Dark Matter Realism: How Referential Semantics Restricts Realism in Contemporary Fundamental Physics*

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Abstract

Philosophers increasingly treat semantics as decisive for realism about dark matter. I examine a recent proposal by Vaynberg (2024) anchored in Psillos' causal–descriptive theory of reference Psillos (1999, 2012). I argue that, on the strong reference-fixing (kind-constitutive) reading required by semantic dark matter realism, the proposed **Λ**CDM-motivated core description does not do the work assigned to it. It is compatible with entities we do not count as dark matter, and it excludes entities treated as live candidates in the contemporary landscape of models. I close by suggesting that this discrepancy between realist semantics and dark matter may be part in a general pattern in empirically scarce domains — the semantic specificity required by this realist strategy depends on forms of canonical confirmation that are not yet available.

Keywords: Scientific Realism, Dark Matter, Fundamental Physics, Referential Semantics

1 Introduction

Philosophers engaged in exploring the marriage of scientific realism and dark matter have, as is common in many marital contexts, reached opposite conclusions using more

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or less the same semantic apparatus. Despite their ultimate disagreement regarding realism, there is an aspect of scientific realism that all appear to agree constitutes a pivotal point for assessing its viability in the dark matter case: the semantics. This is not surprising. In the absence of decisive, 'canonical' modes of empirical confirmation, much of the realist burden is shifted onto how, and whether, theoretical terms such as 'dark matter' manage to refer. This paper contributes to the dark matter realism debate qua a debate about semantics in two distinct ways.

First, I explicate the general role played by semantics in the dark matter context and explain why it is, and should be, of particular interest for philosophers engaged in dark matter realism. Building on this, I examine a specific account of semantics for realism given by Vaynberg (2024), who employs the causal-descriptive theory of reference Psillos (1999, 2012) to frame a semantic interpretation of dark matter that not only *allows* for empirical confirmation but is in fact *exemplified* as such in the Bullet Cluster observation. On this view, we are provided not only with the semantic template for dark matter realism, but with an epistemology to match. My primary focus is not Vaynberg's realist conclusion as such, but the semantic route taken to reach it — namely, the deployment of Psillos-style causal descriptivism in a context where the relevant causal description is fixed under substantial underdetermination. More specifically, I argue that Psillos' semantics, situated within his general framework of scientific realism as it is, is unsuited as a semantic framework applied in the local context of dark matter. This is in part because of the overlooked metaphysical commitments under the hood of causal-descriptivism, in particular the appeal to kind-constitutive properties that are meant to fix reference, and in part because the conditions given for reference and object turn out to be neither necessary nor sufficient. Accordingly, my negative result is conditional and restricted: *given* this Psillos/Vaynberg-style semantic dark matter realism, the proposed reference-fixing conditions do not behave as advertised in the dark matter case. The extension of 'dark matter' on this account turns out to include entities we do not currently consider to be dark matter and exclude entities that we currently consider could be dark matter, at least insofar as 'dark matter' is understood as the dominant component posited to explain the full range of 'dark phenomena' (as opposed to any non-luminous gravitating component whatsoever).

Second, I suggest that the tension between classical scientific realism and the dark matter case may be more than a local idiosyncrasy. My claim is that the semantic elements in what appears to be the most suitable scientific realism for dark matter tend to be built on the following presupposition: only canonical forms of empirical confirmation can provide us with the causal descriptions necessary to establish that an entity is the referent for its corresponding theoretical term. I contend that *this is a principled issue*, i.e., a built-in limit, part and parcel of the function of scientific realism of the canonical sort under consideration here. In a sense, I am combining the semantic lessons from Martens (2022) and the epistemic lessons from Allzén (2021) to show that the justification for dark matter realism cannot be found in classical accounts of scientific realism. This broader moral should be read as a judgment of where (and why) classical accounts of realism struggles, not as a proof that no realist-friendly semantics could succeed for dark matter. This does not, and should not, be taken to entail or support anti-realism about dark matter, nor does it rationally recommend suspending beliefs about the reality of dark matter — a staunch dark matter realist may simply conclude that if the marriage of classic scientific realism and dark matter has failed, that is symptomatic of the former clinging on to past scientific practice, not the latter being unjustifiable. The main point that this paper seeks to stress is this: it is not by accident, or because of case-specific contingencies, that scientific realism and dark matter are at odds. Rather, this should be an expected outcome from a doctrine the formulation of which is so entrenched in and constructed in parallel with the golden age of particle physics and its associated modes of empirical confirmation. Scientific realism, understood as a child of its time, *would be* ill-equipped to accommodate theories which are so intricately embedded in theoretical networks and so empirically challenging as they have proven to be in 21st-century cosmology and astrophysics. Unlike the cases that shaped traditional realism (e.g., canonical empirical confirmations in particle physics), dark matter inhabits a regime of persistent underdetermination and sparse direct evidence, making it a representative case for testing the applicability of classical scientific realism in 21st-century physics.

If, from this incompatibility, we should conclude that *dark matter realism is unjustified*, or that *scientific realism is an outdated doctrine* built on scientific practice neither desirable nor attainable for much of current and future scientific theory, I cannot definitively argue here. I will nevertheless suggest that the incompatibility highlights a vulnerability in the way scientific realism (of the sort considered) handles contemporary theory and their posited entities which, if systematic, will render it archaic for future science. In other words, the paper's central aim is to identify where a canonical semantic realist overpromises in a domain characterized by deep underdetermination, and to clarify what would have to change — semantically and methodologically — for a realist stance on dark matter to be better supported.

2 Dark matter realism and the problem of semantics

In a recent contribution to the growing literature on the philosophy of dark matter, Vaynberg (2024) offers an argument in support of dark matter realism, understood in terms of an answer to the following question: *"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?"*[1] For anyone not already familiar with the prerequisites of scientific realism, it may seem strange to formulate a question about the reality of a scientific entity as a semantic question about reference, but there are good reasons to do so. Scientific realism is commonly glossed as the view resulting from accepting (some version of) three core elements, often presented below in order of necessary dependence:

> **Metaphysical**: the world exists mind-independently.
> **Semantic**: theoretical claims have truth values, and should be taken at face value.
> **Epistemic:** science is able to identify the truth values of its claims.

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[1] The philosophical interest in dark matter is evident in the growth of research in recent years: Vanderburgh (2003, 2005, 2014b,a), Sus (2014), Jacquart (2021), Merritt (2021b,a), De Baerdemaeker (2026, 2021), De Baerdemaeker and Boyd (2020), de Baerdemaeker and Dawid (2022), Antoniou (2023, 2025), Duerr and Wolf (2023), Wolf and Read (2025), Martens et al. (2022).

The metaphysical element provides the ontological structures necessary for theoretical claims to have truth values. The constitution of the world dictates whether the theoretical claims expressed in science, taken literally, are true or false (importantly, both observable and unobservable entities). The epistemic element expresses optimism that science can determine whether a theoretical claim is true or false. If science provides sufficient reasons for the truth of a theoretical claim, then all the entities, properties, structures, and relations contained in that claim are (and should be) accepted as real parts of the world. In short, scientific realism is the view one ends up with when accepting all three dependent elements above, colloquially expressed as the belief that our best scientific theories provide us with knowledge about real features of the world.

Although scientific realism is classically understood as a general perspective on science, local applications of realism to specific theories are not exempt from dependence on these elements. Note, however, that how the elements are realized is, in principle, irrelevant, which implies that how one assembles the necessary semantics, and the conceptual machinery it contains, is subject to the theoretical aims of the realist. Once a semantic framework is articulated, its specification — as a consequence of elemental dependence — constrains the set of possible ways to specify the epistemic conditions sufficient for empirical confirmation. In what follows, I focus on a proposed way of realizing the semantic element in the dark matter debate: a causal-descriptive approach to reference of the sort developed by Psillos and adopted by Vaynberg. Martens (2022) partially draws on this dependence in a bipartite argument against the prospects of (present-day) dark matter realism. According to him, the semantic concept of dark matter has two reasonable articulations: one specific and one generic.[2] The specific approach takes the concept of dark matter to be fully explicated by plugging in the salient specifics from any currently viable dark matter candidate, for example, a weakly interacting massive particle (WIMP). This gives us not only a semantically meaningful concept of dark matter, but also a discernible way to carve out the sufficient conditions for empirical confirmation. In short, it tells us what dark matter is and how to know when we find it. Deciding which candidate should fill the semantic gap, however, is massively underdetermined:

> the current empirical evidence strongly underdetermines which, if any, of the vast array of completely specific mainstream candidates is to be paired with ΛCDM. (Martens 2022, 4)[3]

The generic approach takes the concept of dark matter to include only the descriptive properties shared by all currently viable dark matter candidates, i.e., their most generic properties.[4] Martens is doubtful that the descriptive properties remaining after stripping the specifics amount to a semantically meaningful concept:

> The common core concept of dark 'matter', especially the lower bound, is so semantically thin, so vacuous, that it barely means anything at all. It is simply not a rich enough concept (yet) for us to be realists about it. (Martens 2022, 16)

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[2] My use of "specific" and "generic" corresponds to Martens' "thick" and "thin". Recently, a novel way to (re)define dark matter has been proposed by De Baerdemaeker (2026).

