Historical Continuity as Justification for Dark Matter

How History Becomes an Epistemic Strategy

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Abstract. After decades of attempts at non-gravitational identification, the nature of dark matter's constituents remains unresolved despite robust gravitational support. Research histories contribute to the justification of continued commitment by presenting contemporary searches as stages in an established inquiry into a single, enduring object. I examine how this historical pedigree is constructed and how it supplies grounds for sustaining the research program. I examine this process in Bertone and Hooper's *History of Dark Matter*, combining citation analysis of its broad circulation with close reading and historical reconstruction. Earlier astronomers used dark matter to explain both dynamics and the absorption of light. In the work of Oort and Holmberg, these roles entered the same arguments and calculations, jointly constraining the material under investigation. A history organized around dynamics follows the explanatory strand that has survived into the present characterization of dark matter. Identifying that strand with the history of one object requires interpreting some earlier commitments as descriptions of the continuing target and others as belonging to different inquiries. Through anchoring, stabilization, and rationalization, this selection gives present research a cumulative pedigree and makes sustained commitment intelligible despite the target's unresolved nature. The present characterization selects the lineage through which its own target then appears historically established. The integrated earlier practice makes this dependence visible and shows why the survival of explanatory requirements cannot by itself establish the continuity of their object.

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1. Introduction

Dark matter combines robust gravitational and cosmological support with persistent uncertainty about the nature of its constituents. Many lines of observation and modeling support a non-luminous mass component, yet decades of searches have not delivered an agreed non-gravitational identification of its constituents. This combination has sustained a proliferation of candidates alongside debate about how the program should proceed (Bertone and Tait, 2018; Merritt, 2021). It also raises a question about the identity of the inquiry: in what sense do contemporary searches concern the same object investigated by the astronomers whose work supplies dark matter's historical pedigree?

Research histories offer an answer. They connect earlier investigations to present practice by identifying a continuing target whose properties have become better understood. Bertone and Hooper's *History of Dark Matter* (Bertone and Hooper, 2018) is a particularly consequential example. It is widely cited across research areas, reconstructs the emergence of missing-mass arguments, and explicitly connects early estimates of unseen matter to present attempts at particle detection. By connecting these investigations through a continuing target, the history presents a reason to regard current research as the continuation of earlier scientific achievements.

I argue that this historical identity is itself part of the justification the narrative supplies. Dynamics provides the principal connection because it belongs to the explanatory commitments that have survived into the present characterization of dark matter. A history following that strand presents earlier estimates of unseen matter as stages in understanding what contemporary searches investigate, while other historically integrated roles acquire a different status. This genealogy gives continued commitment the pedigree of an established inquiry even while the

nature of its object remains unresolved. The question is how the survival of selected explanatory commitments comes to support that account of the object and its history.

Early uses of 'dark matter' make the grounds of this continuity a substantive historical question. Alongside its use in accounts of a gravitational mass deficit, astronomers used the term for light-obscuring material, sometimes relating its absorption and dynamical effects within the same argument or calculation. Since these roles were integrated in earlier investigations, their subsequent separation requires an account of why one explanatory strand constitutes the lineage of the present target while another is treated as incidental to it.

The general observation that scientific histories reorganize the past around present commitments is familiar from Kuhn's account of textbook history and from historiographic discussions of retrospective selection (Kuhn, 1970, ch. XI; Kragh, 1987; Pestre, 1999; Staley, 2008). The point here is not to reiterate this observation, but to scrutinize the *function* of historical selectivity in *identifying an object whose nature remains unresolved*. De Swart and collaborators explain how distinct missing-mass problems came to be treated as a common anomaly (de Swart et al., 2017; de Swart, 2020). I build on that distinction between separate problems and a unified target, while asking how later histories connect those problems to the ancestry of the present target. The evidential significance of the 1974 synthesis is examined separately in Allzén (2025). Here the issue is how later histories identify the object of that inquiry across these changes and use its history to support continued commitment.

This argument requires a distinction between a continuing explanatory role and a settled referent. I have examined the limitations of a particular strong reference-fixing strategy elsewhere (Allzén, 2026b, Sections 3–7). The modern usage analysis in Allzén (2026a) likewise documents changing discourse without treating linguistic change alone as proof of changed reference. Those arguments supply context for the narrower question here: how a research history establishes the identity through which past and present investigations are connected. The present analysis does not require a verdict on every possible semantics of 'dark matter'.

I use an ADS corpus to establish the circulation of the selected history through its citation patterns, and combine a close reading of its continuity claims with a reconstruction of earlier practice from historical sources. The historical reconstruction shows what is retained when the dynamical strand becomes the lineage of the present target. The philosophical analysis examines how that identification makes continued commitment intelligible as the continuation of earlier achievements. Whether particular readers adopt this interpretation or act on it is a further causal question.

2. Research history as epistemic structure

I use *research history* for a genre of scientific synthesis that narrates a past in order to orient present inquiry. Staley describes research histories as:

> explicitly historical but highly selective accounts of the emergence and implication of a theory, experiment, or discovery that are presented in major research or research review papers. (Staley, 2008, p. 297)

Such texts select turning points, identify predecessors, and connect their achievements to questions that remain worth pursuing. When earlier results and conjectures become stages in understanding one object, present research appears to continue an established inquiry. Questions

about its unresolved characteristics then belong within that inquiry. This is how the historical organization supplies a reason for continued commitment.

To understand how this identity is established, we need to distinguish three forms of continuity. *Continuity of a problem* concerns the questions or phenomena that remain under investigation. *Continuity of a description* concerns the properties and explanatory roles attributed to a proposed cause. *Referential continuity* concerns whether the successive uses identify the same entity or kind. These forms of continuity can come apart: changing descriptions need not entail changing reference, and the persistence of a problem does not by itself establish a common referent. The distinction between an explanatory description and stronger reference-fixing conditions is examined in Allzén (2026b). For present purposes, we need to identify which continuity the historical narrative presents and what makes it plausible. I describe the construction and use of that continuity through three operations.

1. **Anchoring.** A research history selects which earlier episodes, actors, and uses of a term count as antecedents of the present target. The present characterization guides which features of those episodes supply the path through the past. In the dark-matter case, the surviving dynamical role provides the principal connection.

2. **Stabilization.** The narrative treats the selected connections as identifying a continuing object of inquiry. Heterogeneous uses are interpreted as partial descriptions of that object, superseded conjectures about its nature, or investigations peripheral to its lineage. Stabilization concerns what the historical account presents researchers as having tracked. It cannot make an entity exist or independently settle the reference of their terms.

3. **Rationalization.** The resulting historical identity supplies a forward-looking reason for commitment: present research continues an inquiry into the object earlier scientists were already studying, with its unresolved nature presented as a remaining question within that inquiry.

