The Dark Galaxy Hypothesis

Michael Weisberg, Melissa Jacquart, Barry Madore,
and Marja Seidel*†

Gravitational interactions allowed astronomers to conclude that dark matter rings all luminous galaxies in gigantic halos, but this only accounts for a fraction of the total mass of dark matter believed to exist. Where is the rest? We hypothesize that some of it resides in dark galaxies, pure dark matter halos that either never possessed or have totally lost their baryonic matter. This article explores methodological challenges that arise because of the nature of observation in astrophysics and examines how the blend of observation, simulation, and theory we call the Observing the Invisible approach might make detecting such dark objects possible.

---

1. Introduction. An outstanding problem in modern cosmology is the mismatch between the mass accounted for observationally and the amount of mass in the universe predicted by the best cosmological models. To remedy this problem and to account for a variety of other anomalies in the observational record, *dark matter* was introduced to astrophysics. Dark matter, currently unobservable at any electromagnetic wavelength and only detected via its gravitational interactions (hence, "dark" matter), accounts for 24% of the total mass energy of the universe. However, this raises fundamental questions including "Where is this dark matter?" and "Why are we justified in accepting its existence?"

Astronomers widely agree about part of the answer: Luminous galaxies are embedded in *dark matter halos*, and these halos extend well beyond the edge of every visible galaxy. Although the existence of dark matter halos surround-

---

*To contact the authors, please write to: Michael Weisberg and Melissa Jacquart, Department of Philosophy, University of Pennsylvania, 433 Cohen Hall, Philadelphia, PA 19104. Barry Madore and Marja Seidel, Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101. Corresponding author: Michael Weisberg (weisberg@phil.upenn.edu).

†The authors gratefully acknowledge the support of the National Science Foundation (STS-1557138) and the Carnegie Institution for Science.

Philosophy of Science, 85 (December 2018) pp. 1204–1215. 0031-8248/2018/8505-0037$10.00

ing luminous galaxies has been well established (Rubin, Ford, and Thonnard 1980), these halos only constitute a small fraction of the amount of dark matter that is predicted to exist by cosmological simulations (Mo, van den Bosch, and White 2010). For both very small and very large galaxies, there are enormous discrepancies between the number of dark matter halos predicted and the number of individually luminous galaxies that are contained within them (Kamionkowski and Liddle 2000; Weinberg et al. 2015). As such, one of the biggest questions for astrophysicists today is: Where are the rest of the predicted dark matter halos?

The *dark galaxy hypothesis*, which we defend, is that at least some of the missing dark matter is in galaxies that are entirely devoid of baryonic matter and composed entirely of dark matter. But how could such a dark galaxy be found, given the supposition that dark matter is not detectable at any wavelength? Our proposal is that such galaxies can be found by their effects. We are engaged in a project that uses dark matter's power to interact with visible galaxies by gravity as a marker. We have adopted a research program that we call Observing the Invisible. This program blends simulation, citizen science, and telescope-based observations to help find these dark galaxies.

This article describes the background of the dark galaxy hypothesis, as well as the astrophysical observations and simulations necessary to investigate it, and reflects on the nature of observation in contemporary astrophysics, especially concerning dark matter objects. We ask: What is the nature of observation in contemporary astrophysics, especially concerning dark matter objects? What might evidence look like in these contexts? What are the evidential limits when dealing with dark matter and with astrophysical phenomena more generally?

2. Dark Matter and the Missing Satellites Problem. Like the unobservable entities of other sciences, dark matter was introduced to astrophysics in order to account for the behavior of observable entities. The velocity of stars and other galactic bodies can be inferred from *redshifts*, changes in light frequency because of the motion of bodies producing the light. In the 1970s and 1980s, astronomer Vera Rubin studied the rotational velocity of stars as a function of their distance from the center of galaxies. She expected to see the velocity decrease from the center to the edge of the galaxy, but there was actually little decrease in velocity toward the edges. This suggested that stars at the edge of visible galaxies are close to the middle of a massive spinning body that was not visible. Since that time, many additional lines of evidence have suggested the need to postulate a nonobservable form of matter, including the structure of galaxy clusters, the large-scale structure of the universe inferred from sky surveys, measurements of the cosmic background microwave radiation, and spectroscopic measurements of gas in galactic collisions (Jacquart, forthcoming).