[3] Here, Martens refers to the standard cosmological model, ΛCDM, which posits cold dark matter (CDM) as the dominant component explaining the full range of dark phenomena, in addition to a cosmological constant (Λ) accounting for dark energy.

[4] I will hereinafter assume that 'dark matter' tracks the dominant component posited to explain the full range of *dark phenomena*, rather than any non-luminous gravitating contribution whatsoever.

Here, Martens stresses the imprudence of being a realist about the vacuous concept produced by a generic approach — realism requires our concept of dark matter to be specific enough to discriminate between individual unique entities. The general reason supporting specificity is rooted in problems of referential success. Even in cases where the description of a scientific entity is only marginally generic — say, compatible with at least two distinct theoretically possible entities — referential success becomes trivial. The reason is that whichever of the two entities proves to be real was somehow the one we managed to successfully refer to all along. The damning part, of course, is that it should not be irrelevant which of the entities actually exists for successful reference to obtain. For example, describing an unknown sample merely as "a metal" may succeed in referring to a broad class, but it does not fix whether the sample is iron, copper, or gold. Generic descriptions can thus refer at a coarse grain, yet they fail to do the non-trivial reference-fixing work required when the realist payoff depends on discriminating between relevant alternatives. It is a core function of our descriptions that they can discriminate between entities sufficiently.[5]

Martens' two-horned objection to semantic realism effectively terminates the process toward dark matter realism at the semantic junction. His clear focus on the semantic element of scientific realism explains why Vaynberg, in response, frames the question about the justification of dark matter realism as a question of semantics, more specifically as a question of successful reference. In the above exposition, it is evident that the semantic aspects of the term 'dark matter' — the proliferation of dark matter concepts, their common descriptive core, and the prospects of successful reference — constitute a central issue for dark matter realism. In the following section, I will explicate and challenge Vaynberg's account, which I take to be the most comprehensive and thoroughly constructed proposition in favor of dark matter realism thus far, and I do so by focusing on whether a Psillos-style causal-descriptive semantics can deliver the non-trivial reference-fixing work it is supposed to provide in the dark matter case.

3 A semantics for dark matter realism

Vaynberg's semantic framing of dark matter realism, introduced at the beginning of the previous section, persists in his more exhaustive recipe for the view:

> 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. (Vaynberg 2024, 82)

The attentive reader will notice that, in addition to the standard elements of scientific realism, a prerequisite objective is proposed: stipulating a theory of reference. This is an advisable measure to ensure that the semantic account one employs when dealing with the issues raised by Martens is rooted in a vetted theory. The theory of reference

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[5] This is not to say that descriptions of entities cannot be generic, or even vacuous, at the conception of new theory. Such descriptions can still secure reference in a weak, genus-level sense, functioning as semantic seeds that equip scientists with a minimal but necessary structure to further develop a theory. Theoretical progress and empirical input usually increases the specificity of the description, but, and this is Martens core point, realist commitment should not precede the point at which a theory reaches sufficient descriptive specificity.

Vaynberg adopts is the causal-descriptive theory of reference, as formulated by Psillos (2009). The choice is well motivated since Psillos' version of the causal-descriptive theory is adjusted for handling specific referential issues of the kind found in scientific realism. It is also, dialectically, an attractive choice in the dark matter context precisely because it promises a route from a causal-explanatory description to non-trivial referential success. According to Psillos' theory, successful reference is achieved under the following conditions:

1. A term t refers to an entity x iff x satisfies the core causal description associated with t.
2. Two terms t^* and t denote the same entity iff:
   (a) their putative referents play the same causal role with respect to a network of phenomena;
   (b) the core causal description t^* takes up the kind-constitutive properties of the core causal description associated with t.

The "core causal description" in (1) is constituted by the description of the properties an entity necessarily must have in order to cause the phenomena it was introduced to explain. At this point, an important distinction will matter for the remainder of the paper. One may interpret "core causal description" as either (i) merely as a *role description* — constraints sufficient for playing the relevant explanatory role in the target domain — or (ii) as a *reference-fixing* description that does the further work of picking out a distinct kind (or entity-kind) via kind-constitutive properties. In Psillos, these descriptive properties are denoted "kind-constitutive properties", since they are meant to describe the properties that constitute a natural kind. Natural kind membership is dependent on, and determined by, the entity possessing precisely those properties. The presence of (2b) makes it clear that Psillos' account, as stated, is not exhausted by (i) because sameness of causal role is not sufficient, unless the relevant kind-constitutive properties are also taken up.[6] Vaynberg adopts Psillos' understanding of a natural kind 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"* (Vaynberg 2024, 82). The concept of a natural kind is thereby anchored to its *differentia*, i.e., the properties, characteristics, or any sui generis mix thereof, which distinguish it from other kinds. Psillos describes how all this is supposed to play out:

> 'Phlogiston' fails to refer because no entity has the kind-constitutive properties attributed to phlogiston. [...] The one and only entity to which the term refers is the entity which is characterized by the relevant kind-constitutive properties. (Psillos 2012, 226)

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[6] Thanks to an anonymous reviewer for pressing me to clarify this point. I initially thought that the presence of (2b) was redundant, but upon closer inspection, it is clear that it is not. The condition (2a) is compatible with a purely role-based interpretation of the core causal description, on which reference is fixed by whatever plays the relevant causal role. The addition of (2b) makes it clear that Psillos' account is not exhausted by a role-based interpretation, since it requires that the core causal description also includes kind-constitutive properties that are meant to pick out a distinct kind. This is important for understanding the specific way in which Vaynberg applies Psillos' theory to dark matter realism, and for evaluating whether the proposed kind-constitutive properties can indeed do the work of fixing reference in the intended sense.

This is the sense in which I take Vaynberg's proposal to be committed to *non-trivially* fixing a reference. Referential success is not achieved by "there exists something that can play the relevant causal role" but that the term 'dark matter' is anchored by a stable set of kind-constitutive properties that can underwrite referential success in the realist's intended sense. The process of identifying the relevant kind-constitutive properties for a term is, for pragmatic reasons, necessarily theory-dependent.[7] In Vaynberg's application of Psillos' causal-descriptive account, the theory (or model, in this case) most suitable to supply the kind-constitutive properties of 'dark matter' is ΛCDM.[8] Here follows Vaynberg's reasoning and the subsequent stipulation of the kind-constitutive properties of dark matter as extracted from ΛCDM:

> 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).* (Vaynberg 2024, 82-3) [my emphasis]

Putting all this together, we arrive at the following claim, which I take to be about the kind-constitutive properties making up the core causal description that can satisfy the semantic element in a scientific realism about dark matter:

> *Semantic Dark Matter Realism (SDMR)*: The one and only entity to which 'dark matter' refers is the entity possessing the following kind-constitutive properties: (i) non-baryonic; (ii) electromagnetically neutral; (iii) gravitationally interactive; (iv) acts like a collisionless fluid.[9]

The following evaluation of SDMR is divided into two steps. The first scrutinizes the feasibility of applying Psillos' framework to the dark matter case as articulated by Vaynberg. Certain theoretical commitments embedded in Psillos' causal-descriptive theory of reference are overlooked by Vaynberg. In particular, I make explicit what must be assumed about kind-constitutive properties for them to fix reference as intended, and how those assumptions interact with the underdetermination present in the dark matter case. Explicating these embedded commitments illuminates substantial issues when revisiting the given kind-constitutive properties that provide the

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[7] (Psillos 2012, 226): "Since we have no theory-independent access to the kind-constitutive properties of a natural kind, we have to rely on theories and their causal-explanatory descriptions of the entities they posit."

