about which we have detailed evidence, in order to be viable at all any alternative theory of gravity must be empirically indistinguishable from GR within the margin of error in the current observations for those systems. This is to say that possible deviations from GR's predictions are highly constrained within systems that are roughly the size of a solar system or smaller, since those are the systems for which we have detailed precision tests of GR. (Vanderburgh (2003, 814–815), makes this case in detail.)

To take one example of how an alternative theory of gravity fits within these evidential constraints, consider Milgrom's version of MOND. MOND holds that the action of gravity deviates from the predictions of GR below a certain threshold of acceleration. Although this empirical difference is predicted by MOND regardless of scale, in practical physical situations MOND only becomes observationally distinguishable from the Newtonian limit of GR at very large distances, much larger than a solar system. There is room for MOND at these scales both because such distances are required to get the very weak acceleration fields in which MONDian effects appear, and since the empirical constraints on the action of gravity are much looser at these scales since precision tests are not available. MOND's biggest empirical success is that it can reproduce the qualitative form of the observed rotation curves for spiral galaxies without the need for dark matter; similarly, it predicts motions within clusters that are similar to those observed, but requiring much less unseen mass than analyses that use the Newtonian limit of GR. Note that some attempts to devise viable comparative tests of MOND *versus* GR at less-than-galactic (but still incredibly large) scales have involved velocity dispersions within globular clusters, which are compact agglomerations of hundreds of thousands of stars that orbit parent galaxies. Scarpa, Marconi, Carraro, Falomo, and Villanova (2011), for example, find velocity dispersions in globular clusters that resemble those in elliptical galaxies. In both types of systems the velocity dispersions are constant beyond a given radius, contrary to what would be expected given the visible distribution of matter within them and the predictions of the Newtonian limit of GR. They speculate that this similarity might have a common origin, possibly a breakdown of Newtonian dynamics below the MOND acceleration threshold, but they acknowledge at the end of their paper that this would actually contradict MOND's original predictions for globular clusters, in which the acceleration field of the parent galaxy should be at or above the acceleration limit. If the observed velocity dispersions are in fact a result of an acceleration threshold effect, the standard explanation of elliptical galaxies' velocity dispersions in terms of dark matter haloes is incorrect. As of now this remains an unproven possibility.

Perhaps because of the sorts of sociological and institutional factors López-Corredoira (2014) identifies as operating in the discipline of cosmology—factors that over-emphasize the epistemological status of "received views" and function to effectively prevent non-standard theories from getting significant attention or being developed—gravitational alternatives to dark matter are generally not well-regarded in the community of physical scientists. In fact, however, as will be discussed below in more detail below, on the evidence available the standard "GR+DM" paradigm for addressing the dynamical discrepancy in galaxies and larger systems is observationally indistinguishable from non-standard models of "alternative gravity with only ordinary matter." In the current evidential situation, reasons for preferring one class of solutions over the other must be extra-empirical. It is plausible that this is due in part to the underdevelopment of both the evidence and the theoretical constructs: as scientists gather more evidence and find new ways to deploy it, and as they flesh out the details of the competing theories, it could well turn out that some of the current competitors will cease to be viable.

In the interests of full disclosure, let me remark that my own preference is for a matter solution to the dynamical discrepancy. However, it also seems to me that in order to eventually establish any such solution we will need to provide as objective an analysis of its epistemic status as possible. My own evaluation of the current evidential and theoretical context leads me to the conclusion that there is insufficient warrant to be confident in any particular class of solutions (let alone any particular solution). Opinions aside, what is of genuine general philosophical interest is that the dark matter case presents a very intriguing study of the nature of scientific reasoning.

Indeed, the study of dark matter is a very fertile ground for historians and philosophers of science in many ways. The subject is only just beginning to receive the attention it deserves. Dark matter raises a host of philosophical issues in new ways or in especially interesting contexts—evidential reasoning, scientific methodology, confirmation, explanation, unification, theory choice, underdetermination, limits to what is knowable, paradigm shifts, natural kinds, and unobservable entities are just a few of the sorts of issues that historians and philosophers of science could profitably approach through attention to dark matter. Among the works that have begun to give philosophical attention to dark matter are, for example, Hamilton (2013), Hudson (2007, 2013), Minasyan (2008), and Zinkernagel (2002). (Hamilton (2013, 7–10), includes a good summary of the current state of the evidence relating to dark matter. For an astronomer's perspective on the history of and evidence for dark matter, see Trimble (1987, 2013)).

