Journal for General Philosophy of Science (2021) 52:577–595
https://doi.org/10.1007/s10838-021-09566-2

ARTICLE

The Anti-Metaphysical Argument Against Scientific Realism: A Minimally Metaphysical Response

Raphaël Künstler[1]

Accepted: 13 April 2021 / Published online: 4 September 2021

Abstract
The anti-metaphysical argument against scientific realism (AMA) is the following: (1) Knowledge of unobservable entities implies metaphysical knowledge; (2) There is no metaphysical knowledge. Therefore, there is no knowledge of unobservable entities. This argument has strangely received little attention in the profuse literature on scientific realism. This paper claims that the AMA is logically more fundamental than both the pessimistic meta-induction and the underdetermination argument. The second and main claim of this paper is that the instrumentalists' use of AMA is incoherent. The gist of my argument is that experimental knowledge requires minimally metaphysical knowledge, and that minimally metaphysical knowledge—when associated with empirical knowledge—suffices to yield a minimal knowledge of the unobservable. I then examine and reject two possible responses: minimally metaphysical instrumentalism and algebraic instrumentalism.

Keywords Scientific realism · Antirealism · Instrumentalism · Metametaphysics · Neo-experimentalism · Duhem

1 Introduction

Is it more legitimate to believe in quarks than in telepathic waves, given that we can never hope to see either of these with our own eyes? Philosophers interested in this type of question are accustomed to call 'unobservable' any reality that is impossible to perceive directly and 'theoretical' any proposition describing unobservable objects.[1] Our initial question can be rephrased: is it possible to know the unobservable? Does science provide theoretical knowledge?

While philosophers who answer this question in the affirmative are said to be scientific realists, scientific anti-realists answer in the negative. *Prima facie*, an anti-realist commitment should lead to a global rejection of science since antirealists reject the cognitive ambition of scientists who aim at uncovering the hidden structures of reality.

[1] In this technical sense, not all propositions in a theory are 'theoretical'.

✉ Raphaël Künstler
raphael.kunstler@univ-tlse2.fr

[1] Philosophy Department, Université Toulouse - Jean Jaurès, Toulouse, France

Instrumentalism is the philosophical position holding that being anti-realist does not imply being anti-scientific. The two most prominent instrumentalists, Duhem (1906) and van Fraassen (1980) aim at proving that anti-realism does not involve the rejection of most of our current experimental and theoretical practices. Even if they do not help us to uncover the unobservable, experimental practices provide knowledge of observable regularities. Even if they are not literally true, theories can be understood as instruments that allow the deduction of a large number of already experimentally known empirical regularities.

Van Fraassen distinguishes two kinds of arguments for instrumentalism: constructive and critical arguments. The constructive arguments demonstrate that antirealist scientists could practice science in exactly the same way as realist scientists (van Fraassen 1980, 5). In other words, anti-realism does not lead to the destruction of scientific practices. In the same fashion, Duhem conceives his masterpiece *The Physical Theory. Its object, its structure* as a constructive argument proving the sustainability of scientific practices not pursuing the uncovering of unobservable mechanisms (Duhem 1991, 332).

The critical arguments demonstrate that scientific practices—when pursued with a realistic goal—are not sustainable. The underdetermination argument and the pessimistic meta-induction are usually regarded as the most important arguments against scientific realism (see Chakravartty 2007; Vickers 2015; Wray 2018). However, Bas van Fraassen does not use either of these arguments (see van Fraassen 2008, 346; Wray 2018, 85). Similarly, as we will see, the main critical argument of Pierre Duhem against scientific realism is neither the pessimistic meta-induction, nor his famous under-determination argument.

The main critical argument of instrumentalists can be reconstructed as the following *modus tollens*:

(1) Theoretical knowledge implies metaphysical knowledge. *(Indispensability)*
(2) There is no metaphysical knowledge. *(Anti-metaphysical skepticism)*
∴ There is no theoretical knowledge. *(Scientific anti-realism)*

Since this argument is based on the meta-metaphysical premise that denies any epistemic value to metaphysical statements, I choose to refer to it as the *anti-metaphysical argument against scientific realism* (from now on, AMA).

The goal of this paper is to support two claims. First, I claim that the AMA is more fundamental than the two arguments that are usually regarded as the most central anti-realist arguments: the pessimistic meta-induction argument and the underdetermination argument (Chakravartty 2007; Stanford 2006; Wray 2018). The gist of my argument is first that the AMA justifies the pessimistic meta-induction; and second that the AMA justifies a crucial implicit premise of the underdetermination argument. Second, I claim that the use of the AMA by instrumentalists is incoherent, and that they should choose between being anti-scientific anti-realist or scientific realist. The gist of my argument is that experimental knowledge requires minimally metaphysical knowledge, and that minimally metaphysical knowledge—when associated with empirical knowledge—suffices to yield a minimal knowledge of the unobservable. Therefore, instrumentalists must either reject experimental knowledge or accept theoretical knowledge.