[8] Later, I will also consider whether the ensuing critique is robust under alternative ways of extracting a ΛCDM-motivated core — e.g., formulations closer to mass and interaction-strength constraints — since the present section is intended to reconstruct Vaynberg's proposal as he formulates it.

[9] Instead of Vaynberg's (a) and (b), I partitioned the properties through (i) - (iv), since this more clearly individuates on the *property level*, so is more compatible with the kind-constitutive framework. This partition is not meant to presume whether the properties are 'intrinsic' in any strong metaphysical sense, but only is a presentational choice meant to track the form of Psillos' criterion, where reference-fixing is attributed to a set of kind-constitutive properties. Note that despite adopting Psillos' "one and only entity", I take that to mean *entity-kind* rather than entity full stop, in the sense that all members of the natural kind dark matter share the same set of kind-constitutive properties. This does not necessarily imply realism about natural kinds themselves. A weaker, purely role-based interpretation — on which 'dark matter' refers to whatever plays the relevant causal role — will be noted where relevant, but SDMR, as formulated here, is the stronger reference-fixing version that is meant to do the realist work Vaynberg requires.

core causal description of dark matter. The consequence is a metaphysics unable to fix reference, which therefore bears directly on Vaynberg's strategy to frame dark matter realism in terms of successful reference.

The second approach assumes, *arguendo*, that issues emerging from the first can be amended, and instead evaluates the consequences of taking SDMR at face value. Even so, I argue, Vaynberg's semantic realism in its current form does not deliver a semantics of dark matter that can justify realism. More precisely, I argue that the SDMR conditions, as employed, fail to be both necessary and sufficient for the intended kind of referential success, and that this failure is not an artifact of the particular presentation in (i)–(iv) but tracks a deeper problem about how much discriminatory semantic work can be extracted from the ΛCDM based causal description under persistent underdetermination. The next sections expand and develop these criticisms in the order of appearance above.

4 Hidden metaphysics

4.1 Natural kind dependency

Let us begin by explicating the metaphysical commitments that are typically alluded to in order to fix reference in Psillos' causal-descriptive theory — most prominently, a natural-kind framework. Psillos, although not explicitly defending or arguing for any particular account of natural kinds, still makes extensive use of concepts and ideas found in their literature. This is most evident in his causal-descriptive theory:

> Only theories can tell us in virtue of what internal properties or mechanisms, as well as in virtue of what nomological connections, a certain substance possesses the properties and displays the behavior it does. Similarly, only theories can tell us in virtue of what internal properties an item belongs to this rather than that kind. And only theories can tell us whether a certain collection of entities, samples or items is a candidate for a natural kind. [. . .] The kind-constitutive properties are those whose presence in an item makes that item belong to a kind. I will not argue here for the existence of natural kinds. But if there are natural kinds at all, then there are kind-constitutive properties. (Psillos 1999, 288)

In later work, Psillos reaffirms his position on the metaphysics for kind-constitutive properties, but stresses that these properties:

> are those *whose presence makes* a set of objects have the same, or sufficiently similar, *manifest properties, causal behaviour*, and causal powers. [. . .] If we assume that natural kinds have boundaries – based on objective similarities and differences – we can see how causal descriptions succeed in fixing the reference of a term. (Psillos 2012, 226)

Psillos' formulation of kind-constitutive properties — "objective similarities and differences," "internal properties," "properties presence in an item" — naturally invites an essentialist reading, in the sense that reference-fixing is supposed to be grounded in stable features of the would-be referent.[10] In its standard formulation, essentialism also fits Psillos' claim that kind-constitutive properties instantiated in an entity predetermine its causal behavior and *manifest properties*:

> According to essentialism, natural kinds are groupings of entities that share a common essence — intrinsic properties or structure(s) uniquely possessed by all and only members of a kind. An intrinsic property is a property that an entity has independently of any other things, while an extrinsic property is the one that a thing has in virtue of some relations or interactions with other entities. The basic idea is that the essence causes and explains all other observable shared properties of the members of a kind and allows us to draw inductive inferences and formulate scientific laws about them. Brzović (2018)

Taking stock, this means that the core causal description meant to fix the reference of 'dark matter' must consist of kind-constitutive properties — i.e., properties that are sufficiently stable and sufficiently discriminating to delineate a kind (or entity-kind) rather than merely constrain a role. On a full-blooded essentialist construal, this is naturally glossed in terms of an essence: a set of intrinsic (or at least 'internal') features that explains the relevant manifest behavior and supports inferences. It's not that the role-relevant constraints *must* be intrinsic, but that SDMR assigns them a function to fix reference that typically requires more than merely relational or negative constraints.

At this point, it may be prudent to reiterate that Vaynberg accepts Psillos' framework without modification, and that the arguments presented in the following section are not intended as objections against Psillos' theory in general, but rather against its application in the dark matter case. That said, Allzén (2021) formulates a critique against the general feasibility of Psillos' explanationist flavor of scientific realism using dark matter as a case study. He argues that its explanatory power forces a Psillos-style realist to accept dark matter realism in which case the possible (non-gravitational) detection of dark matter would be epistemically redundant with respect to realism. If my argument against Vaynberg is correct, it strengthens this dialectical pressure: it suggests that a Psillos-style explanationist implies dark matter realism, while the corresponding reference-fixing semantics struggles to deliver the intended non-trivial referential success in the dark matter case. Contrary to Martens and Allzén, Vaynberg offers a more positive outlook on (present-day) dark matter realism — one that fully endorses a Psillos-style semantics:

> 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. (Vaynberg 2024, 82)

Now that we have a better understanding of the natural kind metaphysics, and crucially, the ambition to anchor reference-fixing to kinds, that makes the causal-descriptive theory of reference tick, let us revisit the kind-constitutive properties proposed by Vaynberg as the core causal description of 'dark matter'.

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[10] Again, this comes down to the previous interpretation of Psillos' condition (2b). Psillos explicitly frames kind-constitutive properties as boundary-making and Vaynberg appeals to them to "single out the entity as being a distinct kind" (see V1). Nothing here turns on whether 'kind-constitutive' must be cashed out as *strict* metaphysical essentialism, what matters is whether the proposed properties can plausibly play the discriminating, reference-fixing role assigned to them.

4.2 Is dark matter a natural kind?

Vaynberg's formulation invites an essentialist conception of natural kinds insofar as it appeals to classic essentialist schematics. We have *necessity*: in the set of kind-constitutive properties, each property is individually necessary (all members of the kind must have it). We have *sufficiency*: taken together, the set of individually necessary properties is sufficient to pick out the kind, since any entity that possesses all necessary properties belongs to the kind.

> The sufficiency of the core causal description of dark matter provided by CDM is achieved because these properties compose a set of kind-constitutive properties that collectively make an entity belong to a unique kind. (Vaynberg 2024, 82)

In the remainder of this subsection, I argue that the properties enlisted as kind-constitutive for the core causal description of 'dark matter' are unfit for the role SDMR require them to play. Even if one grants that some of them function as genuine ΛCDM-motivated constraints on admissible candidates, they do not plausibly serve as kind-constitutive, reference-fixing properties in Psillos' sense — i.e., they do not collectively deliver the kind of discriminability required to "make an entity belong to a unique kind." The relevant question has now been reduced to: are the kind-constitutive properties proposed by Vaynberg capable of constituting a natural kind in the sense required by the strong, kind-anchoring metaphysics on which Psillos' causal-descriptive theory of reference depends? I argue that, viewed through this lens, the proposed kind-constitutive properties of SDMR appear less plausible as candidates for a natural kind essence. Let us begin with the general worry about properties defined by absence, exclusion, and negation that are present in SDMR. The properties (i) non-baryonic and (ii) electromagnetically neutral both appear as exclusionary definitions. I use *exclusionary* when a property is defined by absence, exclusion, or negation, and *affirmative* when defined by presence, inclusion, or instantiation. The problem is that although negative constraints can matter in science, they are often compatible with many distinct positive realizers, and so — without further positive structure — they tend to be too coarse-grained to properly fix reference in the way required by SDMR. They may constrain a role, but they do not, by themselves, delineate a kind. This connects and emphasizes the intrinsic/extrinsic point that a negation, even if 'internal' in some sense, can still be radically non-discriminating.