Kosso (2013) is another entry in this burgeoning field of philosophical studies of dark matter. Kosso's main point is to extend the discussion of an apparent limitation on the empirical testability of gravitation theories that was raised in Vanderburgh (2003). In what follows I analyze Kosso's arguments and some related issues, ultimately concluding that Kosso's main point is uncontentious but not very contentful, and that the evidential status of theories of gravity at galactic and greater scales is changed very little by the observations of weak gravitational lensing in the Bullet Cluster that inspired Kosso's contribution. Sus (2014) also comments on Kosso (2013), and I critique various aspects of that piece along the way as well.

2. Implications of dark matter for testing alternative theories of gravity

Peter Kosso (2013) draws attention to the results of Clowe et al. (2006) regarding the Bullet Cluster. X-ray maps of the density of hot gas compared to density maps derived from weak gravitational lensing of background objects by the Bullet Cluster reveal that the two centers of mass of the baryons (hot gas) are not co-located with the two centers of mass of the cluster as a whole. This is interpreted as the consequence of a collision of two sub-clusters of galaxies in which the hot gas from the two interacted and slowed while their component galaxies and dark matter halos passed through each other without frictional braking. This result is widely taken to be a new *kind* of evidence for dark matter, and certainly the most direct proof available of the existence of dark matter. Since the other kinds of evidence for dark matter have already been discussed in detail in the other works cited above, in my comments below I will follow Kosso in focusing solely on the new implications of the Bullet Cluster evidence for dark matter and the testing of gravitational theories.

Kosso uses the Bullet Cluster evidence as a springboard to argue that

> Vanderburgh's (2003) double bind is worth a closer look, because it highlights where more detail on the interpretive role of GTR is needed. Testing a theory of gravity require[s] knowing the distribution of masses in the system. But, since dark matter can only be detected by its gravitational effects, the only way to know the distribution of masses—if some of it is dark matter—is by using a theory of gravity, presumably the one being tested. What needs to be clarified is just *how* the theory of gravity is used to locate the dark matter. More specifically, what part of the theory is used? It will turn out… that in at least one special case, the only aspect of GTR that has this interpretive role is an aspect it has in common with all currently viable theories of gravity. The interpretive work is not done by GTR, *per se*, but by the more basic principle of equivalence (Kosso, 2013, 145).

Kosso goes on to describe the fact that the equivalence principle, which is common to all metric theories of gravitation, is all that is needed to produce gravitational lensing (the bending of the path of light by a massive object). Since all viable theories of gravity are metric theories, it follows that the equivalence principle, and not any more fully-fleshed-out theory of gravity, is all that is needed to detect the existence of dark matter in certain gravitational lensing situations. This is an important detail to add to the discussion.

Note, however, that in studies that attempt to address the dynamical discrepancy in astrophysics, the point is not to "detect" or "locate" the dark matter. Numerical simulations of galactic stability and various observations already quite clearly establish that if dark matter exists it is distributed in roughly spherical halos around galaxies and clusters of galaxies. 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. To have some hope of determining what dark matter is, it is likely that we will first need to know how much of it there is. The total mass of dark matter and the precise ways in which it is distributed at various scales are key parts of the evidence for trying to figure out which dark matter candidates are viable and which are not. In this respect Kosso's conclusion that we can (merely) detect dark matter using the equivalence principle alone without needing to invoke an entire theory of gravity, while correct and interesting as far as it goes, does not really go very far. To do anything substantive in the way of resolving the dynamical discrepancy, or to begin to meaningfully compare rival gravitational theories at galactic and greater scales, requires much more than just the detection of dark matter that can be achieved with the equivalence principle by itself. To move from "detecting" to "measuring" dark matter does require invoking the specifics of a particular full theory of gravity.

In another reference to the dark matter double bind, Kosso writes, "detecting dark matter seems to require a reliable theory of gravity, since the hypothesized matter interacts only by way of the gravitational force…. [I]f we use GTR as the gravitational theory to detect dark matter we preclude the possibility of challenging GTR" (145). This is not quite an accurate way to describe the dark matter double bind. Here is how it was originally formulated:

> In order to evaluate the empirical adequacy of any gravitation theory at galactic and greater scales, the mass distribution in dynamical systems at those scales must first be known—but because of the astrophysical dynamical discrepancy the mass distribution is not known. In order to infer the mass distribution from the observed motions, a gravitational law must be assumed—but such a law cannot legitimately be assumed, since the very thing at issue is which gravitational law ought to be taken to apply at galactic and greater scales (Vanderburgh, 2003, 824).

