https://doi.org/10.65166/a2pvvr92

Journal of Frontier Science and Futures
Volume I, Issue 1, July 2026
https://journal.ijhba.com/index.php/jfsf
https://slsipress.com

What Fills the Missing Equation? Unseen Entities, Scientific Inference, and the Search for Order

Ramon George Atento, PhD

Abstract

Modern science frequently advances under conditions of partial visibility. Across physics, cosmology, astronomy, and planetary science, investigators are often confronted by anomalies, residuals, or structural gaps between what is directly observed and what must be present for a theory, model, or causal account to remain explanatorily coherent. In response, science routinely posits unseen terms, entities, mechanisms, or parameters that are not initially available to direct observation but are treated as inferentially warranted. This paper examines that recurring epistemic pattern and argues that the unseen is not an embarrassment to science but one of its normal working conditions. Drawing on philosophy of science, especially abduction or inference to the best explanation, the paper distinguishes among several kinds of scientific posits: constants and parameters, theoretical terms, inferred entities, hidden mechanisms, model-dependent placeholders, and structured absences. It then traces this logic across a graded series of cases, including Neptune, the Higgs boson, black holes, dark matter, dark energy, planetary habitability, and Candidate Dark Galaxy-2 (CDG-2), a dark-matter-dominated system in the Perseus cluster inferred from sparse visible traces. The paper argues that scientific commitment to the unseen is neither uniform nor arbitrary: some posits later receive striking empirical confirmation, whereas others remain explanatorily indispensable but ontologically unresolved. It further contends that the repeated success of such inferences creates a philosophical temptation to extend scientific placeholders into teleological or metaphysical claims about design, purposive evolution, or hidden intelligence. That extension, however, is not epistemically equivalent to the scientific inferences from which it is often derived. The central question, therefore, is not whether science may posit what it cannot yet directly observe, but how scientific inquiry can distinguish disciplined explanatory inference from speculative overreach when confronting the missing pieces of the universe.

Keywords: *scientific inference; abduction; dark matter; dark energy; black holes; Higgs boson; habitability; CDG-2; scientific realism; theoretical entities; teleology; philosophy of science*

1. Introduction

Science is often portrayed as a domain that moves straightforwardly from direct observation to stable fact. Actual scientific practice is less orderly. Many major advances have emerged when the visible world proved insufficient—when the data did not fit, when residuals persisted, when equations required terms whose physical referents were not yet known, or when observed effects implied the presence of something not directly seen. Under such conditions, science does not simply suspend judgment. It proceeds by disciplined inference and provisionally admits that something more must be there.

This paper begins from that recurring condition of inquiry: the problem of the missing explanatory term. By this is meant a situation in which what is observable appears insufficient to account for what is happening, and explanatory pressure forces the introduction of some further term, structure, mechanism, or entity. A mathematical theory may require a constant whose value is measured rather than deduced from deeper principles. An astronomical anomaly may suggest the existence of an unseen body. A particle theory may imply a constituent long before available instruments can detect it. A cosmological model may fit the data only by incorporating components whose gravitational or dynamical effects are evident while their nature remains obscure.

The larger argument developed here is that the unseen is not anomalous within science; it is one of the normal working conditions of frontier inquiry. At the same time, unseen scientific posits are not all of the same kind. Some become well-confirmed constituents of accepted ontology. Some remain powerful but incomplete explanatory terms. Others function as structured thresholds or enabling conditions rather than hidden objects. Because these categories differ, scientific inferences to the unseen must be evaluated in graded rather than undifferentiated fashion.

Within this frame, the paper aims to clarify how science justifies belief in what is not directly observable, to classify the principal forms that such missing pieces take across modern inquiry, and to determine where disciplined scientific inference ends and teleological or metaphysical extension begins. These objectives are pursued through a cross-disciplinary analysis that moves from philosophy of science to historical episodes of prediction and confirmation, then to contemporary frontier cases such as dark matter, dark energy, CDG-2, and planetary habitability.

The significance of the inquiry is twofold. First, it addresses a methodological issue internal to science: how theories, models, and observations cooperate when the explanatorily decisive term is not fully visible. Second, it addresses a philosophical issue that repeatedly emerges in public and scholarly discourse: whether the recurrent scientific need to posit the unseen encourages stronger claims about order, purpose, or hidden intelligence in nature. The paper argues that such philosophical questions are legitimate, but they cannot simply inherit the evidentiary authority of scientific posits whose own ontological status remains tiered and case-dependent.