These operations describe how a historical account can offer a justification within an ongoing research program. Their connection concerns the dependence of that justification on the selected antecedents and the identity constructed through them. It does not constitute a causal model in which a history first changes readers' meanings and subsequently determines their investments. Whether readers accept the justification, and what decisions follow, are further empirical questions. We can nevertheless examine the account's justificatory role by asking *which antecedents it selects*, *which identity it constructs* through them, and how that *identity connects present research to past achievements*.

The epistemic issue arises because the present characterization helps select the predecessors whose investigations then give the present target its historical pedigree. Dynamics is conspicuous in this process because it is among the explanatory commitments that survived. Following that survival supplies a genealogy of problems and methods; presenting it as the history of one object makes a further commitment about what those investigations share. Earlier results and conjectures thereby become contributions to determining the nature of the present target. Section 6 examines the justificatory use of this identification after the historical analysis.

The following sections examine these operations in the dark-matter case. Section 3 establishes the circulation and scope of Bertone and Hooper's review and identifies the dynamical connection it draws between early astronomy and present searches. Sections 4 and 5 reconstruct

the broader historical usage, concentrating on cases where dynamics and absorption were integrated. Section 6 then examines how changing explanatory requirements affect the identity presented by the history and how the surviving commitments become the basis of a cumulative pedigree.

3. Continuity narrative in the history of dark matter

A history of dark matter identifies its subject across periods in which both its attributed properties and the phenomena it was invoked to explain have changed. Starting from a present understanding of dark matter directs attention toward earlier investigations that share its surviving commitments. In the case examined here, dynamics supplies the connection through which earlier estimates of unseen matter become antecedents of present searches. The question is how that selected continuity comes to characterize the history of the object itself.

3.1. The circulation and scope of the case

Simplified accounts often connect Zwicky's cluster work to later rotation-curve observations and the eventual acceptance of dark matter. For example:

> Fritz Zwicky used a telescope [...] to measure the radial velocities of galaxies in the rich Coma cluster. He found surprisingly large velocity dispersions, indicating that the cluster density was much higher than the one derived from luminous matter alone. He named this invisible matter dark matter, and [...] in the 1970s, Vera Rubin and collaborators, and Albert Bosma measured the rotation curves of spiral galaxies and also found evidence for a missing mass component. (Baudis, 2016, p. 1)

Similar connections appear in Sanders (2010, p. 12) and Turner (2022, p. 9). By compressing the connections between these episodes, such accounts make it especially easy to read them as evidence accumulating about the same object over time. Bertone and Hooper explicitly seek to improve on accounts organized around a few pioneers. Their review is therefore a demanding case for the present argument: a narrative can substantially broaden the history while continuing to privilege one basis for identifying its subject. The ADS analysis establishes the extent of its citation uptake and thus why this particular text warrants attention.

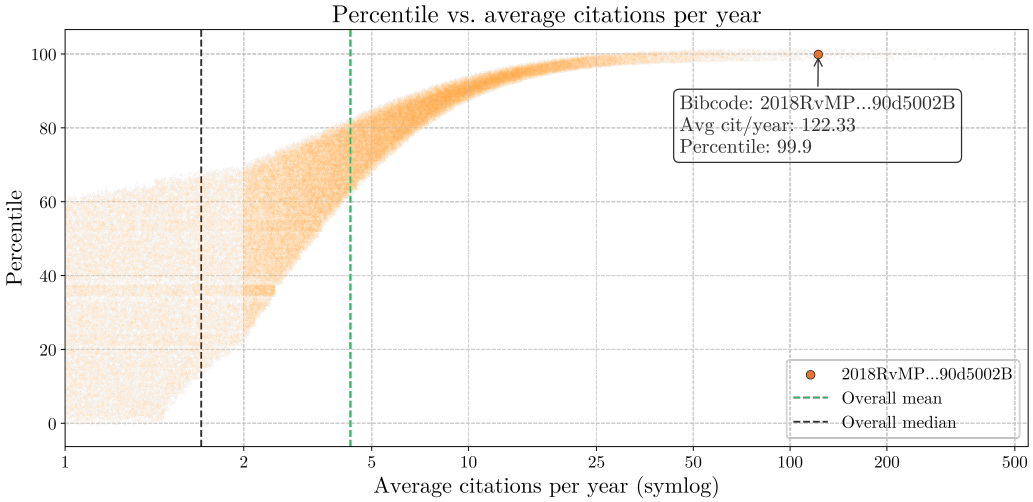


Figure 1: Citation-rate rank of Bertone and Hooper within the 158,367 records with eligible citation metrics. Percentiles use average ranks, including ties; records with zero rates are omitted from the logarithmic display but retained in the percentile denominator. The review has a rate of 122.33 citations per year and percentile 99.87. The appendix defines the rate and separates this comparison set from the full retrieval corpus.

Under the retained annual citation-rate measure, the review lies at approximately the 99.87th percentile among 158,367 records with eligible citation metrics, with 122.33 citations per year. The full retrieval corpus contains 201,272 records; it is not the denominator of this percentile. Other historical treatments in the corpus include Bergh (1999), Sanders (2010), and Swart et al. (2017). The comparison in Appendix A locates Bertone and Hooper among these named treatments without claiming an exhaustive survey of historical writing or a like-for-like ranking of genres.

3.2. A history of dynamics

Bertone and Hooper reconstruct the emergence of the missing-mass problem, debates over clusters and galactic rotation, baryonic proposals, modified gravity, particle candidates, cosmological consolidation, and experimental searches. They discuss unsuccessful proposals and changing beliefs, and draw extensively on primary sources. Their declared aim is to explain how the scientific community adopted dark matter as part of the standard cosmological model. Within this broad reconstruction, my criticism concerns the basis on which earlier investigations are identified with the present target.[1] The first part of the review connects the conceptual emergence of dark matter to dynamical estimates:

> We study the emergence of the concept of dark matter in the late 19th century and identify a series of articles and other sources that describe the first dynamical estimates for its abundance in the known Universe. (Bertone and Hooper, 2018, p. 4)

The explicit connection to present research appears at the end of the local-dynamics discussion:

[1]Quotations and page references to Bertone and Hooper follow the 2018 accepted manuscript, dated 6 July 2018, made openly available by APS at https://link.aps.org/accepted/10.1103/RevModPhys.90.045002. Its pagination differs from the journal version and the earlier 2016 preprint.