The point here, again, is not about "detecting" dark matter. Rather, it is about acquiring a sufficient quantity and quality of information regarding the mass distributions in large scale systems so that we are then able to (a) conduct precision tests at those large scales which would (b) give us adequate warrant to accept one from among the potential rival gravitational theories. It is perfectly possible that we could successfully detect dark matter, in the sense of having sufficiently strong evidence to accept that it definitely exists, while at the same time still not having sufficient evidence to resolve the dark matter double bind. In that case, we might not have sufficient evidence to either determine the nature of dark matter or to test and hence empirically distinguish competitor gravitation theories. I contend that the possible evidential situation just described is rather similar to the actual evidential situation at the present time.

3. On the importance of considering the total evidence

As does Vanderburgh (2005, 1325–1326), Kosso (2013, 144) mentions the Uranus and Mercury discrepancies in Newtonian celestial mechanics which were resolved, respectively, through the successful conjecture of otherwise-unknown matter (Neptune) and the development of a new theory of gravity (GR). To view this analogy in a new way, note that even if GR had already been developed by the time the Uranus discrepancy was discovered we would still need Neptune, and of course the discovery of Neptune in fact did not contribute to the solution of the Mercury discrepancy. The solution for the *total evidence* for the solar system was new matter *plus* new gravity. It is possible that this way of describing things in the solar system is analogous to the situation we find ourselves in regarding the total evidence from the Bullet Cluster. We might need *both* dark matter *and* a new theory of gravity. At least, such a possibility cannot be ruled out—in fact, it is a possibility that has just as much warrant as the standard "GR+DM" does on the available evidence.

The observations of weak gravitational lensing in the Bullet Cluster indicate the presence of a large gravitational potential that is not co-located with the visible mass. The most obvious explanation of this is the existence of additional non-baryonic mass that is not associated with the visible mass. In other words, the total evidence from the combination of the visible light, X-ray and gravitational lensing observations indicates that there exists significant mass in addition to the visible mass that is directly detectable in the galaxies of the sub-clusters and in the hot gas ripped from them by the collision of the sub-clusters. Even though this is indeed a strong indication of the existence of dark matter, note that it does not tell us exactly how much dark matter there is in the system. What we learn from this result is that there is a gravitational field disturbing the images of background sources. Just how much mass must be present in order to create the observed gravitational deflection of the background light depends on which law of gravity correctly describes gravity at those scales.

Part of the reason we do not know more about the mass distribution in the Bullet Cluster is that the weak gravitational lensing calculations are subject to fairly large uncertainties. Even in the case of normal ("strong") gravitational lensing the calculation of the amount of mass causing the lensing effect is not very precise:

> Fairly large margins of error are present in lensing calculations because of the need to make assumptions that cannot be definitively checked observationally—including assumptions about the diameter of the lens, the shape of its overall mass distribution, its distance from us, and its distance from the background object (Vanderburgh, 2005, 1332–1333).

In the case of mass distributions derived from weak gravitational lensing such as we find in the evidence from the Bullet Cluster, the conclusions are even weaker:

> Interpreting the data from gravitational lensing is very complicated…. The light that is bent by the mass of the cluster comes from objects that are…off axis. This so-called weak lensing results in images that are only slightly distorted, stretched out instead of rotationally symmetric. And the use of multiple sources of light requires a complex statistical analysis to determine even the simplest information about the lens (Kosso, 2013, 147).

If it is correct that we *detect* the existence of dark matter thanks to the weak lensing in the Bullet Cluster, this is indeed a significant result. (But see the comment on Milgrom in the final section below.) The important issue then, though, would be how to infer the mass distribution from the image the light gives us after passing through the gravitational field of the cluster (including the total amount of mass as well as its three-dimensional distribution, not just its general density map in two dimensions across the line of sight). What is the margin of error in the lensing calculations? What assumptions about the lens are needed in order to make possible the inference from the image to the characteristics of the lens mass distribution? How sensitive are the images, and hence the inferences, to small changes in the assumptions or in the description of the initial conditions such as the angular separation between the source and lens, the mass and shape of the lens, and the distance of the background galaxy lensed? In short, making the precise mass calculation depends upon much more than just what we can learn using the equivalence principle by itself.