To organize this argument, the paper first reviews the philosophical literature on abduction, theoretical terms, scientific realism, and underdetermination. It then reconstructs a historical pattern in which some unseen posits moved from calculation or indirect effect to stronger empirical standing. The discussion subsequently examines dark matter, dark energy, and CDG-2 as frontier cases of incomplete but disciplined ontology, before turning to habitability and fine-tuning as cases where scientific description generates strong pressure toward existential meaning. The paper concludes by arguing that the appropriate response to the missing pieces of science is neither crude skepticism nor metaphysical inflation, but explanatory boldness matched by ontological restraint.

2. Review of Related Literature

2.1 Abduction and Inference to the Best Explanation

Abduction, or inference to the best explanation, is the philosophical framework most closely associated with science's movement from anomalous effect to candidate unseen cause Niiniluoto, 1999). It differs from deduction because it does not guarantee the truth of its conclusion), and from simple induction because it is not merely a projection from repeated instances (Trajkovski & Williamson, 2021). Rather, it selects or advances a hypothesis because, if true, that hypothesis would make a puzzling set of observations more intelligible, coherent, or unified (Heckman & Singer, 2017; Ward et al., 2016).

In scientific practice, abduction is indispensable wherever observable effects exceed the explanatory reach of currently available terms (Gillespie et al., 2024). It allows investigators to move from residuals, structural mismatches, or anomalous behavior to a disciplined hypothesis about what must be added to the explanatory frame (Chiffi et al., 2019; Gillespie et al., 2024). The importance of abduction for the present study lies in its ability to explain why unseen entities in science need not be treated as arbitrary inventions. They are often inferential responses to persistent empirical pressure (Romeijn, 2008).

At the same time, abduction is inherently provisional. It organizes uncertainty; it does not erase it. For that reason, the literature emphasizes comparative fit, explanatory power, and coherence with established theory, and the provisional nature of abductive inferences implies openness to revision (Romeijn, 2008),(Ward et al., 2016). These features make abduction the correct starting point for analyzing how science handles missing explanatory pieces without collapsing into either speculation or premature certainty.

2.2 Theoretical Terms, Unobservables, and Scientific Realism

The literature on theoretical terms clarifies why scientific language often extends beyond what is directly observable. A term may function as theoretical because it refers to nonobservational entities or because its meaning is partly fixed by a theory's structure (Frigg, 2022),(Andreas & Schiemer, 2021). This matters because modern science regularly works with concepts whose referents are not given in ordinary perception but are nonetheless indispensable to successful inquiry.

Scientific realism becomes relevant at precisely this point. Realist positions hold, in varying degrees, that successful scientific inquiry can warrant belief not only in observable phenomena but also in unobservable features of the world (Sankey, 2016).

For the present paper, realism is useful not as an all-or-nothing doctrine but as a graded stance. Some unseen scientific posits may warrant relatively strong ontological commitment because of their evidential integration and explanatory success, while others may warrant only cautious or partial realism because their physical nature remains unresolved.

This literature also helps resist a false dichotomy. The issue is not whether a term is directly observable or merely fictive. The better question is whether it is inferentially disciplined: whether it arises from convergent evidence, yields explanatory unification, survives empirical testing, and remains productive in further research (Niiniluoto, 2016). Theoretical terms and scientific realism together, therefore, provide a framework for understanding why the unseen can be epistemically legitimate without being epistemically uniform.

2.3 Historical Pattern of Success: From Prediction to Confirmation

Historical episodes in science show that some unseen posits move through a recognizable career: from anomaly-driven inference to increasingly strong empirical confirmation (Sagrafena, 2023). The discovery of Neptune is a classical example. Irregularities in the orbit of Uranus were explained by positing an unseen planet, whose location was then calculated and eventually observed near the predicted position). The case became emblematic of the prestige of indirect but mathematically disciplined scientific inference).