The mysterious matter postulated to account for galactic rotational curves was quickly dubbed ‘dark matter’ because it is not detectable in any of the normal ways matter can be detected. Specifically, it does not couple to electromagnetic radiation at any wavelength, and hence it cannot be detected using a telescope or spectroscopic instrument. Because of this, the nature of dark matter remains unknown. Additionally, attempts to find the dark matter particle in a particle accelerator have been unsuccessful. Yet this is not taken to be evidence of the nonexistence of dark matter. Instead, dark matter remains mysterious.

Although dark matter was introduced to account for observational data, it has become a central feature of modern cosmological models. Modern theories of the formation and evolution of the universe are characterized by the gravitational interactions of the inhomogeneous distribution of cold dark matter in the universe as it emerged from the first inflationary period of the Big Bang. The most common cosmological model, called the Λ-Cold Dark Matter (ΛCDM) model, shows how the distribution of dark matter gives rise to the large-scale structures of the universe including clusters, filaments, voids, as well as groups, pairs, and ultimately individual galaxies. Halos of dark matter serve as gravitational basins of attraction for baryonic matter. When baryonic matter falls into the sphere of the halo’s influence, it radiatively cools, dissipates, and collapses further, ultimately forming visible stars and galaxies (for an extensive discussion of these processes, see Mo et al. [2010]).

Cosmological models predict the number and mass distribution of dark matter halos (e.g., see discussion in Kamionkowski and Liddle 2000; Weinberg et al. 2015), but virtually all ΛCDM models predict an overabundance of low-mass dark-matter halos as compared to the number of observed low-mass/low-luminosity galaxies and satellites. This has come to be known as the *missing satellites problem* (Klypin et al. 1999; Bullock 2010). When sky surveys are compared to simulations, there are missing dark-matter halos at all masses and luminosities. At the low-mass end, the disparity between simulation and observation is nearly a factor of 100. But an even more awkward observation is the deficit of higher mass halos that have been said to be too big to fail to form or capture the gas and stars that make up luminous galaxies.

A variety of suggestions have been made and several observational proposals have been offered to circumstantially detect the presence of additional halos. One suggestion is that the relevant number of halos exist and contain some baryonic material, but star formation is somehow suppressed in these halos, making them dark at all measurable wavelengths. A possible mechanism for this is that the first generation of star formation produced stellar winds and supernova shock waves that were powerful enough to drive the interstellar medium totally out of low-mass systems, leaving them devoid of baryonic matter and effectively dark (Tegmark, Silk, and Evrard 1993; Côté, Martel, and Drissen 2015). Another possible mechanism is that the ultraviolet cosmic background radiation field halted the infall of intergalactic gas by heating and ionizing it, leaving halos devoid of baryonic material (first suggested by Babul and Rees [1992] and Efstathiou [1992], this idea has more recently been elaborated on by Benson et al. [2002] and Somerville [2002]). Although these ideas have merit, searches in the 21-centimeter line of neutral hydrogen for optically dark but gas-bright galaxies have failed to uncover any convincing examples of these suppressed galaxies (Papastergis et al. 2011). If they exist, they are not found in the vast numbers required by cosmological theory.

Another pair of explanations proposes different mechanisms for small and large halos with missing stars and gas. For low-mass halos, it has been proposed that supernova explosions have expelled all of the gas and dust, leaving just the first generation of stars behind (Dekel and Silk 1986). For high-mass halos, it has been proposed that super-massive black holes and active galactic nuclei, along with their attendant radio jets, could have depleted halos of the gas needed for star formation. This is an intriguing idea, but to date, there have not been candidate observations with the requisite properties.

Finally, some researchers have approached the missing satellites problems by undertaking blind searches across the sky for “almost dark” galaxies. For example, Janowiecki and colleagues (2015) conducted a search at radio wavelengths for dark-matter halos that still contain neutral hydrogen gas but few or no stars. These astronomers found three candidate “almost dark” galaxies. This is intriguing, yet such a low number of almost dark galaxies will not substantially aid in resolving the missing satellite problem.