> the pioneering work of Kapteyn, Jeans, Lindblad, Öpik and Oort opened the path toward modern determinations of the local dark matter density, a subject that remains of importance today, especially for experiments that seek to detect dark matter particles through their scattering with nuclei. (Bertone and Hooper, 2018, p. 10)

This connection places early local dynamics within the ancestry of current particle searches. The density estimate has a methodological use, while the historical connection also identifies the present search as a continuation of those earlier investigations. These functions are related: a surviving method supplies the connection through which the history presents its continuing subject. The review also places Zwicky's work in continuity with the astronomers studying local stellar dynamics:

> Although [Zwicky] doesn't explicitly cite any article, it is obvious [...] that he was well aware of the work of Kapteyn, Oort and Jeans discussed in the previous chapter. His use of the term "dark matter" is, therefore, in continuity with the community of astronomers that had been studying the dynamics of stars in the local Milky Way. (Bertone and Hooper, 2018, p. 11)

Here two connections need to be distinguished. One concerns Zwicky's use of terminology shared with his contemporaries. The other concerns the later identity of the target investigated under that terminology. Although the dynamical connection makes both plausible within the narrative, continuity of terminology does not settle the identity of the target. What can legitimately be carried from earlier to later investigations depends on the intervening descriptions and explanatory requirements.

The review's structure alone cannot establish the proposed selection. Both "*Dark Stars, Dark Planets, Dark Clouds*" and "*Dynamical Evidence*" belong to its chapter "*Prehistory.*" Absorption is also acknowledged later, in the discussion of Lundmark and Holmberg. The issue is therefore how these strands function in the account, rather than which receives the label "*prehistory.*" A cosmological history can reasonably select antecedents relevant to cosmological dark matter. The selection becomes consequential here because the dynamical commitments retained in the present account also supply the criterion for identifying its historical subject. The resulting lineage presents the target of contemporary searches as the object that earlier investigations were progressively characterizing. The historical reconstruction examines what this identification retains from the integrated practice of the very actors through whom the connection is drawn.

3.3. Co-citation and distribution

Bertone and Hooper's history has been widely cited across several research fields. The retained citation links identify 729 distinct papers citing the review, of which 551 have a primary arXiv classification in the metadata. Figure 2 displays the four largest groups; nuclear physics and quantum physics contribute seven further papers each. This distribution gives the history an opportunity to orient research across communities, although citation alone does not establish agreement with its interpretation.

I also examine whether papers citing the review cite its early sources. Seven pre-1960 references are recoverable from its outgoing links in the retained graph. They are a linked subset, not its complete early bibliography.

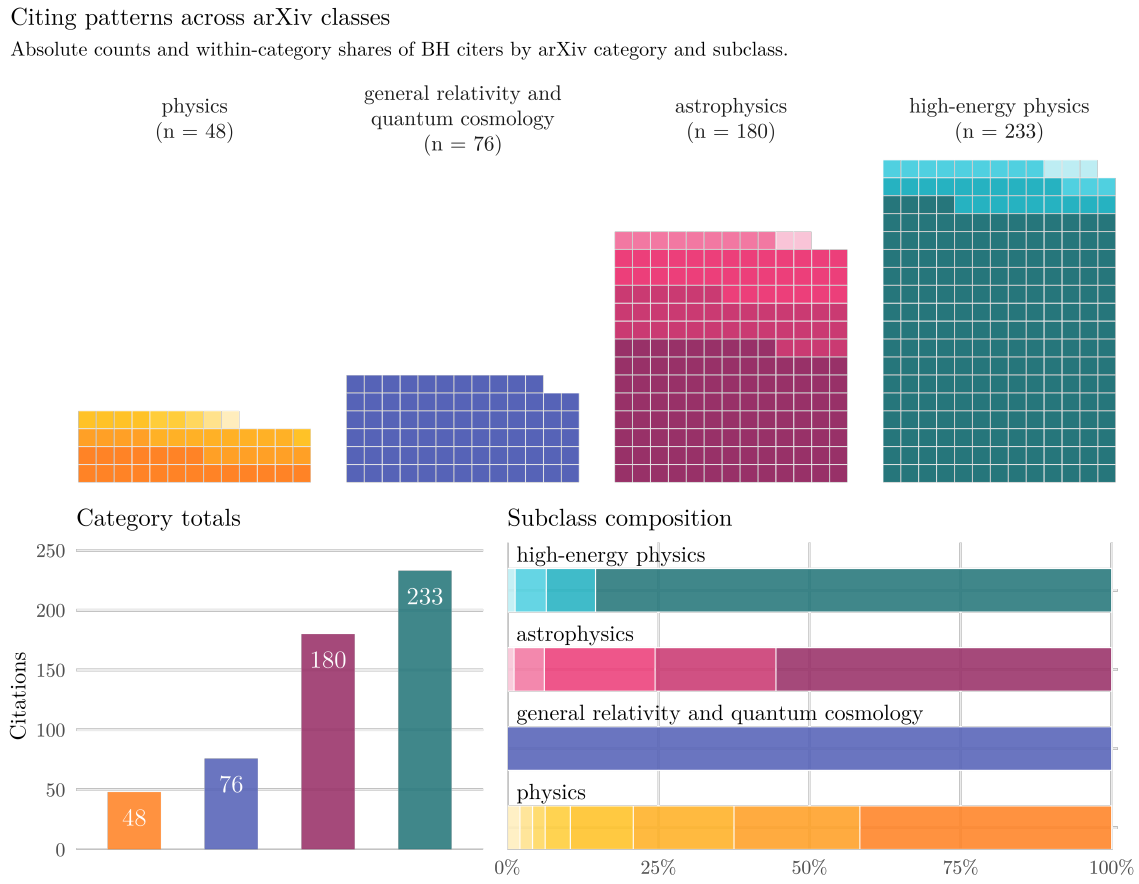


Figure 2: Primary arXiv classifications of papers citing Bertone and Hooper in the retained data. The four displayed groups contain 233 high-energy-physics, 180 astrophysics, 76 general-relativity/quantum-cosmology, and 48 physics papers. Seven nuclear-physics and seven quantum-physics papers are outside the displayed groups. Classification is available for 551 of the 729 linked citing papers.

In a logistic model of 55,140 eligible articles and e-prints published in 2018–2025, citation of Bertone and Hooper is associated with citation of at least one of these sources (odds ratio 6.91, 95% Wald interval [5.17, 9.22]), controlling for linked reference count and year-bin × field strata. The mean standardized probability difference is 5.52 percentage points. Figure 3 shows differences at each displayed stratum's mean linked reference count.

Papers citing the review are also more likely to cite other pre-1960 sources outside that linked subset (odds ratio 3.40, 95% Wald interval [1.47, 7.90]). Shared historical interest can therefore contribute to the association. Taken together, these patterns establish substantial citation uptake across several research communities and document an association with the use of early sources. They therefore justify examining Bertone and Hooper's review as a widely circulating research history. Neither result establishes that readers adopted the review's organizing principle. The evidence for the narrative's specific justificatory structure comes from its contents and their relation to the historical practice reconstructed next.