A modern analogue is the Higgs boson. Long before experimental confirmation in 2012, particle physics already treated the Higgs field and its boson as theoretically necessary to account for how elementary particles acquire mass (Wolf, 2023). Its eventual discovery did not merely add a new particle; it confirmed the fertility of a deeply theory-led inferential commitment. Black holes present a related but distinct trajectory: they were first established scientifically through the effects they exerted on nearby matter and radiation, and only later developed a more direct observational approach through imaging (Afshordi et al., 2024).

These cases matter not because they prove that every current frontier posit will be similarly vindicated, but because they demonstrate that scientific reasoning beyond immediate observability has often been productive and legitimate. The history of science therefore justifies taking current unseen posits seriously, while still requiring discrimination regarding their evidential maturity.

2.4 Frontier Cosmological Posits: Dark Matter, Dark Energy, and Structured Absence

Dark matter and dark energy represent contemporary cases in which explanatory necessity outruns ontological closure. Dark matter is inferred because visible matter alone does not account for observed gravitational effects, including galaxy rotation, cluster dynamics, and lensing (Petersen & Rosenlyst, 2019). Dark energy is named as the unknown driver of the universe's accelerating expansion (Debnath et al., 2024). In both cases, the scientific commitment is substantial, yet the underlying physical ontology remains unresolved.

A related frontier logic appears in CDG-2, a recently discussed low-surface-brightness galaxy in the Perseus cluster. Here the issue is not only unseen mass in the abstract but also what may be called structured absence: a system becomes scientifically significant because sparse visible traces—globular clusters and extremely faint diffuse emission—support an inference to a much larger and largely unseen galactic structure (Li et al., 2025). CDG-2 is therefore valuable for the literature because it demonstrates how weak but patterned visibility can still justify strong explanatory commitment.

The dark-sector literature is important to this paper not simply because it concerns hidden components of the universe, but because it reveals a mature scientific culture operating under ontological incompletion. These are not arbitrary labels, yet neither are they final metaphysical answers. They are frontier posits: evidentially constrained, explanatorily central, and still open to revision in their ultimate interpretation.

2.5 Habitability, Fine-Tuning, and the Pressure Toward Meaning

The literature on planetary habitability and cosmological fine-tuning introduces a distinct but related form of explanatory pressure. Habitability concerns the structured environmental conditions under which liquid water and, by extension, life becomes plausible (Kane & Byrne, 2024). Fine-tuning generalizes the issue by asking whether the universe's constants, parameters, or initial conditions fall within narrow ranges compatible with complexity and life (Gil & Alfonseca, 2022).

These discussions are scientifically significant, but they are also philosophically volatile (Adams, 2019). Once science identifies narrow life-permitting conditions, the temptation arises to interpret such conditions as evidence of design, purpose, or hidden intentionality(Ćirković, 2002). Yet the literature does not support a single inevitable conclusion (Adams, 2019). Design-oriented readings, anthropic reasoning, multiverse proposals, and more cautious accounts of contingency all remain in play(Ćirković, 2002; Gil & Alfonseca, 2022).

For the present paper, this body of literature is essential because it shows how scientific description can generate strong pressure toward existential meaning without itself settling the metaphysical question. Habitability and fine-tuning therefore stand at the boundary where scientific explanation begins to invite, but does not conclusively authorize, teleological interpretation.

2.6 Synthesis

Across these themes, a common insight emerges: science repeatedly confronts missing explanatory pieces and responds through disciplined posits of the unseen. Abduction explains the logic of this movement, debates on theoretical terms and realism explain its epistemic status, historical cases demonstrate that such inferences can mature into well-confirmed knowledge (Forber & Griffith, 2011), frontier cosmology shows the persistence of ontological incompletion (Kaisheng & Longji, 2025), and habitability studies reveal how quickly scientific structure becomes charged with questions of meaning.

Taken together, the literature suggests that the unseen is neither alien to science nor automatically equivalent to metaphysical speculation. Instead, it occupies a graded field in which different kinds of scientific posits carry different evidential strengths and ontological implications (Chakravartty, 2021; Psillos, 2021). This synthesis provides the conceptual basis for the present paper's analytical framework.

2.7 Gaps in the Literature

Despite the richness of the relevant literatures, two gaps remain. First, discussions of unseen scientific posits are often fragmented by discipline. Philosophy of science examines abduction and realism; physics discusses dark sectors; astronomy presents cases like black holes or CDG-2; planetary science discusses habitability (Kane & Byrne, 2024). Less often are these brought together under one comparative analytical frame focused explicitly on the logic of missing explanatory terms.