In his comment on Kosso, Sus (2014) makes a similar point. He argues that the equivalence principle does not indicate *where* the mass is in the case of observed lensing nor does it indicate exactly how much mass is present—the mere fact of "being a metric theory" does not tell us *how* mass shapes the metric in that theory. That depends on details of the theory.

In some speculative interpretations of TeVeS, it could even turn out that the contributions of the extra fields in the theory to the bending of light rays are responsible for weak lensing effects such as those observed in the Bullet Cluster. Note that this suggestion goes well beyond the original motivation of MOND, which was to account for astrophysical phenomena without the need for dark matter:

> Although there is nothing intrinsically inconsistent with having the new fields that mediate the modifications of gravity envisioned in MOND act as dark seeds of structure or dark concentrations of gravitational lensing, this necessity detracts from the cleanliness of the original MOND vision: What you see is apparently not what you get, even in MOND (Ferreira and Starkman, 2009, 815).

On the best available evidence and interpretations, MONDian theories now seem to require twice as much baryonic mass as is visible (in galaxies), a massive halo of otherwise undetected and unmotivated neutrinos (for ordinary clusters) and, in what could be judged the worst *ad hoc* move of all, otherwise undetected and unmotivated "dark field haloes" that have not even been shown to possibly arise naturally in the theory (to account for the weak lensing observations in the Bullet Cluster). So, while we may concede that "situations such as that arising in the Bullet Cluster in which gravitational lensing apparently locates some mass where no ordinary mass is detected might be interpreted as produced by ordinary mass that is simply located differently" (Sus, 2014, 70), it would seem imprudent to say that this is more than a mere possibility. It is a mere possibility, moreover, that has not really been shown to be viable—though neither has it been ruled out on available interpretations of available theories and data. A lot would depend on whether a proposed mechanism for generating such dark field haloes in cluster collisions or in some other way that would leave them behind in a cluster collision could also still account for the other astrophysical observations relevant to the dynamical discrepancy. These include the gravitation lensing of clusters, velocity distributions in clusters and elliptical galaxies and rotation curves in spirals galaxies, among others. We do not know, for example, whether a version of MOND in which dark fields form is still consistent with the MONDian explanation of the dynamics of various astrophysical systems. To this extent, Sus (2014) seems to give too much credence to the MONDian possibility of dark fields mentioned in Ferreira and Starkman (2009).

Of course, MONDian theories are not the only possible alternatives to GR; considerations about *ad hoc* dark fields would not be relevant to most of them.

To return to the main line of the argument, let me summarize the situation: Weak gravitational lensing is observed in the Bullet Cluster, and there is not sufficient baryonic mass in the region where the weak lensing is observed to account for the observed effects; hence *something* non-baryonic is causing that effect. It could be dark matter, or it could be a "dark field" whose possible existence has not really been established.

At most, then, weak gravitational lensing thus allows us to *detect* dark matter in the Bullet Cluster. Until we have a better account of the theory of gravity governing the weak gravitational lensing, we cannot infer sufficiently precise information from the weak gravitational lensing to *measure* the dark matter, and until we have a precise account of the matter distribution we cannot use the weak lensing results to comparatively test competing theories of gravity.

The upshot here is that saying we can detect the existence of dark matter is very different than saying the weak lensing allows us to measure the details of the mass distribution and know exactly how much dark matter is present, or even that it allows us to establish the precise ratio of visible to dark matter. When Kosso says, "To locate the lens we need only that part of the theory that says that light is bent by mass, and all viable metric theories agree on this" (147), he means that we learn the general pattern of the mass density map—more precisely, we learn the amount of the displacement of light from background objects, and then from that information plus other theories and assumptions we can infer the pattern of the mass density map. Next, we compare this derived mass density map with relatively straightforward observations of the matter in the cluster that is visible in various parts of the electromagnetic spectrum. Doing so, we find that the visible matter is distributed in a pattern that is not at all similar to that of the mass density map derived from the weak lensing. It follows that there must exist additional, non-visible mass in the cluster, the distribution of which is different than that of the visible (baryonic) mass. However, as Kosso admits, in order to go farther and determine the actual mass density of this newly detected matter—its total value, not just the general density profile—we would need to invoke a specific theory of gravity. Then, of course, the dark matter double bind applies to the Bullet Cluster just as it does to any other attempt to determine the mass distribution in large scale systems.