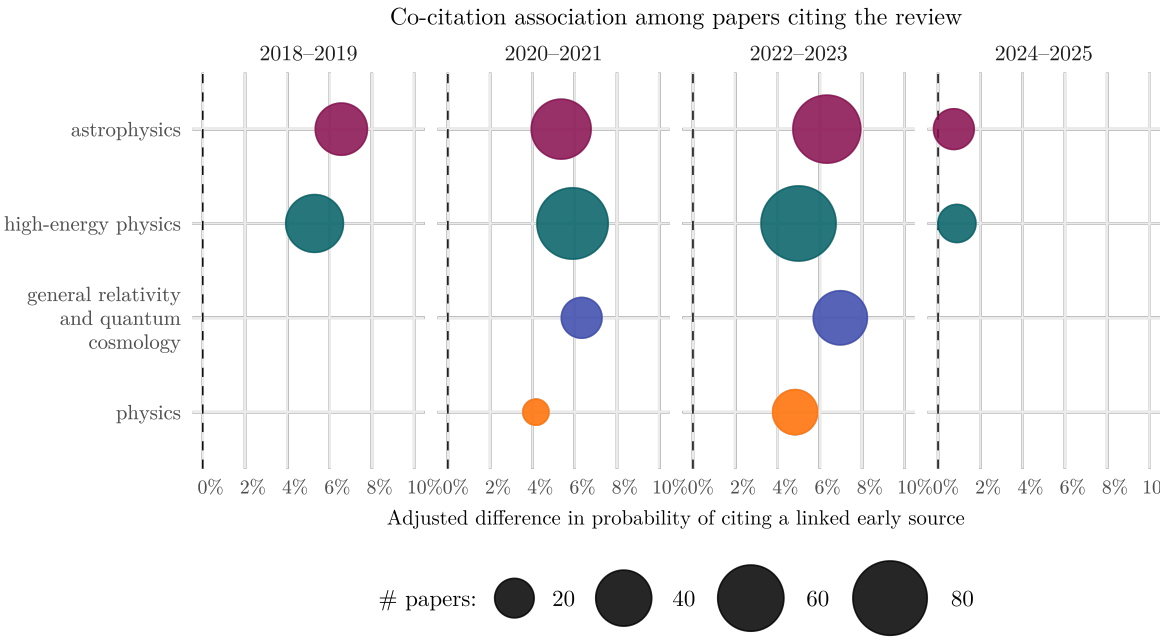


Figure 3: Adjusted differences in the probability of citing at least one of the seven linked early references, comparing papers that cite Bertone and Hooper with papers that do not. Predictions use the same fitted logistic model, evaluated at each stratum's mean log(1 + linked reference count). Circle area indicates the number of citing papers; displayed strata contain at least 10 papers citing the review and 100 comparison papers. Differences are associations, not effects of assigning a citation.

4. Dark matter: a conceptual duality

I agree with Bertone and Hooper that Zwicky's terminology belonged to an established astronomical discussion. The question is which properties and explanatory roles that discussion associated with dark matter. Dynamical estimates provide one route into it, but do not exhaust its scope. The cases below move from non-luminous bodies inferred through dynamics to obscuring material identified optically, then to arguments connecting both. This sequence shows what is retained when the surviving dynamical strand is made the basis for identifying the historical subject. The systems investigated also differ: local stellar populations, the Galaxy, other galaxies, and galaxy clusters should not be treated as one unchanged cosmological domain.

4.1. Lord Kelvin and the 1884 Baltimore Lectures

In 1884, Sir William Thomson (henceforth [Lord] Kelvin) gave the Baltimore Lectures at Johns Hopkins University (Thomson, 1904). One of the topics concerned the velocity of stars in the Milky Way, in particular a star called "1830 Groombridge". Kelvin, quoting Newcomb, considers whether the visible stars account for all the mass required to explain the observed motion:

> Newcomb has given a most interesting speculation regarding the very great velocity of 1830 Groombridge, which he concludes as follows: – "If, then, the star in question belongs to our stellar system, the masses or extent of that system must be many times greater than telescopic observation and astronomical research indicate. We may place the dilemma in a

> concise form, as follows: – Either the bodies which compose our universe are vastly more massive and numerous than telescopic examination seems to indicate, or 1830 Groombridge is a runaway star, flying on a boundless course through infinite space with such momentum that the attraction of all the bodies of the universe can never stop it." Thomson (1904, p. 273 §16) (Newcomb quoted in Kelvin)

In the subsequent pages of the lecture notes, Kelvin adopts the former option: vast quantities of 'dark bodies', or 'dark stars', contribute to the dynamical behavior of the galactic system. By treating the system as analogous to particles of gas, he seeks to estimate its size and the velocity dispersion of its stars:

> Many of our supposed thousand million stars, perhaps a great majority of them, may be dark bodies [...] It is nevertheless probable that there may be as many as 1000 million stars within the distance r (5); but many of them may be extinct and dark, and nine-tenths of them though not all dark may be not bright enough to be seen by us at their actual distances. Thomson (1904, p. 274 §18 – 277 §20)

Kelvin considers the possibility that luminous mass is only a fraction of the total mass in the universe (which at the time was thought to be the Milky Way), and considers the 'dark bodies' to be extinct or faint stars. The discussion cited here appears in the lecture volume published in 1904. The idea that non-luminous objects could inhabit our universe was shortly thereafter picked up by French polymath Henri Poincaré.

4.2. Poincaré and the age of the Milky Way

In a paper applying the theory of gases to the Milky Way, Poincare (1906), building on Kelvin's 1884 method of analogy, provides a much lower estimate of the ratio between dark bodies and luminous ones, based on a comparison between Kelvin's results and empirical data from telescopic observation:

> There are the stars which we see because they shine; but might there not be obscure stars which circulate in the interstellar spaces and whose existence might long remain unknown? Very well then, that which Lord Kelvin's method would give us would be the total number of stars including the dark ones; since his number is comparable to that which the telescope gives, then there is no *dark matter*, or at least not so much as there is of shining matter. Poincare (1906, pp. 480–481) [My italics]

The gas analogy is a method for reasoning about stellar dynamics under gravity: motions constrain the mass of the system, including bodies too faint to observe. Poincaré also considers the relation between the age of the stellar system and the luminous lifetimes of its stars. His difficulty is to reconcile the limited amount of unseen mass suggested by the dynamical comparison with a picture in which the observed stars occupy only a luminous phase of a longer evolution:

> Must we believe that the evolution of the Milky Way began when matter was still dark? But how did the stars which compose it reach the adult age all at the same time, an age which is to last so brief a space? Or are they rather to reach it successively and are those that we see only a small minority compared with those which are extinct or that will one day shine out? But how shall we reconcile that with what we have said above about the absence of dark matter in considerable proportion? Should we abandon one of the two hypotheses, and which one? Poincare (1906, p. 488)

The alternatives concern whether the system began dark and its stars reached their luminous phase together, or whether the observed stars are a minority among bodies not yet luminous or already extinguished. The latter would require reconciling a large dark population with the earlier dynamical estimate. These are connected physical questions, not evidence of two independently fixed referents. Poincaré's discussion thus shows how a broad non-luminous category could enter both dynamical estimation and reasoning about stellar evolution. Its role is wider than that of a uniquely characterized constituent.