> A thing has its intrinsic properties in virtue of the way that thing itself, and nothing else, is. [...] The intrinsic properties of something depend only on that thing. [...] a sentence or statement or proposition is entirely about something iff the intrinsic properties of that thing suffice to settle its truth value. (Lewis 1983, 197)

4.2.1 Non-baryonic

It is questionable whether non-baryonic should be considered a suitable kind-constitutive property for SDMR's reference-fixing purposes. As ordinarily used in the dark matter context, 'non-baryonic' functions primarily as a constraint — ruling out ordinary baryonic matter as the dominant explanans of the dark phenomena — rather than as a positive characterization of what the relevant stuff is. Oxford Reference defines 'non-baryonic' as "a hypothetical form of matter not containing baryons —

that is, without protons or neutrons." As a constraint this is informative, but as a would-be differentia it remains compatible with an enormous range of distinct positive microphysical possibilities. The property of not having protons and neutrons therefore does not by itself say enough about what dark matter is to anchor a unique kind.

We can illuminate this with an example. Consider including "atoms not having 1 proton" as a kind-constitutive property for oxygen. This exclusionary definition only tells us that whatever oxygen is, it is not hydrogen. It is of course *true* of all members of the natural kind oxygen that its atoms do not have 1 proton, but we cannot from that infer what *makes it true*, as per Lewis above. Having any number of protons except 1 would make it true, which also violates uniqueness. Our exclusionary definition effectively underdetermines which specific number of protons makes the exclusionary definition true. Affirmative descriptions of properties, on the other hand, face no such issues. For instance, "atoms having 8 protons" *makes* "atoms not having 1 proton" true, and from this affirmative definition we also get to conclude that it is a candidate for uniqueness. Affirmative definitions of properties also enable us to further specify the causal behavior determined by an entity possessing them, since having 8 protons fixes the electron configuration, which determines reactivity patterns, bonding behavior, and its role in combustion.

The key point here is that only an affirmative description of a positive attribute instantiated in dark matter can ground the truth of the exclusionary definition 'non-baryonic'. In other words, it is by virtue of some positive, as-yet-unknown property that dark matter is non-baryonic — but the description of the former cannot be inferred simply from knowing the truth of the latter.[11] So while non-baryonic may be a reasonable *constraint* on candidates, it cannot fix reference: it constrains too little, and does so in a way compatible with many distinct kinds. This disqualifies non-baryonic as a kind-constitutive property in the strong sense required by SDMR.

4.2.2 Electromagnetically neutral

The property of being electromagnetically neutral may be taken as an exclusionary definition as well, since it is defined by the absence of interaction with the electromagnetic field. We may, however, reframe it in affirmative terms as the property of having *zero electromagnetic charge*. Yet, even when so construed, it does not seem to qualify as a kind-constitutive property necessary for uniquely delineating a kind. The reason is that this reframed definition is not universally instantiated across all dark matter candidates, some of which are hypothesized to possess small but non-zero charges. More importantly for present purposes, even if one idealizes to 'zero', the constraint remains massively non-discriminating: many physically distinct entities (and kinds) would satisfy it. In addition, as a property definition it fails to yield any positive causal entailment. Having zero electromagnetic charge does not fix a determinate causal profile, it merely ensures that no Coulomb attraction or repulsion, and no photon coupling, will accompany whatever causal powers an entity *does* in fact possess. Gravitational interaction, often cited in this context, is not a consequence of zero charge but rather a consequence of mass-energy. Thus, zero charge operates

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[11] Unless one provides evidence to support that baryonic/non-baryonic completely exhausts theoretical possibilities, making it a binary.

only as an exclusionary constraint and not as an essence-bearing property capable of individuating a natural kind in the SDMR sense.

4.2.3 Gravitationally interactive

Being gravitationally interactive is clearly formulated as an affirmatively defined property, one that marks the intended explanatory role: whatever dark matter is, it must gravitate. Nevertheless, its reference-fixing leverage is limited, simply because gravitational interaction is (as far as current physics indicates) near-universal across mass-energy (with notable exceptions like photons, which gravitate despite being massless). Moreover, modified gravity proponents would interpret 'gravitationally interactive' differently — not as a property of matter but as a feature of spacetime dynamics. Thus, while this property successfully distinguishes matter candidates from pure structural alternatives, it does little to discriminate among matter candidates, which is what SDMR requires. So the worry is not that the property is false or unphysical, but that it functions more like a background condition on admissible explanations than like the difference-maker that can single out a unique kind. This disqualifies it as a kind-constitutive property for SDMR's purposes, because the distinction it enforces is too coarse-grained to do the intended semantic work.[12]

4.2.4 Collisionless fluid

Acting like a collisionless fluid perhaps most obviously fails to qualify as an apt candidate for kind-constitutiveness in the strong, reference-fixing sense, since collisions by definition are extrinsic behavior. Moreover, in the ΛCDM context, 'collisionless' is best understood as an *effective* behavior in certain regimes, not as a microphysical essence. The relevant question is how nearly collisionless the dark component is at the scales and epochs that matter for the inferences. We once again see the exclusionary addition of *not* colliding with other entities (or itself). As a constraint this can be empirically important, but it is not fit to function as an essence carrying property. It is scale-sensitive, thresholded, and compatible with multiple microphysical realizations. Nevertheless, this is perhaps the most interesting property in the set since it is an emergent property sensitive to both environmental conditions and scale. At sufficiently large scales, galaxies exemplify this property, despite the fact that part of their total mass is baryonic, which, on sufficiently small scales, does not itself exemplify this property. This makes it difficult to assess it as a property an entity possesses, rather than as an emergent property manifesting in systems under certain conditions. If collisionless is weakened to *effectively collisionless in the relevant regimes*, then

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[12] I want to address the discrepancy between the phrasing "only interacts gravitationally" in the quote from Vaynberg and the subsequent condition "interacts gravitationally" in the core causal description. This difference materially impacts the range of possible entities that can be logically included. I take this discrepancy to be a clerical oversight, based on assuming that the sentence containing "only interacts gravitationally" most likely intended gravitational interaction to serve as a contrast class to electromagnetic interaction. Nevertheless, I shall cover this version as well, just in case. When 'only' is included, we introduce a significant constraint on possible dark matter candidates, by definition excluding a range of dark matter candidates not yet empirically ruled out: WIMPs couple via the weak force and the Z/Higgs, Scalar singlet interacts via Higgs exchange, Fermion singlet to the Higgs and the weak force by mixing, minimal dark-matter multiplets ($SU(2)_L$) couple to the weak force as does the lightest Kaluza-Klein particle. Although the inclusion of a restrictive modifier acts as a clear differentia for natural kindhood, it obviously excludes too much.

SDMR inherits the further problem that the property becomes too imprecise to bear the reference-fixing role it is assigned. At any rate, (iv) should be disqualified as a kind-constitutive property in the SDMR sense.

In summary, all of the properties enlisted to serve as the kind-constitutive basis for the core causal description of 'dark matter' appear ill-suited to the particular semantic job SDMR assigns them. They may well be defensible as ΛCDM-motivated constraints on a role, but the problem is that when taken as a bundle of kind-constitutive properties meant to single out a unique kind, they are too coarse-grained, too threshold sensitive, or too compatible with many distinct realizers to plausibly function as reference-fixers in Psillos' intended sense. Essentialism about natural kinds may well retain its precision and legitimacy within the general contours of Psillos' scientific realism (although see the remark regarding the paper by Allzén (2021)), but it fails to transfer to cases at the margins, such as dark matter. The exclusionary, relational, and ubiquitous character of the proposed properties leaves us without a positive, intrinsic attribute capable of sustaining kind-constitutiveness. Or, more cautiously: it leaves us without a sufficiently discriminating set of properties capable of sustaining kind-constitutiveness *in the strong reference-fixing sense SDMR requires.*

A natural objection is that NB/EN/GR/CF is not the most obvious articulation of the ΛCDM-motivated constraints on (particle) dark matter. One might instead propose a more 'intrinsic-like' core, along the lines of that the relevant entity is massive within cosmological and laboratory bounds, and neutral or extremely weakly coupled to Standard-Model forces (optionally with free-streaming/velocity bounds that imply 'coldness'). I agree that such constraints track contemporary candidate taxonomy more directly. But the central problem persists nonetheless. At best, these constraints pick out a broad determinable role realized by many inequivalent microphysical determinate options, and tightening them to discriminate between realizers effectively presupposes the kind of canonical detection and parameter determination that SDMR was meant to secure under empirical scarcity. If this is still not convincing, we can consider the consequences of accepting Vaynberg's proposed properties as the core causal description of 'dark matter' at face value.