In section 4, we propose a simpler solution to the missing satellite problem: the hypothesis that at least some of the missing dark halos remain completely dark. These pure dark matter halos are what we call *dark matter galaxies*: halos that have no baryonic matter, either because they lost this matter early on or they never acquired it in the first place. Assuming that such dark galaxies really do exist, the astrophysical question ultimately is: Where are they? Given the nature we have just outlined, convincingly answering this question is going to require a very unique style of argumentation and reasoning. But before we explore this in detail in section 4, we want to highlight the methodological challenges for the detection for dark matter.

3. Methodological Challenges for Dark Matter Observations. A central claim in searches for dark matter is that we can somehow detect dark matter, despite its being invisible at every known wavelength. In traditional discussions of philosophy of science, this would be synonymous with saying that we can either observe dark matter or test a hypothesis about dark galaxies. Yet as just outlined, we cannot see dark galaxies with the naked eye or with classical optical telescopes, and we cannot build a detector for them. What, then, will warrant a claim about detecting them, if such a project is successful?

Observing any astronomical object necessarily involves moving beyond our senses, even augmented in ordinary ways. As Humphreys points out, “one of science's most important epistemological and metaphysical achievements has been its success in enlarging the range of our natural human abilities" (2004, 3). While this is true across the sciences, it is especially true for astrophysics; few fields have harnessed the power of technology and computational power to extend our senses across spacial scale, time, and sensory domains as extensively as astrophysics.

Why does astrophysics require so much augmentation? Astronomical objects are simultaneously visible and hard to detect. Objects such as galaxies are enormous, often 100,000–1 million light-years in diameter. Astronomers can either get detailed information about an extremely tiny fraction of the whole or else highly compress the image and data, learning about the average properties of hundreds of billions of stars. The latter course is usually taken because most luminous astrophysical objects of interest are very far away. This distance also means that the astrophysical events observed happened a very long time ago. Thus, astronomical observation involves trying to get a grip on objects that are very large, very far away, and whose present state has to be inferred from events in the far past. In addition, many events studied by astrophysicists happen very slowly. When astrophysicists speak of one galaxy colliding with another, this is not a momentary event but actually an event that takes place over about 1 million years.

In addition to the challenge of augmentation, astrophysics faces challenges due to the fact that it is an observational science. Like with all scientific methods that are observation based, astronomers have to deal with the fact that their target systems cannot be manipulated (Parke 2014). This means that one can only see the configurations that nature has provided; no new ones can be created. Astronomy has the additional complications that, in nearly every case, there is only a single vantage point (on or near earth) and that one has to look at what happened at a fixed time in the past.

Some might say that this presents astrophysics with another unique challenge related to the sparseness of data, given astrophysics only has access to one snapshot of these interactions that take place over such large timescales. While this is true, there is also a sense in which astronomy has a special advantage relative to other observational sciences. The observable reaches of the universe, even from the vantage point of earth, are so vast, it is likely that astronomers can find every interesting interaction just as a matter of large numbers. If there is a particular configuration of states that you want to see as an astronomer, the best thing to do is look systematically, for it is likely to occur somewhere. Of course, looking for a rare event is difficult, perhaps the central challenge of astronomy (see, e.g., Panek 2012). But one thing astronomers have done for a long time, and are doing with increasing efficiency, is to create sky surveys so that particular configurations can be hunted within a survey. The idea is to systematically record the sky over the course of many nights, then create a catalog or database of these observations. Traditional sky surveys such as the *Catalogue of Southern Peculiar Galaxies and Associations* (Arp and Madore 1987) involved visually inspecting telescope images recorded on photographic plates and then compiling the data by hand. Modern surveys such as the Sloan Digital Sky Survey (SDSS) are automatically collected and archived as a database. Once the database is created, the contents of the database itself become objects of study (Ratti 2015). The next generation of sky surveys will collect an SDSS amount of data every few nights, so astronomers will have a time series as well as a survey, and this will give them even more of the data they need to draw the inferences traditionally associated with experiments.