4.3. Kapteyn and Jeans – dynamics and dark matter

In the early 1920s Dutch astronomer Jacobus Kapteyn (1922) published a theory of the dynamics and size of the Milky Way that he had spent much of his life developing. In the abstract, Kapteyn describes the phenomena his theory – "a general theory of the distribution of masses, forces and velocities in the sidereal system" – can account for. The final proposed contribution concerns the amount of dark matter:

> It is incidentally suggested that when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect. Kapteyn (1922, p. 302)

This suggestion follows from Kapteyn's calculation of the effective mass in the Milky Way: the gravitational mass divided by the number of luminous stars. To estimate the stellar count, he uses the empirical luminosity function to infer the number of faint stars:

> Remark. Dark matter. It is important to note that what has here been determined is the total mass within a definite volume, divided by the number of luminous stars. [...] Now suppose that in a volume of space containing l luminous stars there be dark matter with an aggregate mass equal to Kl average luminous stars; [...] We therefore have the means of estimating the mass of dark matter in the universe. Kapteyn (1922, p. 314).

Kapteyn defines effective mass as total mass divided by the number of luminous stars. If there are l luminous stars of average mass m and dark matter of mass Klm, total mass is $l\,(1 + K)m$ and effective mass is $(1 + K)m$. This distinction avoids confusing an aggregate with the per-star quantity used in his comparison.[2]

Kapteyn concluded that the amount of dark matter in the Milky Way must be relatively small. Jeans also considered non-luminous mass, but arrived at a different estimate. In "The Motions of Stars in a Kapteyn-Universe", Jeans reconsiders the relation between the average mass inferred from binary stars and Kapteyn's effective mass, arriving at a different estimate of the amount of dark matter (Jeans, 1922; Kapteyn, 1922, p. 314):

> Assuming the average star to have a mass of 0.8 times the sun's mass, our value of M must be interpreted as showing that if the stars are in a steady state, there must be about three dark stars in the universe to every bright star. Subject to our being able to assume the existence of this very appreciable amount of dark matter, it appears that the observed motion of the stars can be explained. Jeans (1922, pp. 130–131)

[2]The expression in the omitted sentence is not reproduced here. The distinction between total and effective mass is explained separately from the quotation, using Kapteyn's preceding definition.

Jeans derives the mass of an "average star" by taking the mass of the average *visible* star and increasing it by the ratio "of dark matter to visible stars in the universe" [126–7]. Again, both Kapteyn and Jeans appear to use 'dark matter' to refer to something like dark stars, or dark bodies. As with Poincaré, the ontology assumed here is that dark matter is simply matter without enough luminosity to be observed. The relevant contrast in these passages is between observed luminous stars and additional bodies insufficiently luminous to enter that count.

4.4. Trumpler's light-obscuring mass

Trumpler (1932) provides one example of semantic divergence when attempting to explain a 'dark hole', captured in a photograph of the Sagittarius cloud of the Milky Way by Barnard (1919). Trumpler refers to the cause of this phenomenon as 'dark, opaque material'; 'obscuring masses'; 'dark obstacles'; 'dark matter'; and 'dark stuff' — the presence of matter which *interfered* with light coming from the otherwise dense region of stars. The proposed explanation of the dark region required optical obstruction by material bodies. Trumpler described two forms in which astronomical matter could be organized:

> The matter constituting our universe is evidently found in either of two states: In organized bodies like the Sun and the stars, which by their peculiar regular and symmetrical constitution have reached a stage of luminous radiation [...]; or in unorganized, chaotic masses of tiny particles irregularly scattered through vast space, mostly dark, only in few places becoming visible as nebulae. (Trumpler, 1932, p. 182)

Interaction with light is necessary to this explanation: the material is identified through its obstruction of light, rather than first through a gravitational mass deficit. Although such matter would also gravitate, whether it could supply the mass needed in a particular dynamical problem depends on its constitution and distribution. The historical issue is whether astronomers connected these optical and dynamical constraints within their conception of dark matter. The next cases show that they did.

Trumpler's 1930 analysis makes the integration especially explicit. Having inferred general and selective absorption from open clusters, he considered what scattering medium could produce it. Free atoms would require a density incompatible with the observed stellar velocities. Taking the dynamical density limit instead, he inferred that fine solid particles could supply the optical effect (Trumpler, 1930, pp. 225–226). Optical behavior and gravitational constraints thus jointly discriminated between proposed constituents. Their use within the same investigation shows that the connection went beyond a shared term: *dynamical constraints helped determine what kind of optically identified material was physically possible*.

4.5. Lundmark's ratios of luminous and dark matter

At the same period as Kapteyn published his *magnum opus*, the Swedish astronomer Knut Lundmark (1921) uses dark matter to explain the observed 'dark lanes' found in photographs of the spiral nebulae Messier 33. He conjectures that the appearance of these dark lanes could result from:

> [...] whorls of dark matter between whorls of nebular matter and much pictorial evidence is in favor of this idea. (Lundmark, 1921, p. 324)

Later, Lundmark treated the presence of dark matter more confidently. After calculating the total mass of the visible stellar universe, he qualified his estimate: *"of course, dark stars and dark matter exist and increase that value"* (Lundmark, 1925, p. 896). 5 years later Lundmark (1930) revisits dark matter as it appears in estimates of the total mass in galactic systems, determined by the ratio between light and dark matter, a ratio derived using spectrographic data of the rotational velocities of galaxies (see Figure 4). Lundmark's work thus uses dark matter to explain both light absorption *and* galaxy dynamics. Bertone and Hooper acknowledge this connection in their rotation-curve discussion, describing Holmberg's use of absorption to interpret Lundmark's mass-to-light estimates (Bertone and Hooper, 2018, pp. 14–15).

Tabelle 3.

Objekt	Gravitationsmasse	Totale absolute Größe M_{tot}
Andromedanebel	$0.2 \cdot 10^{10} \odot$	$-17^{M}.5$
Messier 33	$0.15 \cdot 10^{10} \odot$	-15.8
Messier 81	$76 \cdot 10^{10} \odot$ (?)	-17.6 (?)
N. G. C. 4594	$3 \cdot 10^{10} \odot$	-18.0
Messier 51	$0.1 \cdot 10^{10} \odot$	-16.6
Milchstraßensystem	$10 \cdot 10^{10} \odot$	-17.2

Tabelle 4.

Objekt	Verhältnis: Leuchtende + dunkle Materie / Leuchtende Materie	Mittlere Zahl der Sterne für $\frac{1}{3}$ Lichtjahre
Messier 81	100:1 (?)	0.20 (?)
N. G. C. 4594	30:1	0.042
Andromedanebel	20:1	0.006
Messier 51	10:1	0.012
Milchstraßensystem	10:1	0.08
Messier 33	6:1	0.026

Figure 4: From (Lundmark, 1930). Table 4 describes the relative presence of luminous vs. dark matter in five spiral systems, including the Milky Way.