5 A model-space for dark phenomena

For the sake of argument, let us ignore the issues outlined in the previous section and assume that the properties proposed as kind-constitutive for a core causal description are qualified as such by some metaphysics or other. Taking SDMR at face value implies that for any entity, if that entity possesses the kind-constitutive properties (i)–(iv), it is a member of the natural kind dark matter. This follows from the claim that the relevant properties are jointly sufficient:

> 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. (Vaynberg 2024, 82)

The set of statements jointly offered in support of, and as a definition of, dark matter can be summarized as follows. The term dark matter refers to the members of a natural kind. Membership in the natural kind is restricted to entities instantiating a set of properties (i)–(iv). Properties (i)–(iv) satisfy the core causal description from ΛCDM. All present or future entities that satisfy the core causal description by instantiating properties (i)–(iv) will be members of the natural kind, and thus what the term dark matter refers to. At present, there is no empirically confirmed entity that satisfies the core causal description by instantiating properties (i)–(iv) and thereby serves as the referent of *dark matter*.

In order to gauge the implications of SDMR, it is useful to think about the space of possible models of dark matter. In table 1, we have a compact, many-sorted first-order language framework, L, that will help us articulate a model-space for candidate explanations of dark phenomena.

Table 1 L: signature

Symbol	Term	Object
ϕ	variable	network of phenomena
φ	variable	phenomena
x	variable	entities
s, o	constants	modes of x (structure or object)
α	variable	ontological individual
P	unary predicate	properties
dm	individual constant	theoretical term 'dark matter'
m	variable	model
$\mathbb{M}$	set	over models
$\mathrm{E}, \mathrm{C}, \mathrm{D}$	ternary predicate	takes m, x, φ
Em	unary predicate	empirically confirmed
$\mathrm{R}(t, \alpha)$	binary predicate	term t refers to α
$\Diamond P(x)$	modal operator	possibility

First, we can define the *explanandum* for which the term 'dark matter' is taken to be the *explanans*, as well as the cause. We remain theory-neutral and simply define it in terms of unexplained phenomena for which dark matter has been invoked as an explanation, or in terms of 'dark phenomena':

> The fact of the matter is that the conjunction of the assumptions i) GR, and Newtonian Gravity as its non-relativistic limit, is the correct theory of gravity (and spacetime) and ii) most of the matter in the universe is luminous baryonic matter (the stuff that stars and planets consist of), leads to predictions that have been falsified by observations. We will call these observations 'dark phenomena' or 'dark discrepancies'. (Martens and Lehmkuhl 2020, 2)

Let ϕ_{dark} contain exactly those phenomena the cause and explanation of which are attributed to dark matter, the "dark phenomena" of Martens and Lehmkuhl (2020).

$$\text{DARK MATTER PHENOMENA:} \qquad \phi_{\text{dark}} := \{\varphi : \varphi_{dark}\} \tag{1}$$

We have two individual constants o and s to represent the two modes of ontology represented in dark matter models such that:

$$o \neq s \quad \text{and} \quad \forall x\,(x = o \;\vee\; x = s) \quad (\text{here } x \text{ ranges over } \textit{modes} \text{ when used in E, C, D})$$

This ensures that even though the variable x is present, it is taken to be either an ontological object (o) or an ontological structure (s) when used in the context of the predicates $\mathrm{C}, \mathrm{E}, \mathrm{D}$. These predicates should be interpreted as expressing that the model ascribes a cause for the phenomena, an explanation of the phenomena in terms of the cause, and a description of the entity causing the phenomena:

$\mathrm{C}(m, x, \varphi)$: in m, x is a cause of φ
$\mathrm{E}(m, x, \varphi)$: m explains φ with x
$\mathrm{D}(m, x, \varphi)$: m describes x *qua* cause of φ

We can then define the model-space for candidate explanations of dark phenomena as:

$$\mathbb{M} := \Big\{\, m \colon \forall\varphi \in \phi_{\text{dark}} \exists x \Big(\mathrm{E}(m, x, \varphi) \wedge \mathrm{C}(m, x, \varphi) \wedge \mathrm{D}(m, x, \varphi)\Big)\Big\} \tag{2}$$

5.1 Regions and boundaries

We can partition model-space to distinguish a subset of $\mathbb{M}$ in which all models are restricted with respect to ontological *objects*, i.e., models that add new ontological kinds to explain the phenomena. These would be models typically containing a new particle, field, or other novel ontic object, taken to cause and explain φ, which the model provides a description of. We define this subset, $\mathbb{O}$, as:

$$\mathbb{O} := \Big\{\, m \colon \forall\varphi \in \phi_{\text{dark}} \exists x \Big(x = o \wedge \mathrm{E}(m, x, \varphi) \wedge \mathrm{C}(m, x, \varphi) \wedge \mathrm{D}(m, x, \varphi)\Big)\Big\} \tag{3}$$

Mirroring the same reasoning gets us a partition of *structure*-restricted models, $\mathbb{S}$, i.e., models that do *not* add new ontological kinds to explain the phenomena, but rather make the case that the phenomena can be explained by a reconfiguration of already accepted entities and their properties (s). These would be models typically attempting to reconceptualize the description of gravity such that the resulting gravitational dynamics is taken to cause and explain φ.

$$\mathbb{S} := \Big\{\, m \colon \forall\varphi \in \phi_{\text{dark}} \exists x \Big(x = s \wedge \mathrm{E}(m, x, \varphi) \wedge \mathrm{C}(m, x, \varphi) \wedge \mathrm{D}(m, x, \varphi)\Big)\Big\} \tag{4}$$

Structure-based ($\mathbb{S}$) models are included here only as contrast-class competitors in the landscape of explanations for ϕ_{dark}. SDMR's reference-fixing constraint is explicitly object directed, and so $\mathbb{S}$ models do not count as candidates that satisfy SDMR's ontological requirement. We define the current catalog of known, empirically viable models as a subset of object-and structure-based models, $\mathbb{K} \subset (\mathbb{O} \cup \mathbb{S})$. For completion, we can define a space in $\mathbb{M}$ designated to unknown, or unconceived, alternative models, i.e., models that give possible explanations and causes for ϕ_{dark} described by some yet-to-be-considered physics, as:

$$\mathbb{U} := \{m \in \mathbb{M} \colon m \notin \mathbb{K}\} \tag{5}$$

This makes the model-space completely constituted by their partitions in the following way:

$$\mathbb{M} = \mathbb{O} \cup \mathbb{S} \cup \mathbb{U} \tag{6}$$

According to Vaynberg, any future detection of *actual* dark matter will show that, whatever model is true of actual dark matter, it will contain the kind-constitutive properties in $\mathbb{VDM}$. That implies a sharp boundary for what a possible model of dark phenomena in model-space can be. Let's see how the space of possible dark matter models looks under Vaynberg's constraints. We can abbreviate the four kind-constitutive properties in SMDR as follows:

$$\mathbb{VDM} \colon \left\{ \begin{array}{l} \text{NB} = \text{Non-baryonic} \\ \text{EN} = \text{Electromagnetically neutral} \\ \text{GR} = \text{Gravitationally interacting} \\ \text{CF} = \text{Acts like a collisionless fluid} \end{array} \right\} \tag{7}$$

We take the joint instantiation of these properties in some ontological object to be $\mathbb{VDM}(\alpha)$. This encodes, or imparts, the joint property constraints $(\text{NB}, \text{EN}, \text{GR}, \text{CF})$ on the *object* α to which the term 'dark matter' refers (object because the kind-constitutive properties exclude models of modified gravity — which hold that the referent of 'dark matter' is void). Vaynberg's $\mathbb{VDM}(\alpha)$ gives us a boundary condition for what dark matter *could possibly be*:

$$\text{VAYNBERG CONSTRAINT:} \qquad \mathbb{V} := \{\ \alpha \colon \mathbb{VDM}(\alpha)\} \tag{8}$$