4. On "ugly" solutions

Given the foregoing, we must say that even in the case of the Bullet Cluster—in which we know there is dark matter—we cannot be sure *how much* dark matter there is exactly and, thus, we cannot perform precision comparative tests of GR against its rivals at the scales in question. It is possible, then, that there is dark matter in clusters *and* the correct law of gravitation for these systems is a successor to GR. This is the "ugly solution" Vanderburgh (2005, 1333) raises as a possibility in the context of related evidence that in some galaxies clouds of gas detected by X-rays have different orientations than do the visible masses, which is an indication that gas orientation mirrors the way the more massive dark halo is oriented. As is the case for the Bullet Cluster, these results indicate the real existence of dark matter but do not rule out revisions to GR because the *detection* of dark matter is not the same as a *measurement* of its total mass and distribution that would be sufficient to test GR and distinguish it from rival gravitational theories.

Note that despite the kinds of factors mentioned by López-Corredoira (2014) that tend to push out non-standard views, MOND-like theories are still earning journal space. Thus this sort of theory remains part of the conversation despite the fact that the majority of physicists and astronomers prefer a "dark matter plus GR" paradigm. It is true that MOND/TeVeS cannot get by entirely without additional matter even for standard clusters of galaxies (Bekenstein, 2011, 5006), let alone for the Bullet Cluster. However, the excess matter they require is on the same order as the known baryonic matter, rather than the 10–100 times more dark than visible matter that the standard GR paradigm requires. One could make the case that an "ugly" solution consisting of modified gravity plus a significantly smaller amount of unknown dark mass (and possibly also unknown dark fields) is methodologically preferable to a theory that requires the existence of a huge amount of extra mass that is unlike anything else we have ever before directly detected or had reason to think exists. If we are just doing *ad hoc* curve-fitting either way, where Occam's razor cuts would seem to be something of a matter of taste.

Sus (2014, 70) asks, "can we consider gravitational lensing to be evidence for DM; and if so, for precisely which hypothesis concerning DM?" The answers are *yes* and *none*. Sus does not carefully distinguish weak gravitational lensing (such as we have in observations of the Bullet Cluster) from other cases of gravitational lensing (such as we have from other clusters of galaxies). Apparently thinking of the latter, Sus writes, "It is possible…that this extra matter is made up of neutrinos and is located somewhere other than the center of the lens" (70). There are two problems here: First, in weak gravitational lensing there isn't really a "center" but rather an overall mass density distribution the parts of which are collectively responsible for the overall observed lensing effects; second, neutrinos have been ruled out as dark matter candidates because their features make them incompatible the formation of galactic structures, so that at most neutrinos constitute a small fraction of the total dark matter. The more general term "weakly interacting massive particles" (WIMPs) refers to the class of still-viable candidate dark matter particles.

5. Conclusion

Ultimately the point made in Vanderburgh (2003, 2005) still stands: The evidence at galactic and greater scales does not provide sufficient warrant to prefer GR over members of a class of rival gravitation theories. We would need to know the precise details of the mass distribution in such systems (including the total amount of mass present as well as its pattern of location) in order to conduct precision tests of GR at those scales, and we need to assume GR (or some other specific, well-developed theory of gravity) in order to be able to infer the precise mass distributions from the available observations. This is so even despite the fact that the Bullet Cluster and other observations now strongly indicate the existence of dark matter.

The "ugly" solutions may be the only open alternatives left to the standard GR+DM paradigm now that the "pure" alternative gravity solutions seem to be in doubt. Even so,

> Any non-standard gravitational force that points back to its source and scales with mass can't reproduce our lensing results without invoking preponderant concentrations of unseen matter. Our demonstration of dark matter doesn't preclude nonstandard theories of gravity, but it does remove their primary motivation. (Clowe as quoted in Schwarzschild, 2006, 24.)