4.6. Pannekoek and Harper

Two other Swedish astronomers, Gustav Strömberg and Bertil Lindblad, had roughly a decade earlier suggested a model for the Milky Way, hypothesizing that it was a rotating spiral galaxy (or nebula) just like the extragalactic nebulae astronomers had observed. The model could explain the observed asymmetric velocities of local stars, but it was argued that the hypothesis entailed that the galactic nucleus must contain a large mass for the predicted dynamics to fit observations. The Dutch astronomer Anton Pannekoek (1927, p. 40) explicitly used this duality when attempting to account for the mass needed in the galactic nucleus, should the hypothesis that our galaxy is a rotating spiral system be true:

> Thus we come to the conclusion that visible stars of the galactic system cannot provide the required central attracting masses. [...] Cannot the dark matter itself act as a part of the

> attracting masses? In the visual aspect of the Milky Way the dark absorbing nebulae have the same importance as the luminous star clouds.

Two years later, Pannekoek's idea is picked up in Harper's annual address for the Royal Astronomical Society of Canada (Harper, 1929). In *"current progress in astronomy"* we find a discussion on the "Rotation of Galaxy", centered on the work of Strömberg and Lindblad, who had hypothesized that our galaxy was a rotating spiral nebula. Harper refers to a pair of papers published by Oort which are "tending to verify the soundness" of the rotation hypothesis. One implication of the hypothesis is that the mass "required at the centre to give the requisite rotational velocity" is estimated at around $8 \times 10^{10} M_{\odot}$, prompting Harper to question the evidence for the presence of such a mass:

> This central nucleus is situated in the plane of the galaxy and in galactic longitude approximately 325° in the general direction of the constellation *Sagittarius*. Here the Milky Way clouds are brighter than in other parts of the sky, and Pannekoek examines their total luminousity to see if they would yield the necessary mass. He is forced to admit that [...] the visible stars of the galactic system cannot provide the central mass required. The question arises, would not the dark matter in our system yield this attracting mass? Photographs of distant spirals seen edge-on suggest enormous masses of obscuring material. Similar evidence is afforded nearer home in the almost complete obliteration of faint stars in certain regions of the sky by occulting matter which must be extremely tenuous but nevertheless of great effect when summed up over large volumes of space. (Harper, 1929, pp. 124–125)

These cases show that the historical use of 'dark matter' to account for a deficit in the mass-density budget included arguments connecting light absorption and dynamics. As Harper notes, this connection also appears in the work of Oort.

5. Integrating dynamics and light absorption

Two accounts show in more detail how astronomers integrated the optical and dynamical roles of dark matter. The first appears in the doctoral thesis, published in 1937, of Swedish astronomer Erik Holmberg (1937). The thesis included a chapter called *The Existence of Dark Matter in the Galaxies*.[3] Holmberg (1937, p. 80) explicitly incorporates absorption into his dynamical estimates:

> At this place it may be remarked that K. LUNDMARK has determined the proportions of dark and bright matter for five spirals by using their spectroscopically determined rotation velocities. In a table, the following ratio f has been given:
>
> $$f = \frac{\text{Dark + Bright matter}}{\textit{Bright matter}}$$
>
> The values of f change between 100 : 1 and 6 : 1. In the computation of the bright matter, LUNDMARK has, however, not considered the absorption effects within the spirals. Here we will make an attempt to take these effects into consideration. The following denotations will be introduced:

[3] The presence of the topic of dark matter in Holmberg's thesis is unsurprising, as he was supervised by Knut Lundmark, who, as we have seen, was a notable forerunner in the conceptual and empirical exploration of dark matter.

m_a = the total mass of dark matter
m_b = the total mass of bright matter
m'_b = the mass that corresponds to the observed light

In this way we get:

$$f = \frac{m_b + m_a}{m'_b} = \frac{m_b}{m'_b}(1 + k)$$

Here k is the ratio of the total dark matter to the total bright matter. If we put the ratio m_b/m'_b equal to the corresponding ratio of light, and if the absorption concerning the total magnitude of the object is denoted by ΔM, we get the following relation:

$$\Delta M = 2.5 \log \frac{m_b}{m'_b} = 2.5 \log f - 2.5 \log(1 + k)$$

Holmberg's relation connects a dynamical mass-to-observed-light estimate, the ratio of dark to bright matter, and the correction for absorption. Given f, the inferred absorption still depends on k and on the assumed correspondence between light and stellar mass. The dynamical deficit therefore does not uniquely determine the extinction. Both nevertheless enter the same calculation, requiring the amount and constitution of dark matter to be assessed together with the light it prevents us from seeing. Their dependence within this calculation establishes a stronger historical connection than the mere occurrence of two senses of a term.

For Oort, estimates of the mass, velocity, and rotation of a stellar system depended on a reliable assessment of its luminosity. Absorption by dark matter introduced uncertainty into that assessment. In a public lecture entitled *Non-Light Emitting Matter in the Stellar System*, Oort (1927) cites Lundmark and uses dynamical calculations to estimate the amount of dark matter, then considers how much absorption that mass could produce under different assumptions about its constitution.

> Do we then have to give up hope to learn about the absorption in the interstellar gas? Not entirely. [...] I have told you above that *the observed velocities of the stars allow us to make an estimate of the mass of the non-light-emitting matter*. [...] It is not unreasonable to assume that apart from the light-emitting stars there could be a large quantity of dark bodies in the universe. If these bodies would be in the form of very faint stars of the same size and mass as the observed stars, then it is easy to show that there cannot be enough of these dark stars to provide an observable extinction. It becomes completely different, when the available mass would be in the form of small solid particles, distributed throughout the Galactic System. We then have just about enough to give rise to a significant absorption over distances of a thousand light-years and we can easily assume these particles to be spread out so densely over a large area of space that more distant stars are completely extinguished. (Oort, 1927, pp. 61–62)

Oort's inference is explicitly conditional on constitution. A dynamically permitted mass in faint stars would produce little extinction, whereas the same available mass in small solid particles could produce significant absorption. The connection makes dynamical information relevant to an optical question while allowing observations of absorption to discriminate between material proposals. Although the proposed constituents differ, the reasoning relates them within a common investigation of non-light-emitting matter. This is the integrated practice that a history

organized primarily around the survival of dynamical inference must explain. The following examples document the recurrence and persistence of the optical usage, without constituting a census of its prevalence throughout astronomy.