This is the space of entities that could possibly be the referent of 'dark matter' — a constraint for what is ontologically admissible for a model — as predicted by the claim that any future detection of dark matter, whatever it may amount to, will at least satisfy the Vaynberg constraint. We can think of this as a prerequisite condition for membership in the dark matter kind. Models in $\mathbb{O}$ compatible with some $\alpha \in \mathbb{V}$ are inside the Vaynberg boundary, pure $\mathbb{S}$ models fail the object-requirement. $\mathbb{V}$ constrains which entities can be realized by models in $\mathbb{M}$, some entities admissible by $\mathbb{V}$ may have no current model in $\mathbb{K}$. To make the model-space partitions, as well as the Vaynberg

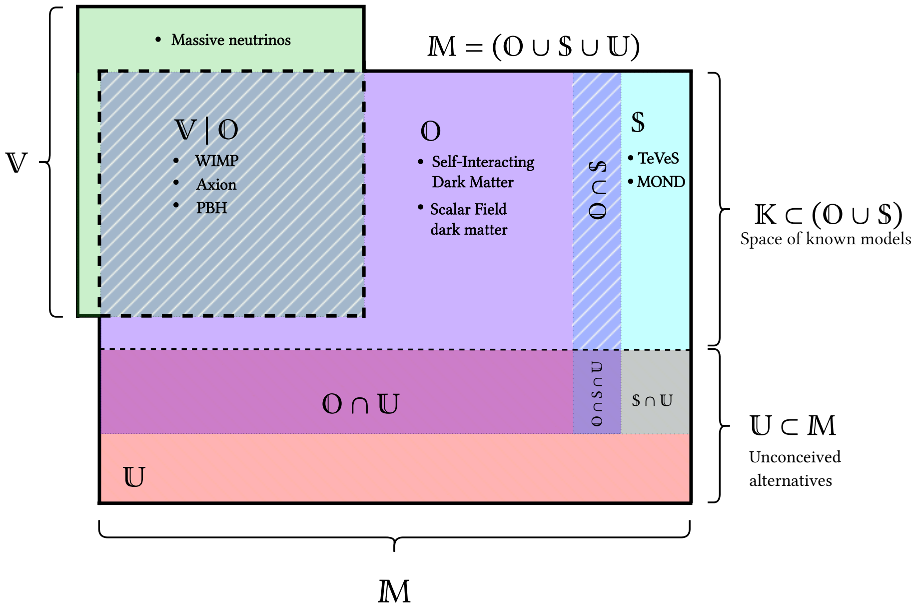

Fig. 1 Model-space. Y axis is split between known and unknown models, the X axis is split between object and structure based models. The shaded area is the Vaynberg constraint $\mathbb{V}$, and PBH is the abbreviation of Primordial Black Holes.

constraint, more intuitive, we can use figure 1 as a heuristic device. The idea is to get a spatial map of "where models live" based on the partitions. $\mathbb{V}$ is not a strict part of model-space, but is superimposed on top of it, highlighting the region where its constraints correspond to a model specification.

6 The referential failure of 'dark matter'

A clarification before moving on. There are two questions one might conflate: (i) a question of physical admissibility — what constraints a ΛCDM-compatible dark-sector model must satisfy to remain a live option given the successes of ΛCDM, and (ii) a semantic question — what conditions must obtain for 'dark matter' to refer on a Psillos-style causal–descriptive semantics that treats certain properties as kind-constitutive reference-fixers. The claims about necessity and sufficiency below concern (ii), not (i). They assess whether Vaynberg's proposed bundle of reference-fixing properties ($\mathbb{VDM}$) can play the semantic role assigned to it. The plotted models in the diagram above foreshadow the central points I am about to make in this section, in the sense that we see the $\mathbb{V}$ boundary of admissible objects extend beyond model space, and additionally cut right through the space of known models. This section clarifies why, and provides a diagnostic for SDMR. I identify two types of *semantic mistakes*, showing that the kind-constitutive properties are neither necessary nor sufficient for the intended purpose.

6.1 Semantic mistake: type a

One type of semantic mistake shows that the kind-constitutive properties are not *necessary* for securing the referent. We can say that it is possible that an individual object α is in a causal-explanatory model for phenomena $\varphi \in \phi_{\text{dark}}$, and 'dark matter' refers to α ($\mathrm{R}(dm, \alpha)$). But if α does not instantiate the joint property constraints in $\mathbb{VDM}$, then the kind-constitutive properties are not necessary for securing the referent of 'dark matter'. This is a failure of *necessity.*

$$\text{TYPE A } (\neg \text{ NECESSARY}): \qquad \Diamond\exists\alpha \Big(\mathrm{R}(dm, \alpha) \wedge \neg\mathbb{VDM}(\alpha)\Big) \tag{9}$$

Vaynberg tells us that the "mode of gravitational interaction tells us to expect dark matter to act like a collisionless fluid." This expectation comes from galaxy-scale observations and cosmological modeling under ΛCDM. This implies no significant non-gravitational self-scattering that alters those dynamics in the relevant regimes. But that ambiguity is precisely what makes CF ill-suited to serve as a reference-fixing constraint. Read strictly as excluding non-gravitational self-interactions, it excludes families of live dark-sector proposals that preserve ΛCDM's large-scale phenomenology. Read weakly as effectively collisionless in the currently probed regimes, it becomes a regime-relative modeling idealization as opposed to a stable kind-constitutive differentia. Either way, CF cannot plausibly be a necessary condition for kind-membership in the strong SDMR sense.

1. **Self-interacting dark matter**
   Cold halos with elastic self-scattering produce cores and shape/abundance effects; a velocity-dependent cross section aligns dwarfs/galaxies vs clusters. Example: $\sigma/m \sim 0.1$–$1\ \mathrm{cm}^2\mathrm{g}^{-1}$ at $v \lesssim 300\mathrm{km\ s}^{-1}$, dropping to $\lesssim 0.1$ at cluster scales. This is explicitly non-collisionless while preserving the ΛCDM gravitational function. See Spergel and Steinhardt (2000), Tulin and Yu (2018)
2. **Dissipative / double-disk dark matter**
   A dark $U(1)$ with a (possibly light) dark photon enables radiative cooling in a subcomponent of dark matter, forming dark disks/compact substructure while the bulk remains cold on large scales. Example: kinetic mixing $\varepsilon \lesssim 10^{-9}$ (model-dependent); a sub-dominant fraction $f_D \lesssim$ few% is enough to alter inner-galaxy dynamics. Again, not collisionless. See Fan et al. (2013)
3. **Mirror dark matter**
   An exact standard model copy $(e', p', H', \dots)$ with gravity and tiny photon–mirror-photon mixing. Mirror electromagnetism makes the sector dissipative, permitting cooling, disks, and distinctive halo thermodynamics — not collisionless — yet the same gravitational role is played. Example: $\varepsilon \sim 10^{-9}$ appears in halo and supernova-heating phenomenology. See Foot (2014)
4. **Superfluid dark matter**
   Strongly interacting, light bosons condense in galactic interiors. Phonon excitations mediate an additional force reproducing MOND-like scaling while retaining

ΛCDM on cosmological scales. The inner halo is a fluid with non-negligible self-interaction — not collisionless — yet still fits the gravitational brief. Berezhiani and Khoury (2015), Khoury (2016). See Martens and Lehmkuhl (2020) for discussion of superfluid dark matter as object vs. structure (matter vs spacetime). For present purposes, the key point is that it violates CF while preserving the gravitational-explanatory role.

5. **Strongly interacting massive particles**
   Relic abundance arises via $3 \to 2$ processes in a strongly-coupled dark sector; the same dynamics generically yield large elastic self-interactions in the core-forming window. Example: $m \sim 10$–100 MeV; σ/m often in the 0.1–10 $\mathrm{cm}^2\mathrm{g}^{-1}$ regime (model-dependent). See Hochberg et al. (2014)

In all of the above models, the relevant explanatory gravitational role is preserved while *collisionless* is systematically violated (elastic self-scattering; radiative cooling; phase structure; strong number-changing dynamics). Therefore, CF is *not* necessary for the causal-explanatory function ΛCDM assigns to dark matter. Any semantics that includes it in the kind-constitutive core will misclassify live realizers.