Second, the literature rarely offers a systematic distinction between legitimate scientific inference to the unseen and the more speculative teleological or metaphysical interpretations that such inference can provoke. The public discourse surrounding dark matter, fine-tuning, or life-permitting conditions often collapses these levels. The present study addresses that gap by developing a typology of scientific posits and using it to mark the boundary between disciplined explanatory inference and speculative overreach.

3. Methodology

This paper uses a conceptual-analytical research design appropriate for a theory-oriented JFSF manuscript. Rather than generating primary experimental data, it synthesizes and interprets scientific and philosophical materials in order to examine a recurring epistemic pattern: the inferred inclusion of unseen terms, entities, mechanisms, or condition sets when observable effects exceed current explanatory reach.

The corpus informing the analysis consists of two classes of materials. The first includes philosophy-of-science sources dealing with abduction, theoretical terms, scientific realism, underdetermination, fine-tuning, and teleology. The second includes scientific materials and institutional summaries concerning historically successful cases of inferred entities and contemporary frontier cases such as dark matter, dark energy, black holes, habitability, and CDG-2. These materials are used not as isolated evidentiary fragments but as analytically comparable cases within a broader conceptual problem.

Analytically, the study proceeds in four steps. First, it identifies the common structure underlying cases in which science posits what is not yet directly seen. Second, it classifies these posits into distinct epistemic types, including constants and parameters, inferred entities, hidden mechanisms, placeholders, structured absences, and conditional architectures. Third, it compares historical and contemporary cases to determine how unseen posits differ in evidential maturity and ontological weight. Fourth, it evaluates where scientific inference ends and teleological or metaphysical projection begins.

The method is interpretive rather than quantitative, but it remains disciplined by explicit conceptual criteria: explanatory role, degree of empirical integration, openness to revision, and ontological scope. On this basis, the study does not aim to prove or disprove metaphysical positions such as design. Rather, it seeks to clarify what current science legitimately warrants, what remains underdetermined, and what kinds of philosophical extension require additional argument beyond the empirical cases themselves.

4. Results and Discussion

4.1 A Typology of Scientific Posits

The first result of the analysis is the need for a typology. Not all scientific missing pieces are of the same kind. Constants and parameters are fundamental elements that characterize a system within scientific theories (Keyser, 2017), acting as fixed values or invariants within a modeling setup (Keyser, 2017). Inferred entities, such as Neptune or the Higgs boson, are posited as supposed real existents whose existence is inferred from observations that accord with theoretical principles (Beck, 1950). Hidden mechanisms provide explanations for how processes unfold, allowing for a scientific understanding of phenomena by characterizing the mechanisms that produce them (Salmon, 1993). Model placeholders serve as linguistic tools to facilitate discussions of scientific models, often as a way to refer to abstract entities without necessarily implying a serious ontological commitment (Antoniou, 2021). Structured absences allow for inferences about largely unseen structures based on sparse visible traces, a process that involves making claims about what is not taking place and evidencing their counterfactual relevance (Rappert, 2015). Habitability, in this context, identifies a conditional architecture where specific conditions make certain outcomes possible, as evidenced by discussions on system architecture influencing long-term planetary habitability (Vervoort et al., 2022). This systematic categorization allows for a more nuanced understanding of how scientific reasoning accommodates the unobserved, moving beyond a simplistic dichotomy between observable and unobservable phenomena to appreciate the diverse epistemic roles these posits fulfill.

This typology matters because the scientific legitimacy of unseen terms cannot be assessed adequately through a single yes-or-no question about observability. Different kinds of scientific posits warrant different degrees of ontological confidence. Without this classification, dark matter, the speed of light, the Higgs field, and the habitable zone could be misleadingly treated as though they all functioned in the same epistemic manner. This distinction is particularly crucial when differentiating between rigorously inferred scientific concepts and those speculative interpretations that often blur the line into teleological or metaphysical claims (Trommler & Hammann, 2020).