Already in 1929, Markov (1929, p. 342) estimates the local ratios of luminous to dark matter on the basis of this dual function: "spirals […] seen edge-on show a darkening on the edge, indicating a light absorption. Thus the disagreement with the theory here quoted can be considered only as an indication of the presence in spirals of dark matter, not only in the periphery, but in all latitudes, connected with the spiral. Yet it must be said only that the amount of dark matter in a volume unit of the galaxy must be tens of times greater than in a unit of volume of intergalactic space." Estonian astronomer Ernst Öpik (1929) concludes that "in some cases absorption by dark matter appears probable" as an explanation of obscured regions in space. Dutch polymath de Sitter (1932, p. 91) writes that "evidence has accumulated" in support of the idea that "clouds of dark matter […] prevent us from seeing the stars".[4] Wallenquist (1939, p. 48) infers a pattern of light absorption from the distribution of dark matter, and Lindsay (1950, p. 8) claims that the clearest evidence for the existence of dark matter is its light-obscuring properties: *"The stream [of stars] has been blacked-out by nearby dark matter. There is therefore ample evidence for all to see of the presence of non-stellar matter in our galaxy"*.

Lindblad (1951, p. 60) discusses the presence of dark matter in spiral nebulae, suggesting that the morphology of optically identified dark lanes can inform an interpretation of internal motions:

> This may be exemplified by the nebulae M81 and M31, which have characteristic features that are similar to those of the barred spirals, especially with regard to the internal motions revealed by the run of certain extended lanes of dark matter.

Finally, Oort (1952, p. 235) discusses the material constitution of astronomical systems and connects the presence of interstellar gas with the presence of dark matter: "there are two kinds of observations that can tell us at least something about the more common ingredients that other systems are made of. The first relates to the interstellar gas, which can be observed by its well-known emission lines or by the dark matter that usually accompanies it."

These cases establish a wider historical use than a solely dynamical characterization would suggest. The optical usage persisted at least into the early 1950s, as the passages from Lindsay (1950), Lindblad (1951), and Oort (1952) show. The dark lanes in Lindblad's discussion are optical structures used in interpreting motion; the passage does not itself supply a gravitational mass measurement. Keeping these inferential routes distinct makes their integration in Oort and Holmberg more informative.

These calculations show that light absorption constrained both the proposed constitution of dark matter and the mass accounting. Dynamics was part of the same investigations, but its subsequent survival does not exhaust what they concerned. Following that strand as the history of one object interprets the remaining commitments as revisable descriptions of that object or contributions to another inquiry. Changes in properties alone do not establish different referents. The historical point is that the surviving dynamical role supplies the criterion for organizing the earlier investigations around the present target. The next section examines the justificatory use of that identification.

[4] See also: Notes of the British Astronomical Association (1930, p. 49)

6. Ontology as a reflection of explanatory requirements

Historical conceptions of the nature of dark matter depended closely on the phenomena it was invoked to explain. Dynamical estimates constrained how much gravitating matter was present, while extinction placed demands on its optical behavior, constitution, and distribution. When these requirements entered a common calculation, they helped determine the physical description of the material under investigation. The identity of that investigation cannot be reconstructed from the surviving dynamical requirement alone without explaining the fate of the others.

6.1. Changing requirements and the identity of the target

The contemporary dark component is constrained by a range of gravitational and cosmological observations, with ordinary baryonic matter unable to supply the dominant component under the standard account. This does not mean that every live candidate is absolutely electromagnetically inert, or that its microscopic properties are already known. The contrast relevant here is with earlier absorbing material whose light interaction was part of the explanation it supplied. The semantic difficulties of treating contemporary constraints as kind-constitutive properties are developed in Allzén (2026b).

Separating obscuration from missing mass involved more than identifying dust at a single decisive moment. Trumpler's work on interstellar absorption (Trumpler, 1930) strengthened the optical case, while the continued usage documented above shows that recognizing an absorbing medium did not immediately eliminate 'dark matter' from descriptions of it. Establishing extinction, estimating the absorbing material's mass, and excluding it as the dominant explanation of dynamical and cosmological discrepancies are different achievements. The present sources establish the integrated earlier practice and its persistence; they do not establish one date on which a unified concept was abandoned.

This redistribution explains why dynamics becomes the basis of the later genealogy. As obscuring material became a more specifically characterized subject and dynamical problems acquired further constraints, the explanatory roles associated with dark matter could be separated. The later history follows the strand retained within the present missing-mass problem, interpreting some earlier commitments as approximate descriptions of its target and others as parts of a different inquiry. That organization presents earlier astronomy as investigation of the object contemporary searches seek to identify.

A defender of the dynamical lineage might respond that non-luminous gravitating matter was the common target throughout, and that optical properties were revisable conjectures about its constitution. This response identifies a genuine continuity, but chooses it from the commitments retained in the present account. Oort and Holmberg show that optical interaction also entered the identification and physical characterization of the material under investigation. Describing those roles as conjectures about a target already identified through gravity interprets their place in the inquiry from the standpoint of the surviving dynamical requirement.

A genealogy can therefore track the persistence of requirements that remain to be satisfied by an explanation. But dark matter is taken to be the material subject of those requirements, whose nature present research seeks to determine. An account of which problems, methods, and descriptions have survived does not by itself establish that the same material subject has persisted through them. The history connects these two levels when it treats the surviving commitments

as identifying an object gradually becoming better understood. The criticism concerns this construction of historical identity, even where the dynamical selection is appropriate for tracing the ancestry of the current problem.

6.2. Historical continuity and reasons for commitment

The genealogy supplies a framework within which continued commitment appears as the pursuit of an established object whose nature remains to be determined. Bertone and Hooper's connection from early dynamical estimates to the density used in particle searches situates current work within that inquiry. Anchoring selects the predecessors through commitments that have survived; stabilization presents their investigations as tracking a common target; rationalization makes continued commitment intelligible through the resulting pedigree. The justificatory work is performed by this organization of the research history. It does not depend on finding an explicit claim that an earlier result confirms a contemporary constituent.

Presenting current searches as stages in understanding an established object offers a reason for sustaining them, independently of any claim that a particular earlier result confirms a contemporary constituent. Whether that reason is adequate depends on the historical identification it employs. An explicit claim of inherited confirmation would require further scientific connections between successive posits and results. The 1974 synthesis provides a useful comparison: de Swart and collaborators reconstruct how previously separate problems became a common anomaly, and the evidential account in Allzén (2025) asks what the new connection contributed. Such changes in evidential relations make the historical identification consequential even before individual confirmation claims are considered.

The present characterization thus has two roles in the historical argument: it guides the selection of the earlier investigations and then receives a cumulative pedigree from the lineage constructed through them. The epistemic issue is obscured if the resulting pedigree is treated as though it established the target's identity independently of that selection. Scientific reasons for retaining the dynamical requirements can be sound while the historical identification of their subject remains a further commitment. Making this dependence explicit allows us to distinguish the continuity of the surviving requirements from the identity attributed to their object, and to assess the grounds for treating current research as the continuation of an established inquiry.