6.2 Semantic mistake: type b

Another type of semantic mistake shows that the kind-constitutive properties are not *sufficient* for securing the referent. We can say that when an individual object α instantiates the joint property constraints in $\mathbb{VDM}$, then ‘dark matter’ refers to α ($\mathrm{R}(dm, \alpha)$). But if α is a known empirically confirmed entity *not* taken to be dark matter, then $\mathbb{VDM}$ is not sufficient to secure the referent of ‘dark matter’. This is a failure of *sufficiency.*

$$\text{TYPE B } (\neg \text{ SUFFICIENT}): \qquad \exists\alpha \Big(Em(\alpha) \wedge \mathbb{VDM}(\alpha) \wedge \neg \mathrm{R}(dm, \alpha) \Big) \tag{10}$$

The second failure shows that the kind-constitutive constraints are not sufficient to secure reference. There are ontic candidates that do instantiate the joint property constraints in $\mathbb{VDM}$ but to which ‘dark matter’ does not (even possibly) refer, because they fail to cause/explain the relevant phenomena in ϕ_{dark}.

1. **Standard model neutrinos**
   Let $\alpha = \nu$ denote the cosmic background of massive, active neutrinos. Neutrinos are non-baryonic (NB), electromagnetically neutral (EN), gravitationally interacting (GR), and (for structure formation) effectively a collisionless fluid (CF). Hence, ν satisfies the *joint constraints* in $\mathbb{VDM}(\nu)$.[13]

Yet ν fails the causal–explanatory role that ΛCDM assigns to the dominant dark matter component (recall footnote 4) across $\varphi \in \phi_{\mathrm{dark}}$ (e.g., seeding/maintaining

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[13] On the cosmology of massive neutrinos, see Lesgourgues and Pastor (2006), for the parameter imprint and suppression of small-scale power, see Hu et al. (1998).

small-scale structure, halo formation). The reason is *free-streaming*: relativistic (or semi-relativistic) neutrinos erase perturbations below a characteristic scale, suppressing the matter power spectrum at $k \gg k_{\mathrm{fs}}$ roughly in proportion to the neutrino fraction $f_\nu = \Omega_\nu/\Omega_m$:

$$\frac{\Delta P}{P} \simeq -8\, f_\nu \qquad \text{and} \qquad \Omega_\nu\, h^2 = \frac{\Sigma m_\nu}{93.14 \text{ eV}} \tag{11}$$

Empirically, the observed abundance of small-scale structure and CMB/large scale structure constraints on Σm_ν jointly rule out neutrinos as the *dominant* dark matter component; they cannot realize the required gravitational-explanatory role in ϕ_{dark}.[14]

There exists an $\alpha(\nu)$ such that $\mathbb{VDM}(\alpha)$ holds while $\neg\mathrm{R}(dm, \alpha)$ also holds. Therefore, $\mathbb{VDM}$ is not sufficient for referential success on a causal-descriptive semantics. Strengthening $\mathbb{VDM}$ by adding ad hoc clauses (e.g., “coldness,” or a bound on free-streaming) simply begs the question, since those clauses are *fixed by* the very explanatory successes at issue. In conclusion, the kind-constitutive properties in $\mathbb{VDM}$ fail to be either necessary or sufficient for securing the referent of ‘dark matter’ on a causal-descriptive semantics. This renders SDMR semantically defective in the dark matter case, and thereby breaks the case for realism about dark matter.

7 Scientific realism and empirical scarcity

Above, I argued that applying scientific realism to the dark matter case as per Vaynberg (2024) is plagued by incompatibility in both metaphysics and semantics. It is my suspicion that this incompatibility is not accidental, nor merely attributable to idiosyncrasies of the dark matter context. Rather, we should view it as endemic to scientific realism in an era in which theory in cosmology, astrophysics, astronomy, and particle physics proves difficult to couple with empirical evidence *of the sort that scientific realism presupposes.* This closing section expands the rationale for this worry by showing how it manifests in the dark matter case and why there is reason to suspect that it extends, more generally, to theoretical environments characterized by empirical scarcity.

7.1 Dark matter, specificity, and truth-preservation

As we have seen, employing the (causal-descriptive) semantics of scientific realism in a case like dark matter is not straightforward. I have explicated two reasons:

A | *Metaphysics*
Causal-descriptive semantics rely on a metaphysics of natural kinds, explicated as the *internal* properties of an object which together constitute a unique kind.

B | *Semantic errors*
Accepting the causal-descriptive semantics for dark matter at face value showed

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[14] For contemporary cosmological bounds and the associated structure-growth implications, see Planck Collaboration (2020).

that its extension failed to contain a meaningful set of entities and structures featured in models currently considered live options.

There are reasons to think that B fails for the same underlying reason as A: the semantics of scientific realism require a level of empirical detail that is not available in the dark matter case. The discussion of intrinsic properties in section 4.2 showed that the metaphysics of natural kinds is ill-suited here in its current state because we lack the empirical resolution needed to identify a unique set of intrinsic properties. We do not know what makes it true that dark matter is, for instance, non-baryonic. Non-baryonic is best described as a determinable property or a genus-level class of properties, like *color* or *shape*.[15] Such properties can be made more precise by specifying a *determinate* property or a *species* of non-baryonic matter — analogous to specifying a determinate red for the determinable *color*.[16] The semantics of scientific realism, as currently formulated, operate on the latter, not the former.

The problem can be expressed in terms of truth-conditions using the concept *hyperintensionality*, used to classify sensitivity to differences in meaning that do not change truth-conditions.[17] Even when different models agree on determinables (e.g., NB, EN, GR, CF), they may disagree in their truth-makers — the fine-grained grounds that make those determinables true. WIMPs and axions are both non-baryonic extensionally, yet what makes this true differs hyperintensionally — WIMPs being neutralinos and QCD axions being Peccei–Quinn (pseudo) Nambu-Goldstone Bosons (PBH's are non-baryonic for a third, non-particle, reason). Consider:

a. Dark matter is non-baryonic
b. Dark matter is a QCD Axion

According to Vaynberg, (a) is necessarily true. If we suppose that (b) is true, and "QCD axion" is a proper name, then (b) is necessarily true. This renders (a) and (b) necessarily equivalent, such that the truth of (a) is preserved when we substitute the predicate "non-baryonic" for "QCD axion". However, we can know (a) without knowing (b). The reason (a) appears robust, and why it features in $\mathbb{VDM}$, is that its truth value is preserved under model substitution — i.e., it is (supposed to be) model-invariant. This can be thought of as the truth-equivalence between (a) and a disjunction of predicates:

c. Dark matter is a WIMP or a QCD axion or a PBH …

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[15] A determinable property is a general property that can be realized by multiple specific properties. For example, the property of being a "color" is a determinable property because it can be realized by specific colors like red, blue, or green. In contrast, a determinate property is a specific property that uniquely identifies an entity. For example, the property of being "red" is a determinate property because it uniquely identifies a specific color. See Wilson (2023).

[16] Note that *red* is also the determinable of properties of increasing resolution: crimson, scarlet, vermilion, burgundy, etc.

[17] "A *hyperintensional* concept draws a distinction between necessarily equivalent contents. If the concept is expressed by an operator, H, then H is hyperintensional insofar as HA and HB can differ in truth value in spite of A and B's being necessarily equivalent" Berto and Nolan (2025).

The truth of (a) is preserved when substituting its predicate with the disjunction of predicates in (c). However, the truth of the individual disjuncts — the predicate-propositions in (c) — is not preserved if we substitute the predicate in one disjunct with a predicate from another. In the analogue, “x has a color” is true if “x is red or x is blue or x is green . . . ” is true, but “x is red” does not remain true if we substitute “red” for “blue” or “green”. The truth of the determinable is preserved under substitution of the disjunction of determinates, but the truth of the determinates is not preserved under substitution of one another. This is a hyperintensional distinction, and it makes all the difference for scientific realism.