The combination of the vastness of the universe and sky surveys provides astronomers with data sets that likely contain the information that one would get from experimental methods. These data sets are enormous and less focused than what one would get from experimental techniques, so their very existence raises new methodological challenges. In the first instance, how is one supposed to examine them? The SDSS has yielded spectra for over 3 million objects. The planned Large Synoptic Sky Survey will yield this volume of data every few nights. As such, the challenge of sparse data might be better placed alongside this abundance of data as its own methodological sparse/abundance data trade-off challenge. Given the sparse data connected to a single phenomenon but a possible abundance of data available for similar systems, there is a question of what warrants astrophysics' bringing in and importing data from other similar systems.

Obviously, it is impossible to sort through this information completely by hand, so astrophysicists have adopted crowd-sourcing techniques to examine it; an enormous number of individuals look for specific features of the images, without necessarily knowing the goal or understanding the underlying astrophysics. Thus, there is a challenge related to the role of expertise and determining what level of expertise is needed to make judgments connected to the data. With each degree of distance from the primary observations—especially those involving thousands of lightly trained volunteers—additional questions of reliability are raised. Most centrally, our best access to a part of the world requires techniques of observation increasingly distant from human senses and the harnessing of a labor force far removed from astronomers. This challenges traditional ideas about observation associated with empiricism. Contemporary astronomical observation is not simply unaided observation with magnification. Rather, these techniques are examples of what Humphreys calls extrapolation, conversion, and augmentation. They involve extending senses along a given dimension (extrapolation), change of sensory modality (conversion), and creation of new detectors (augmentation).

Although extrapolation, conversion, and augmentation all involve taking the astronomer away from conventional observation, they rest on fairly secure epistemic footing. Hacking (1983), Kitcher (2001), and Humphreys

(2004) use what Humphreys calls *overlap arguments* to pass epistemic warrant from domains where we believe it to be unproblematic (ordinary visual observation in good light) to domains where it is much more complex (observation of distant stars by their radio frequency emissions).

Overlap arguments proceed by showing that a given phenomenon can be detected by a technique that has known epistemic warrant and by one whose epistemic warrant is being investigated. For example, an optical telescope might overlap in range with the naked eye: point it at a distant object that the naked eye can just make out, and then get closer to the distant object to verify the telescope showed the object correctly. For the next step, point the telescope to the larger moons of Jupiter, which you can barely see if you squint and compare. Once the optical telescope's warrant is established by overlap arguments, one can investigate other detectors by overlapping with the optical telescope. Behind these overlap arguments lies another methodological challenge astronomers attempt to overcome, domain extension, that is, determining when data obtained on one scale, in a certain domain, can be extended to a new domain.

Moreover, the existence of the exotic objects studied by astrophysicists are also justified, in part, by the overlap arguments that establish the epistemic warrants of the instruments used to detect them. But detecting or observing dark matter galaxies is necessarily different. Dark matter is intrinsically incapable of being observed because no radiation is thought to couple to it. Overlap arguments that establish the epistemic warrants of detectors will not, in any substantial way, provide epistemic warrants to observations of dark matter. If there is nothing to detect, then detectors with good epistemic credentials are not going to help us detect them. If this is the only way of warranting an extension of our senses, then the project of searching for dark galaxies is, epistemically, a fool's errand.

But there may be other ways to justify the epistemic warrant. In the next section, we detail the methodology behind our search for dark galaxies and how this methodology, to some extent, exemplifies augmentation, experimentation, space/abundance data trade-off, expertise reliability, and domain extension.

4. Observing the Invisible.

The dark galaxy hypothesis, if true, provides a tidy solution to the missing satellites problem, but it raises a very big problem of its own: it posits entities that cannot, by definition, be detected. So any search for dark matter galaxies is going to involve indirect evidence and an inference from that evidence.

More specifically, searching for dark galaxies or any dark matter objects necessarily involves looking for the effect of dark galaxies on luminous matter and light. Very little work has been done in this area, but a few research groups have begun searching for dark halos by their effects. One approach is to examine gaps in tidal streams of stars, leading and following certain globular clusters that are being stripped of their stars during a passage through the halo of our galaxy (Carlberg and Grillmair 2013). A second approach uses the phenomenon of gravitational lensing to search for dark galaxies (Dalal and Kochanek 2002). More recently, there have seen searches for "surface brightness anomalies caused by very low-mass (dark matter) substructure" (Vegetti et al. 2012, 341).