4.2 Historical Validation of the Unseen

A second result concerns the historical career of unseen scientific posits. The comparative cases of Neptune, the Higgs boson, and black holes show that some entities first admitted through inference later attain far stronger empirical standing. This history explains why modern science does not treat indirectness as a decisive objection. The fact that something is not directly observed at one stage does not, by itself, make it arbitrary or fictive. Indeed, the progression from theoretical postulation to empirical confirmation for entities such as black holes, inferred from gravitational effects and activity around event horizons, underscores the dynamic and often iterative nature of scientific discovery (Shah, 2023)).

At the same time, the historical pattern must not be overstated. Past successes justify taking frontier posits seriously, but they do not guarantee that every current posit will follow the same trajectory. The result is a graded stance: the history of science supports disciplined openness to the unseen while also preserving room for revision and replacement. This nuanced perspective aligns with the understanding that scientific theories often posit unobservable entities that are nonetheless crucial for explanatory coherence, with their epistemological status evolving as observational capabilities advance or new inferential frameworks emerge (Allzén, 2022; Spiegel, 2021).

4.3 Dark Matter, Dark Energy, and the Frontier of Incomplete Ontology

The third result is that dark matter and dark energy are best understood as frontier posits without final ontology. Dark matter is supported by multiple gravitational and structural observations, yet its composition remains unknown. Dark energy is central to explaining accelerated cosmic expansion, yet its physical nature remains even more unsettled. Both terms therefore exemplify a scientific posture of commitment without finality. Despite substantial observational evidence for its gravitational effects, the precise properties of dark matter remain largely unconstrained, and it is not definitively established whether it constitutes a single type of matter or multiple entities (Khalili, 2023).

This result is significant because it undermines two simplistic views at once. Against crude skepticism, dark matter and dark energy are not empty names attached to ignorance. Against premature metaphysical inflation, neither term should be treated as a completed ontological answer. They are scientifically indispensable and philosophically unfinished. This nuance reflects an ongoing scientific commitment to entities evinced by their effects, even in the absence of direct detection or a complete theoretical framework (Bertolaso & Sterpetti, 2023).

4.4 CDG-2 and the Logic of Structured Absence

CDG-2 provides the paper’s most vivid contemporary case. The analysis shows that a system may become scientifically consequential even when its visible content is extraordinarily slight, provided that the remaining traces are structured enough to support a coherent inference. In CDG-2, the combination of globular clusters and extremely faint diffuse emission points toward a dark-matter-dominated galactic system whose scientific significance lies precisely in its near invisibility (Li et al., 2025).

This supports the broader claim that science often operates successfully under conditions of sparse phenomenological access. CDG-2 is not merely another astronomy curiosity; it is a methodological exemplar showing how the unseen can become epistemically legitimate through patterned residual evidence rather than full luminous display. This illustrates how robust inferences can be drawn even when direct observational data are limited, emphasizing the strength of theoretical frameworks in interpreting subtle empirical signatures. However, it is crucial to recognize that maintaining the "substance presupposition" regarding dark matter could lead to persistent challenges, as theoretical unification may remain a mathematical patchwork rather than achieving true ontological coherence (Kaisheng & Longji, 2025).

4.5 Habitability, Fine-Tuning, and Explanatory Pressure

The analysis of habitability produces a more nuanced result. Scientific descriptions of life-permitting conditions create significant explanatory pressure because they disclose narrow windows within which liquid water, chemistry, and complexity become possible (Bains & Schulze-Makuch, 2016; Solé et al., 2025). Earth's position within a habitable range, together with long-term environmental stability, can therefore appear more than merely contingent. Such cases invite reflection on order, rarity, and meaning.

Yet the analysis reveals that this pressure toward meaning is not identical to proof of design. Habitability and fine-tuning may motivate philosophical interpretation, but they do not uniquely authorize teleological conclusion. The scientific data establish structured contingency; the metaphysical meaning of that contingency remains underdetermined.

4.6 The Boundary Between Scientific Inference and Teleology

The final and most important result is boundary clarification. Scientific abduction and teleological reasoning can share a similar formal shape, since both move from a striking phenomenon to a deeper explanatory postulate (Cruz & Smedt, 2017). However, they differ in ontological burden. Scientific inference ordinarily asks us to accept an unseen factor under empirical and theoretical constraint. Teleological inference asks us to accept purpose, intention, or mind-like direction. That is a stronger claim and therefore requires stronger justification.