One reason is that truth-conditions vary with the level of precision in the description of the referent. The more precise the description, the more constrained the set of possible realizers and the less precise the description, the less constrained the set of realizers. This is a problem for scientific realism because it relies on a *causal-descriptive* semantics that requires a unique set of intrinsic properties to fix reference. If we only have a determinable, then we cannot uniquely fix reference because there are many possible realizers. For example, ‘dark matter is non-baryonic’ can be made true by many different types of non-baryonic matter, such as WIMPs, axions, or PBH’s (see figure 2). The truth of the statement is invariant with respect to model choice at this level of discrimination. But these models vary in what makes it true that dark matter is non-baryonic. As in the proton-number case from section 4.2, unless we provide the determinate property, we cannot provide the intrinsic properties necessary for scientific realism to apply. It is not enough to describe an entity by its determinables. We need to know what *makes it true* that the entity has those properties. It may be a true description of an entity that it has both determinables *color* and *shape*, but realism is apt only when we can say that an entity is red and round, rather than, say, blue and square.

In short, dark matter realism fails here not because determinables are false, but because we lack hyperintensional access to their realizers. Without that grain, causal–descriptive reference and natural-kind individuation cannot be secured. Thus, while determinables guide modeling, they bear no realist weight on a causal–descriptive semantics absent access to their determinates, so realism here must wait for truth-makers or retreat. This embodies the conclusions of Martens (2022) and Allzén (2021): Martens (2022) argues that dark matter realism requires a descriptive semantics that is neither empirically underdetermined nor vacuously true — which Allzén (2021) argues is precisely the descriptive content that canonical forms of empirical confirmation via detection provide. One can remain a dark-matter realist in a pragmatic or provisional sense, but not by invoking classical scientific-realist justification. The failure arises as a consequence of traditional realism in combination with dark matter lacking the required empirical flavor, not from dark matter per se. Insisting that scientific realism at this stage vindicates dark-matter realism constitutes justificatory overreach. For realism, empirical confirmation serves a dual purpose: it confirms the existence of an entity and simultaneously furnishes the semantic description of that entity with the intrinsic properties realism requires.[18] This exposes scientific realism — typically

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[18] See Martens (2025) for a discussion on what the detection of dark matter really means, and Jreige (2024) for a methodological taxonomy of dark matter experiments.

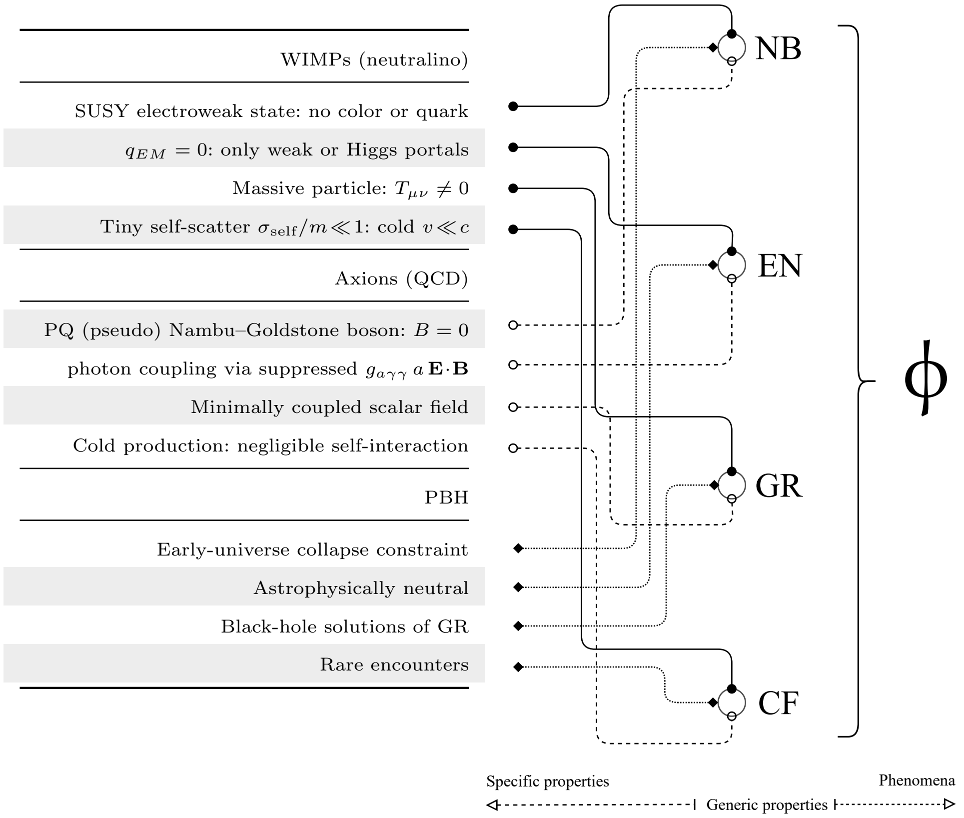

Fig. 2 Determinates (left) for determinables (right) which act as proxy explanations for phenomena.

applied after the moment of confirmation — to the epistemic reality of twenty-first-century science. The situation is revealing because it shows that scientific realism may depend, semantically and epistemically, on a form of empirical confirmation typically unavailable in frontier physics.

7.2 Archaic scientific realism: adapt or perish

The issues outlined above are not obviously unique to dark matter. They are likely to be characteristic of scientific realism in contemporary science, particularly in fields like cosmology, astrophysics, and particle physics, where empirical data are often scarce or indirect — able to fix determinables where realism requires determinates. Modern measurements and large-scale surveys are often summaries and integrated effects: power spectra, lensing maps, event rates. By their nature, such observables are compatible with many different underlying mechanisms. Empirical confirmation of the particle-physics variety provides exactly the semantic detail that the causal–descriptive theory of reference is meant to capture. When ostensive definitions (“that is gold”) are unavailable, the only substitute for sufficiently fine-grained semantics is empirical detection:

> But Locke's old problem, the *qua* problem, looms. A chunk of gold, for example, would have to be included in the reference of the term 'gold' in virtue of one underlying property and in the reference of 'metal' in virtue of quite another. Investigating the world can only tell us what structural properties objects have. It cannot divulge which ones are of interest in specifying the reference of particular terms. To be sure, once we know a lot of physics and chemistry, when we can actually specify the respects in which the internal structures of all samples of gold must agree – or, in other words, when we can provide an explicit description of the internal structure – there is no problem. Prior to that point, what is required is a way of picking out which structural feature is implicated in reference for a particular natural kind term. (Stanford and Kitcher 2000, 109)

In other words, without a principled way to pick out which underlying property (the 'qua' aspect) is doing the referential work for 'dark matter', our semantic success remains in limbo. Scientific realism, as traditionally formulated, assumes that such reference-fixing properties will eventually be revealed by investigation. But in cases like dark matter, we have the phenomena and a label — 'dark matter' — without a determinate property to anchor that label. This reinforces the notion that realism here must either wait for an empirical breakthrough or revise its expectations.[19] Scientific realism has stayed admirably close to the epistemic practices of twentieth-century physics, so it is unsurprising that the scope of its realism extends exactly to the boundary of those practices. Realism — born in the "golden age" of particle physics, where canonical experiments reliably confirmed the entire Standard Model — struggles to accommodate theoretical entities like dark matter, whose confirmation does not follow the usual experimental paradigm. Plausibly, the dark-matter case is not an anomaly but a representative instance of the epistemic state of contemporary physics, which operates at scales, regimes, and physical boundaries practically (and sometimes in principle) inaccessible to past epistemic practices. If this pattern *is* endemic — not a temporary technological impasse but a stable epistemic and theoretical reconfiguration of scientific inquiry — then classical realism risks obsolescence as a doctrine of realism for much of contemporary and future science. According to this diagnosis, the existential threat to scientific realism is not external, but internal. It does not come by counterexample from a determined anti-realist, but from scientific realism's own internal structure being unable to accommodate the evolution of scientific theorizing and epistemic practices. Unless it addresses these issues, scientific realism risks withering away in a changed scientific landscape, barren of the once-abundant forms of empirical confirmation. The choice is to either insist on classical standards and suspend realism, or modify our conceptual framework of scientific realism to fit twenty-first-century science. The wager is clear: either the evidence will, at some point, resolve into the right kind of grain, or the philosophy must.

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[19] Some philosophers equipped with both foresight and providence have laid the conceptual foundations to address precisely such a situation: Dawid (2013, 2017, 2019); Dawid et al. (2015), McCoy (2021, 2019), Vickers (2023), Wolf and Read (2025).

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