Our Observing the Invisible approach, a collaboration between astrophysicists and philosophers, has elements in common with these other searches but involves something even simpler. Like in these other research programs, we are searching for dark matter galaxies by their effects, but we will be looking for the catastrophic gravitational effects that dark galaxies, if they exist, can have on nearby luminous galaxies. This approach has three methodological components: (1) a characterization of target signatures by simulation, (2) a search through existing databases for those signatures, and (3) direct, telescopic, and spectroscopic follow-up observations of the promising candidates.

The first component to the project is simulation based. We have constructed models of dark matter galaxy/luminous matter galaxy interactions and explored them using high-resolution *N*-body computer simulations. By simulating pure dark matter halos colliding with luminous galaxies, we have characterized how the collision effects the luminous galaxy, leaving behind a characteristic signature of the collision: *ring galaxies* and *one-armed spiral galaxies* without optically visible companions. In addition to giving us the gross morphology of luminous galaxies affected by dark matter galaxies, simulations provide the dynamics of such interactions, including the direction of the dark galaxy's orbit and the time elapsed since the collision. With this information, we believe that for a given ring or one-armed spiral, we can predict where the dark galaxy ought to be located.

Simulations can identify the morphology and dynamics of a dark/luminous galaxy collision, but actually finding an object that has the appropriate properties is a different matter. The second component of our project relies on existing *sky surveys*, systematic telescope-based photography of the entire night sky. Specifically, we are examining the entirety of the SDSS, which consists of images of over 200 million astronomical objects. It is impossible to examine such a large catalog by hand, so we have deployed the resources of citizen science to assist us with our review. A team of citizen scientists working with the GalaxyZoo2 project (Willett et al. 2013) has examined the entire SDSS catalog, looking for many features, including rings and single-armed spirals. This type of citizen science project is simply a giant collective effort of looking. It is purposefully designed to be liberal: we want the citizen scientists to identify every ring galaxy. Using this long list, we have identified the rings whose morphologies suggest that they would be most worthy of study.

The final component of Observing the Invisible involves studying the most probable candidates using a telescope. We are currently engaged in a detailed optical and spectroscopic study of several candidate galaxies to take full optical and spectroscopic measurements of target galaxies and their surroundings. As there is no possibility of seeing a dark matter galaxy directly, our observations will measure the morphology and dynamics of candidate luminous galaxies for signatures of collision. For example, our simulations show that tidal debris from a collision is asymmetrically drawn out of the luminous galaxy and points in the direction of the collider. With a detailed characterization of our target luminous object and the surrounding space, we may also be able to look for the effects of gravitational lensing of the dark matter halo on the higher redshift galaxies directly behind the halo. If we can detect them, we will be able to pinpoint the dark collider and learn much about its mass distribution.

5. Alternative Paths to Epistemic Warrant. If our Observing the Invisible investigation yields dark galaxy candidates, what will the epistemic status of these objects be? Some comparisons to other cases of indirect observations in the history of physical science may be instructive. Consider the well-known experiments that convinced physicists and chemists that atoms were real. The most famous of these experiments were studies of Brownian motion. The motion of finely suspended mastic particles was tracked, and then atomic collisions were inferred from the precise details about this motion, especially stratification of columns of particles that could be computed from theory. The stratification depended essentially on Avogadro's number. This evidence, along with many independent ways of calculating Avogadro's number, was the key that convinced the community to accept atomic reality (Perrin 1870/1913; Nye 1972). The reason is that the only way that Brownian motion itself could be accounted for was if the visible particles were colliding with invisible particles—atoms.

Superficially, our dark galaxy project aims to justify dark matter in the same way. We propose to detect dark galaxies by their effects. Instead of atoms buffeting visible particles of mastic, dark galaxies are disrupting luminous galaxies. In both cases, the idea is to detect an unobservable by its effects on observables. Described at this level of abstraction, the detection of dark galaxies is absolutely the same as most of the evidence we have for unobservables.