A history can therefore reinforce a scientific choice already made on other grounds. Once the particle turn has occurred, a continuous pedigree presents that trajectory as further investigation of a target whose identity extends back through earlier astronomy. That account supplies a reason for sustaining the trajectory whether or not it initiated the scientific choice or changes a particular reader's belief or funding decision. Measuring those effects would require reception evidence beyond the co-citation patterns reported here. Pestre describes how scientists situate their work historically:

> At the beginning of their books or articles physicists tend to create a frame in which to insert their own research program. They tend to build a narrative; to draw a coherent itinerary through the past, an itinerary which links their own questions and solutions to the ones previously debated, and currently accepted, by at least part of the community. (Pestre, 1999, p. 203)

In the dark-matter case, this itinerary connects early estimates of unseen matter to searches for

constituents whose nature remains unresolved. Its justificatory use depends on treating those investigations as stages in studying one object, with the surviving dynamical role supplying the criterion for that identification.

7. Conclusion

I have argued that research histories supply grounds for continued commitment by identifying an unresolved target as the subject of an established inquiry. In the dark-matter case, the dynamical strand supplies the lineage because it belongs to the explanatory commitments that survived into the present characterization.

Bertone and Hooper's review connects early estimates of unseen matter to the local density relevant to current particle searches. Its broad coverage of alternatives does not remove the question of how the surviving dynamical strand identifies the historical subject. In the investigations reconstructed here, optical and dynamical requirements were integrated in the reasoning of astronomers who belong to that lineage. Following the surviving strand retrospectively organizes those commitments around the present target, interpreting some as stages in its characterization and others as belonging to different inquiries. The history thereby presents an identity across changes that the persistence of dynamics alone cannot establish.

Through anchoring, stabilization, and rationalization, this retrospective identification gives contemporary searches the standing of further investigation into an object earlier astronomers were already studying. Its unresolved nature becomes a remaining question within that inquiry. The resulting reason for commitment depends on how the earlier work is identified with the present research.

This argument does not require showing that 'dark matter' failed to refer, nor that the present program is unjustified. The citation evidence establishes the circulation and co-citation relationships of the chosen history; the historical reconstruction exposes the selection through which its continuing object is identified. The present supplies the criterion for drawing the lineage from which it then receives its pedigree. In a program whose object remains open to further determination, that construction of identity is itself an epistemic strategy.

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A. Appendix: Data source and methods

The analysis uses the retained ADS tables of the author's historical-continuity workspace, queried for the phrase `dark matter` in full text. The full table contains 201,272 unique bibcodes with publication years 1883–2026. This total counts the records retrieved by the query, which are not exclusively dark-matter research papers. The analysis manifest identifies the input tables by SHA-256 hash and documents the outputs. The original retrieval timestamp is not embedded in the retained tables; the results describe this fixed local dataset rather than a live ADS query.

The citation-rate table contains 158,367 records with eligible annual citation metrics. For each record, I sum annual citation counts from its publication year onward and divide by the number of calendar years from publication through its latest recorded metric year, inclusive. Percentiles are average ranks divided by the number of records in that table. Because the latest metric year can differ between records, the measure does not use a common exposure endpoint and serves a descriptive purpose. Zero-rate records remain in the percentile denominator; only positive rates appear on the logarithmic axis. Bertone and Hooper's rate is 122.33 (1,101 citations across nine calendar years, 2018–2026) and its percentile is 99.866. Prepublication citations are excluded from this rate. The review circulated in preprint form in 2016, so the journal-year convention does not establish the beginning of possible influence. The table below applies the same retained measure to selected historical treatments for comparison. These purposively selected treatments differ in genre and scope; they neither exhaust the population of histories nor provide a causal comparison of impact.

Treatment	Yearly citations	Bibcode
Bertone and Hooper (2018)	122.33	`2018RvMP...90d5002B`
De Swart, Bertone, and van Dongen (2017)	11.30	`2017NatAs...1E..59D`
Sanders (2010), book	4.71	`2010dmp..book.....S`
Van den Bergh (1999)	1.14	`1999PASP..111..657V`

Citation links are deduplicated by the pair of cited and citing bibcodes. The graph contains 729 distinct citers of Bertone and Hooper. Primary field assignment uses the first arXiv classification after ordering by `class_pos`; 551 citers have such a classification. The four groups displayed in Figure 2 account for 537 of these, with seven nuclear-physics and seven quantum-physics papers accounting for the remainder. Multiple classifications are not counted repeatedly. The retained outgoing links from the review identify the following seven references dated before 1960.

Source	ADS identifier
Poincaré (1906), *The Milky Way and the Theory of Gases*	`1906PA.....14..475P`
Lundmark (1925), *The Motions and the Distances of Spiral Nebulæ*	`1925MNRAS..85..865L`
Oort (1932), local dynamical density analysis	`1932BAN.....6..249O`
Zwicky (1933), *Die Rotverschiebung von extragalaktischen Nebeln*	`1933AcHPh...6..110Z`
Zwicky (1933), *How Far Do Cosmic Rays Travel?*	`1933PhRv...43..147Z`
Holmberg (1937), thesis	`1937AnLun...6....1H`
Zwicky (1937), *On the Masses of Nebulae and of Clusters of Nebulae*	`1937ApJ....86..217Z`

The graph is not a complete transcription of the review's bibliography, which includes additional early sources. "Linked early references" therefore denotes this recoverable subset throughout. For the co-citation model, eligible citing papers are articles and eprints published in 2018–2025, with a primary classification in astrophysics, high-energy physics, general relativity/quantum cosmology, physics, nuclear physics, or quantum physics, and at least one retained outgoing reference dated 1800–2025. There are 55,140 such papers, including 513 citers of Bertone and Hooper. Linked reference count is the number of distinct date-eligible outgoing links, not the complete reference-list length. The binary outcome is citation of at least one linked early reference. A binomial logistic model includes an indicator for citing the review, $\log(1 + n)$ for linked reference count, and fixed effects for the interaction of field with four two-year bins (2018–2019 through 2024–2025). The odds ratio and interval reported in the text are obtained by exponentiating the fitted coefficient for citing the review and its 95% Wald limits. To obtain the mean standardized probability difference, I calculate the difference between each paper's predicted probabilities under the two citation-indicator values, holding its other covariates fixed, and then average those differences across papers. Figure 3 instead evaluates each displayed stratum at its mean log reference count and requires at least 10 citers and 100 non-citers.

The comparison model retains the same sample and covariates but changes the outcome to citation of any pre-1960 source outside the seven-item subset. Both outcomes show positive associations with citing the review. These results neither identify a causal influence nor establish a difference between the two coefficients, which is not tested here. Coverage of citation links, shared subject matter, and historical interest remain possible contributors. The accompanying analysis table, model coefficients, stratum predictions, comparator table, and input manifest make these limits and calculations inspectable without interpreting citation as endorsement.
The retained ADS input tables, analysis code, model dataset, coefficient tables, historical comparisons, and verification materials are publicly available in the Zenodo reproduction bundle (Anonymous, 2026): https://doi.org/10.5281/zenodo.23675367. The compact analysis supplement is also supplied as Online Resource 2, with a guide in Online Resource 1.