While fine-tuning arguments, which highlight the precise physical constants enabling life, may not definitively prove theism, they do offer significant evidence that can render theistic belief not unreasonable, functioning as "surprising facts" that challenge purely materialistic expectations (Gillespie, 2018).

5. Conclusions, Recommendations, and Implications

5.1 Conclusions

This paper has argued that the unseen is a normal condition of scientific inquiry rather than a methodological failure. Across philosophy of science, historical cases of successful prediction, frontier cosmology, and planetary habitability, science repeatedly encounters explanatory situations in which what is directly visible is insufficient. Its response is to posit unseen terms, entities, mechanisms, structured absences, or enabling conditions under evidential pressure. This process demonstrates that the rejection of supernatural or teleological hypotheses in scientific discourse typically arises not from a priori exclusion, but from their failure to meet established explanatory criteria such as parsimony and explanatory power, akin to how any other scientific hypothesis is evaluated (Fishman & Boudry, 2013).

The study further concludes that these missing pieces are not epistemically uniform. Some attain comparatively strong ontological standing; some remain indispensable but incomplete; others function as conditional architectures rather than hidden substances or minds. The crucial philosophical lesson is therefore one of discrimination: science is justified in moving beyond immediate observability, but such movement must be evaluated by category, evidence, and explanatory role. This reinforces the idea that scientific methodology is the right one for studying the natural world (Donahue, 2024). This approach, which values explanatory power and empirical coherence, implicitly establishes a boundary for what constitutes a scientifically viable explanation, thereby contrasting with proposals lacking empirical grounding.

Finally, the paper concludes that the transition from scientific inference to teleology is not automatic. Dark matter, dark energy, CDG-2, and habitability may all provoke reflection on order and meaning, but they do not by themselves establish purpose, design, or hidden intelligence. Those remain philosophical extensions requiring further argument. This distinction is critical for understanding the limits of scientific inquiry, as science primarily addresses the "how" of the physical world, not the "why" (Turner, 2018). This necessitates a clear demarcation between scientific explanation, which operates within the confines of empirical evidence and testable hypotheses, and metaphysical or theological interpretations, which often extend beyond these boundaries (Bikaraan-Behesht, 2023). Thus, while scientific findings can inform philosophical and theological discussions, they do not inherently validate or invalidate teleological claims, but rather refine the parameters within which such discussions can meaningfully occur.

5.2 Recommendations

Future JFSF work on controversial or frontier topics should distinguish more explicitly among the different kinds of unseen scientific posits involved in a claim. This will help prevent the common error of treating constants, entities, placeholders, and conditional structures as though they carried the same ontological force.

Further studies may also deepen the comparative analysis by extending the framework to other domains, such as neuroscience, systems biology, climate science, or artificial intelligence, where latent variables, model terms, or hidden structures often play similarly important roles. A parallel line of inquiry may examine how public discourse transforms disciplined scientific incompletion into mythic certainty, conspiratorial narratives, or premature metaphysical closure.

For editorial purposes, papers that move from empirical anomaly to claims of cosmic design or intention should be required to mark clearly where scientific inference ends and philosophical interpretation begins. This would preserve intellectual openness while maintaining evidentiary discipline.

5.3 Implications

The scientific implication of the study is that frontier inquiry should not be judged by a naïve standard of full visibility. Some of the most productive scientific commitments arise precisely where direct access is limited and inference must do the heavy explanatory work. The philosophical implication is that underdetermination remains central: unseen structure may be real and scientifically indispensable without yet yielding a final ontology.

For science communication, the paper implies that public misunderstanding often arises when provisional scientific posits are narrated either as mere fictions or as already complete revelations of ultimate reality. A more careful account of graded ontological commitment may improve public literacy around dark matter, dark energy, fine-tuning, and related frontier topics.

For JFSF specifically, the study demonstrates a viable genre of paper that is both science-grounded and philosophically reflective. It shows that frontier inquiry can engage culturally powerful questions about order, meaning, and hidden structure without sacrificing formal rigor or drifting into sensationalism.