While these comparisons are apt, they do not reveal the whole chain of epistemic commitments, for either the atomic case or the dark matter case. Although in the early twentieth century, the epistemic warrant for atoms and molecules was largely based on measurements of Brownian motion, this is no longer the case. We accept the existence of atoms and molecules because of our ability to detect them via spectroscopy and, more recently, scanning tunneling electron microcopy.

Dark matter is different. As discussed, dark matter only interacts with luminous matter gravitationally and probably does not interact with radiation at all. So even if we can draw a full set of parallels between Brownian motion measurements and dark matter collision measurements, this would provide us with the equivalent of an early twentieth-century, pre–quantum mechanical warrant of atoms. It does not provide anything like the present day warrant we have for atoms and molecules; there can be no spectroscopy for dark matter.

The situation may be even worse. Unlike for the atomic theory of the early twentieth century, there is little consensus regarding theory about the nature of dark matter. The closest thing to consensus is the idea that dark matter is cold or relatively slow moving. This is introduced as an assumption because it helps cosmologists better understand the total mass/energy content of the universe. However, the best cosmological theories were chosen, in part, to account for the presumed presence of dark matter. Beyond this, there is very little known or even postulated about dark matter. There is little agreement about what dark matter is, its properties, its distribution, or any interactions beyond gravitational ones that it might have.

Moreover, unlike the relationship between particle stratification in Brownian motion experiments and atomic reality, the connection between luminous galaxy morphology and pure dark matter halo collision is substantially undertheorized, even in our project. Einstein could calculate the precise density gradient in a column of fine particles because of interactions with atoms as a function of Avogadro's number. The best we can hope for is to study how collisions between a dark galaxy of a certain mass will disrupt the morphology of a luminous galaxy, giving us the new morphology and the velocity and temperature of the stars in the postcollision luminous galaxy. Even in this best case scenario, our simulations essential say that when mass x strikes mass y of morphology z, we get morphology and dynamics of z'. It is all done by brute-force simulation, and there is very little dark matter specific theory behind it. But perhaps that is all that is required in this case.

6. Conclusion. We do not want to end on a pessimistic note, nor are we pessimistic about the prospects of learning more about dark matter and the dark galaxy hypothesis. While our current understanding of dark matter is not even at the level of early twentieth-century atomic theory, we believe our research project will advance our understanding in substantial ways. If our blend of simulation, citizen science, and observation allows us to locate and characterize dark galaxies by their effects on luminous galaxies, we will have added constraints to cosmological models, constraints that will inform the next generation of models. If our project completely fails to find dark galaxies, then we will have strong evidence that there are not many pure dark matter halos of the required mass, orbital characteristics, and concentration classes predicted by theory or that pure dark matter halos do not behave as we think they do. Even with good epistemic warrants for each step, attempts to observe what cannot be seen will always prove difficult, but, in the end, astronomy may advance because of them.

REFERENCES

Arp, H., and B. F. Madore. 1987. *A Catalogue of Southern Peculiar Galaxies and Associations*. Cambridge: Cambridge University Press.

Babul, Arif, and Martin J. Rees. 1992. "On Dwarf Elliptical Galaxies and the Faint Blue Counts." *Monthly Notices of the Royal Astronomical Society* 255:346–50.

Benson, A. J., C. G. Lacey, C. M. Baugh, S. Cole, and C. S. Frenk. 2002. "The Effects of Photoionization on Galaxy Formation." Pt. 1, "Model and Results at Z = 0." *Monthly Notices of the Royal Astronomical Society* 333 (1): 156–76.

Bullock, J. S. 2010. "Notes on the Missing Satellites Problem." arXiv.org, Cornell University Library. http://arxiv.org/abs/1009.4505.

Carlberg, R. G., and C. J. Grillmair. 2013. "Gaps in the GD-1 Star Stream." *Astrophysical Journal* 768 (2): 171.

Côté, B., H. Martel, and L. Drissen. 2015. "Cosmological Simulations of the Intergalactic Medium." Pt. 2, "Galaxy Model and Feedback." *Astrophysical Journal* 802 (2): 123.

Dalal, N., and C. S. Kochanek. 2002. "Direct Detection of Cold Dark Matter Substructure." *Astrophysical Journal* 572 (1): 25–33.