This is so because of the large amount of mass that weak lensing reveals in places where there is no baryonic matter visible at all (no galaxies, no hot gas). This may be the most telling point against non-standard theories of gravity that the Bullet Cluster and similar results can offer. If we know for sure that dark matter exists, then introducing a non-standard theory of gravity no longer allows us to avoid the metaphysical profligacy of holding that there exist extraordinarily large amounts of matter of a hitherto-unknown type. However, Milgrom (undated) argues that there are still methodological benefits to minimizing the amount of this unknown stuff (even if we are forced to admit it exists) by introducing a non-standard action of gravity at large scales. I shall refrain from attempting to adjudicate that particular methodological debate here; there does seem, at least, to be genuine room for debate on this topic. A related point Milgrom and other advocates of alternative gravity solutions to the dynamical discrepancy sometimes make is that if the alternative theory of gravity can reduce the need for excess matter to one or two times the known baryonic matter, it becomes more likely that the excess mass could be explained away as ordinary, merely dim, matter rather than some exotic new type of matter. Finally, even if Kosso's main claim is correct, in itself it proves a version of the Dark Matter Double Bind thesis: GR itself is not tested, just the equivalence principle is tested, in cases involving the "mere detection" of dark matter via weak gravitational lensing. This is to say that the weak lensing tests at galactic and greater scales do not distinguish GR from the viable rival metric gravitation theories.

References

Bekenstein, J. D. (2004). Relativistic gravitation theory for the modified Newtonian dynamics paradigm. *Physical Review D*, *70*, 083509.

Bekenstein, J. D. (2011). Tensor–vector–scalar-modified gravity: From small scale to cosmology. *Philosophical Transactions of the Royal Society A*, *369*, 5003–5017.

Clowe, D., Bradac, M., Gonzalez, A., Markevitch, M., Randall, S., Jones, C., et al. (2006). A direct empirical proof of the existence of dark matter. *The Astrophysical Journal*, *648*, L109–L113.

Ferreira, P. G., & Starkman., G. D. (2009). Einstein's theory of gravity and the problem of missing mass. *Science*, *326*(*5954*), 812–815.

Hamilton, J.-Ch (2013). What have we learned from observational cosmology? *Studies in History and Philosophy of Modern Physics*, *46*, 70–85.

Hudson, R. (2007). Annual modulation experiments, galactic models and WIMPs. *Studies in History and Philosophy of Modern Physics*, *38*, 97–119.

Hudson, R. (2013). *Seeing things: The philosophy of reliable observation*. Oxford: Oxford University Press.

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

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

Mannheim, P. D. (2012). Making the case for conformal gravity. *Foundations of Physics*, *42*, 388–420.

Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophysical Journal*, *270*, 365–370, http://dx.doi.org/10.1086/161130.

Milgrom, M. (2010). MD or DM? Modified dynamics at low accelerations *vs* dark matter. *Proceedings of Science*, *33*, 1–16 (Accessed 02.01.14).

Milgrom, M. (undated). Milgrom's persepective on the Bullet Cluster. ⟨http://www.astro.umd.edu/~ssm/mond/moti_bullet.html⟩, and: The Bullet Cluster. ⟨http://www.astro.umd.edu/~ssm/mond/bullet_comments.html⟩; Accessed 02.01.14.

Minasyan, L. A. (2008). Newest cosmology and philosophy. In *Proceedings of the XXII world congress of philosophy* (Vol. 43, pp. 129–136). 10.5840/wcp22200843332.

Scarpa, R., Marconi, G., Carraro, G., Falomo, R., & Villanova, S. (2011). Testing Newtonian gravity with distant globular clusters: NGC 1851 and NGC 1904. *Astronomy and Astrophysics*, *525*, A148, http://dx.doi.org/10.1051/0004-6361/201014462.

Schwarzschild, B. (2006). Collision between galaxy clusters unveils striking evidence of dark matter. *Physics Today*, *59*(*11*), 21–24.

Sus, Adán. (2014). Dark matter, the Equivalence Principle and modified gravity. *Studies in History and Philosophy of Modern Physics*, *45*, 66–71.

Trimble, V. (1987). Existence and nature of dark matter in the universe. *Annual Review of Astronomy and Astrophysics*, *25*, 425–472.

Trimble, V. (2013). History of dark matter in galaxies. Planets, stars and stellar systems. In: D. Terry Oswalt, & Gerard Gilmore (Eds.), *Galactic structure and stellar populations*, Vol. 5 (pp. 1091–1118). Dordrecht: Springer.

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

Vanderburgh, W. L. (2005). The methodological value of coincidences: Further remarks on dark matter and the astrophysical warrant for general relativity. *Philosophy of Science*, *72*, 1324–1335.

Zinkernagel, H. (2002). Cosmology, particles and the unity of science. *Studies in History and Philosophy of Modern Physics*, *33*, 493–516.