References

Adams, F. C. (2019). The degree of fine-tuning in our universe — and others. Physics Reports, 807, 1. https://doi.org/10.1016/j.physrep.2019.02.001

Afshordi, N., Ashtekar, A., Barausse, E., Berti, E., Brito, R., Buoninfante, L., Carballo-Rubio, R., Cardoso, V., Carullo, G., Dafermos, M., Laurentis, M. D., Río, A. del, Filippo, F. D., Eichhorn, A., Emparan, R., Gregory, R., Herdeiro, C., Kunz, J., Lehner, L., … Wald, R. M. (2024). Black Holes Inside and Out 2024: visions for the future of black hole physics. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2410.14414

Allzén, S. (2022). From Unobservable to Observable: Scientific Realism and the Discovery of Radium. Journal for General Philosophy of Science, 53(4), 307. https://doi.org/10.1007/s10838-022-09614-5

Andreas, H., & Schiemer, G. (2021). Modal Structuralism with Theoretical Terms. Erkenntnis, 88(2), 721. https://doi.org/10.1007/s10670-021-00378-w

Antoniou, A. (2021). A pragmatic approach to the ontology of models. Synthese, 199, 6645. https://doi.org/10.1007/s11229-021-03085-9

Bains, W., & Schulze-Makuch, D. (2016). The Cosmic Zoo: The (Near) Inevitability of the Evolution of Complex, Macroscopic Life. Life, 6(3), 25. https://doi.org/10.3390/life6030025

Beck, L. W. (1950). Constructions and Inferred Entities. Philosophy of Science, 17(1), 74. https://doi.org/10.1086/287067

Bertolaso, M., & Sterpetti, F. (2023). Some reflections on Mitchell's pragmatist variant of scientific realism. THEORIA An International Journal for Theory History and Foundations of Science, 38(3), 389. https://doi.org/10.1387/theoria.24085

Chakravartty, A. (2021). Risk, Reward, and Scientific Ontology: Reply to Bryant, Psillos, and Slater. Dialogue, 60(1), 43. https://doi.org/10.1017/s0012217320000311

Chiffi, D., Pietarinen, A., & Proover, M. (2019). Anticipation, abduction and the economy of research: The normative stance. Futures, 115, 102471. https://doi.org/10.1016/j.futures.2019.102471

Ćirković, M. M. (2002). On the First Anthropic Argument in Astrobiology. Earth Moon and Planets, 91(4), 243. https://doi.org/10.1023/a:1026266630823

Cruz, H. D., & Smedt, J. D. (2017). Intuitions and Arguments: Cognitive Foundations of Argumentation in Natural Theology. European Journal for Philosophy of Religion, 9(2), 57. https://doi.org/10.24204/ejpr.v9i2.1934

Debnath, U., Chaudhary, H., Molla, N. U., Pacif, S. K. J., & Mustafa, G. (2024). Dark Energy Model in Einstein and Horava-Lifshitz Gravity with a new Parametrization of $\omega(z)$: Model Comparison, Analysis and Observational Constraint. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2405.15874

Fishman, Y. I., & Boudry, M. (2013). Does Science Presuppose Naturalism (or Anything at All)? Science & Education, 22(5), 921. https://doi.org/10.1007/s11191-012-9574-1

Forber, P., & Griffith, E. C. (2011). Historical Reconstruction: Gaining Epistemic Access to the Deep Past. Philosophy and Theory in Biology, 3(20170609). https://doi.org/10.3998/ptb.6959004.0003.003

Frigg, R. (2022). Models and Theories. https://doi.org/10.4324/9781003285106

Gil, F. J. S., & Alfonseca, M. (2022). Is the Multiverse Hypothesis capable of explaining the Fine Tuning of Nature Laws and Constants? The Case of Cellular Automata. arXiv (Cornell University). https://doi.org/10.48550/arxiv.1105.4278

Gillespie, A., Glăveanu, V. P., & Laurent, C. de S. (2024). Pragmatism and Methodology. https://doi.org/10.1017/9781009031066

Gillespie, R. (2018). Cosmic Meaning, Awe, and Absurdity in the Secular Age: A Critique of Religious Non-Theism. Harvard Theological Review, 111(4), 461. https://doi.org/10.1017/s0017816018000238

Heckman, J. J., & Singer, B. H. (2017). Abducting Economics. American Economic Review, 107(5), 298. https://doi.org/10.1257/aer.p20171118

Kaisheng, L., & Longji, L. (2025). The Cosmic Rhythm: Empirical Physics of Process Ontology. In Zenodo (CERN European Organization for Nuclear Research). European Organization for Nuclear Research. https://doi.org/10.5281/zenodo.17764760