Dekel, A., and J. Silk. 1986. "The Origin of Dwarf Galaxies, Cold Dark Matter, and Biased Galaxy Formation." *Astrophysical Journal* 303:39–55.

Efstathiou, G. 1992. "Suppressing the Formation of Dwarf Galaxies via Photoionization." *Monthly Notices of the Royal Astronomical Society* 256 (1): 43P–47P.

Hacking, I. 1983. *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*. Vol. 5. Cambridge: Cambridge University Press.

Humphreys, P. 2004. *Extending Ourselves: Computational Science, Empiricism, and Scientific Method*. New York: Oxford University Press.

Jacquart, M. Forthcoming. "Dark Matter and Dark Energy." In *Routledge Companion to the Philosophy of Physics*, ed. Eleanor Knox and Alastair Wilson. New York: Routledge.

Janowiecki, S., L. Leisman, G. Józsa, J. J. Salzer, M. P. Haynes, R. Giovanelli, K. L. Rhode, J. M. Cannon, E. A. K. Adams, and W. F. Janesh. 2015. "(Almost) Dark HI Sources in the ALFALFA Survey: The Intriguing Case of HI1232+20." *Astrophysical Journal* 801 (2): 96.

Kamionkowski, M., and A. R. Liddle. 2000. "The Dearth of Halo Dwarf Galaxies: Is There Power on Short Scales?" *Physical Review Letters* 84 (20): 4525–28.

Kitcher, P. 2001. "Real Realism: The Galilean Strategy." *Philosophical Review* 110 (2): 151–97.

Klypin, A., A. V. Kravtsov, O. Valenzuela, and F. Prada. 1999. "Where Are the Missing Galactic Satellites?" *Astrophysical Journal* 522 (1): 82.

Mo, H., F. van den Bosch, and S. White. 2010. *Galaxy Formation and Evolution*. Cambridge: Cambridge University Press.

Nye, M. J. 1972. *Molecular Reality: A Perspective on the Scientific Work of Jean Perrin*. London: Macdonald.

Panek, R. 2012. *The 4% Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality*. Oxford: Oneworld.

Papastergis, E., A. M. Martin, R. Giovanelli, and M. P. Haynes. 2011. "The Velocity and Width Function of Galaxies from the 40% ALFALFA Survey: Shedding Light on the Cold Dark Matter Overabundance Problem." *Astrophysical Journal* 739 (1): 38.

Parke, E. C. 2014. "Experiments, Simulations, and Epistemic Privilege." *Philosophy of Science* 81 (4): 526–36.

Perrin, J. 1870/1913. *Les atomes*. Paris: Alcan.

Ratti, E. 2015. "Big Data Biology: Between Eliminative Inferences and Exploratory Experiments." *Philosophy of Science* 82 (2): 198–218.

Rubin, Vera C., W. Kent Ford Jr., and Norbert Thonnard. 1980. "Rotational Properties of 21 SC Galaxies with a Large Range of Luminosities and Radii, from NGC 4605/R = 4kpc/to UGC 2885/R = 122 kpc." *Astrophysical Journal* 238:471–87.

Somerville, R. S. 2002. “Can Photoionization Squelching Resolve the Substructure Crisis?” *Astrophysical Journal Letters* 572 (1): L23–L26.

Tegmark, M., J. Silk, and A. Evrard. 1993. “Late Reionization by Supernova-Driven Winds.” *Astrophysical Journal* 417:54.

Vegetti, S., D. J. Lagattuta, J. P. McKean, M. W. Auger, C. D. Fassnacht, and L. V. E. Koopmans. 2012. “Gravitational Detection of a Low-Mass Dark Satellite Galaxy at Cosmological Distance.” *Nature* 481 (7381): 341–43.

Weinberg, D. H., J. S. Bullock, F. Governato, R. de Naray, and A. H. G. Peter. 2015. “Cold Dark Matter: Controversies on Small Scales.” *Proceedings of the National Academy of Sciences of the USA* 1124 (40): 12249–55.

Willett, K. W., et al. 2013. “Galaxy Zoo 2: Detailed Morphological Classifications for 304,122 Galaxies from the Sloan Digital Sky Survey.” *Monthly Notices of the Royal Astronomical Society* 435 (4): 2835–60.