Kane, S. R., & Byrne, P. K. (2024). Venus as an Anchor Point for Planetary Habitability. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2403.08830

Keyser, V. (2017). Experimental effects and causal representations. Synthese, 198, 5145. https://doi.org/10.1007/s11229-017-1633-3

Khalili, M. (2023). A Dialogue among Recent Views of Entity Realism. Philosophy of Science, 90(4), 901. https://doi.org/10.1017/psa.2023.18

Li, D., Liu, Q., Eadie, G. M., Abraham, R., Marleau, F., Harris, W. E., Dokkum, P. van, Romanowsky, A. J., Danieli, S., Brown, P., & Stringer, A. (2025). Candidate Dark Galaxy-2: Validation and Analysis of an Almost Dark Galaxy in the Perseus Cluster. The Astrophysical Journal Letters, 986(2). https://doi.org/10.3847/2041-8213/adddab

Niiniluoto, I. (1999). Defending Abduction. Philosophy of Science, 66. https://doi.org/10.1086/392744

Niiniluoto, I. (2016). Unification and Abductive Confirmation. THEORIA An International Journal for Theory History and Foundations of Science, 31(1), 107. https://doi.org/10.1387/theoria.13084

Petersen, J., & Rosenlyst, M. (2019). A toy model for the dynamical discrepancies on galactic scales. Monthly Notices of the Royal Astronomical Society, 490(3), 3493. https://doi.org/10.1093/mnras/stz2625

Psillos, S. (2021). Scientific Ontology: Fact or Stance? Dialogue, 60(1), 15. https://doi.org/10.1017/s0012217320000360

Rappert, B. (2015). Sensing Absence: How to See What Isn't There in the Study of Science and Security. In Palgrave Macmillan UK eBooks (p. 3). Palgrave Macmillan. https://doi.org/10.1057/9781137493736_1

Romeijn, J. (2008). The all-too-flexible abductive method: ATOM's normative status. Journal of Clinical Psychology, 64(9), 1023. https://doi.org/10.1002/jclp.20516

Sagrafena, C. (2023). The old evidence problem and the inference to the best explanation. European Journal for Philosophy of Science, 13(1). https://doi.org/10.1007/s13194-022-00507-4

Salmon, W. C. (1993). The Value of Scientific Understanding. Philosophica, 51. https://doi.org/10.21825/philosophica.82384

Sankey, H. (2016). Scientific Realism and the Rationality of Science. https://doi.org/10.4324/9781315607849

Shah, D. (2023). Extremal Black Holes in Diffeomorphism Covariant Gravity. Deep Blue (University of Michigan). https://doi.org/10.7302/21599

Solé, R. V., Kempes, C. P., & Stepney, S. (2025). Origins of life: the possible and the actual. Philosophical Transactions of the Royal Society B Biological Sciences, 380(1936), 20240281. https://doi.org/10.1098/rstb.2024.0281

Spiegel, T. J. (2021). Naturalism, Quietism, and the Threat to Philosophy. https://doi.org/10.31267/978-3-7574-0062-0

Trajkovski, M., & Williamson, T. (2021). Abduction, perception, emotion, feeling: Body maps and pattern recognition. Philosophical Perspectives, 35(1), 404. https://doi.org/10.1111/phpe.12142

Trommler, F., & Hammann, M. (2020). The relationship between biological function and teleology: Implications for biology education. Evolution Education and Outreach, 13(1). https://doi.org/10.1186/s12052-020-00122-y

Vervoort, P., Horner, J., Kane, S. R., Turner, S. K., & Gilmore, J. (2022). System Architecture and Planetary Obliquity: Implications for Long-term Habitability. The Astronomical Journal, 164(4), 130. https://doi.org/10.3847/1538-3881/ac87fd

Ward, T., Clack, S., & Haig, B. D. (2016). The Abductive Theory of Method: Scientific Inquiry and Clinical Practice. Behaviour Change, 33(4), 212. https://doi.org/10.1017/bec.2017.1

Wolf, W. J. (2023). Cosmological inflation and meta-empirical theory assessment. Studies in History and Philosophy of Science Part A, 103, 146. https://doi.org/10.1016/j.shpsa.2023.12.006