The paper unfolds as follows: Section 2 presents the argument. Sections 3 and 4 briefly review the justification for its premises. Section 5 argues that the instrumentalist use of this argument is incoherent. The Sects. 6 and 7 examine and reject a first possible strategy to avoid this incoherence, and the Sects. 8 and 9 examine and reject a

second possible strategy. I conclude that instrumentalists' use of AMA collapses either into anti-scientific anti-realism or into scientific realism.

2 The Anti-Metaphysical Argument

The goal of this section it to reconstruct the AMA, and to bring out its relation with the pessimistic meta-induction and the underdetermination arguments. To reconstruct this argument, I will use the first chapter of Duhem's *The Aim and Structure of Physical Theories* and the first chapter of van Fraassen's *The Scientific Image*.

The position of the AMA in Duhem's book indicates that Duhem regards it as his main and fundamental argument against scientific realism: the exposition of the AMA is the object of his very first chapter (see also Duhem 1917, 152). Duhem's first premise is a conditional statement whose antecedent states the realist conception of physical theories[2] and whose consequent states the subordination of theoretical physics to metaphysics:

> If the aim of physical theories is to explain experimental laws, theoretical physics is not an autonomous science; it is subordinate to metaphysics. (Duhem 1991, 10)

His second premise is meta-metaphysical. It states that metaphysical propositions are never consensual[3]:

> None of the systems of thought arising in different eras or the contemporary systems born of different schools will appear more profoundly distinct, more sharply separated, more violently opposed to one another, than those in the field of metaphysics. (Duhem 1991, 10)

Placing these propositions side by side is sufficient to make the conclusion that follows obvious:

> If theoretical physics is subordinated to metaphysics, the divisions separating the diverse metaphysical systems will extend into the domain of physics. (Duhem 1991, 10)

Duhem illustrates this by the way in which Aristotelians, Newtonians, Atomist and Cartesians answer the same question about the explanation of iron magnetization. According to the Aristotelians, who start from the metaphysical principle that all substances consist of matter and form, magnetization results from the fact that magnets modify the substantial form of iron. According to the Atomists, who start from the metaphysical principle that everything is made up of atoms and emptiness, magnetization is explained by the imbalance that the atoms of the magnet produce in the balance of the magnetic atoms present in iron. For the Newtonian Boscovich, who starts from the metaphysical principle that matter consists of points devoid of mass but that attract each other at a distance, magnetization is a manifestation of this general property of matter. While Descartes, assuming that matter

[2] The explanation of experimental laws requires knowledge of the unobservable mechanisms underlying them. Therefore, the claim that such explanation should be the goal of science is a realist position.

[3] In a sentence not translated in the English version of the book, Duhem also writes: 'Il est clair qu'en mettant la physique théorique sous la dépendance de la Métaphysique, on ne contribue point à lui assurer le bénéfice du consentement universel' (Duhem 1905, 17). 'It is clear that making physics dependent on Metaphysics does not contribute to securing for it the benefit of universal consent.' (my translation).

has no other property than extension and that emptiness does not exist, has to use a vortex model to explain magnetization. As each of these schools regards the other's metaphysical entities and properties as suspect, each one also rejects the other's theoretical explanations.

As Duhem conceives the subordination of theoretical knowledge to metaphysics as an epistemic subordination, and as the conflictual character of metaphysics is a symptom of ignorance, Duhem's argument is epistemological (See also Duhem 1892a; 1892b, 37–38; Duhem 1917, 152; Duhem 1996, 233–234). It can be articulated and summarized as the AMA already mentioned in our introduction:

(1) Theoretical knowledge implies metaphysical knowledge. *(Indispensability)*
(2) There is no metaphysical knowledge. *(Anti-metaphysical skepticism)*
∴ (3) There is no theoretical knowledge. *(Scientific anti-realism)*

For reasons related to the history of the philosophy of science in the Twentieth Century, van Fraassen explicitly takes over from Duhem's instrumentalism, holding that 'saving the phenomena' should be the only aim of science (van Fraassen 1980, ch. 2). Van Fraassen's goal is to dissociate empiricism from the form it took in the logical positivism program (van Fraassen 1980). Logical positivism rejected theoretical entities because of the verificationist conception of cognitive meaning (Hempel 1951). On the contrary, van Fraassen contends that the theoretical parts of scientific theories are meaningful (van Fraassen 1989, 217–232). He accepts a strong version of the correspondence theory of truth, construed as an isomorphism between a model and reality (van Fraassen 1980, 68–69). His rejection of realism is thus epistemological rather than semantic: there is no epistemic warrant for the truth of a theory, therefore the goal of scientific theories is not the truth but the empirical adequacy (van Fraassen 1980, 12).

Van Fraassen accepts the conclusion of the AMA. Moreover, van Fraassen holds that without inferences to the best explanation, theoretical knowledge could not be epistemically justified (Ladyman et al. 1997; van Fraassen 1980; 1989). As he also holds that without some previously held metaphysical commitments, inferences to the best explanation are not conclusive (as we will see below), he also accepts the proposition (1). And he is vehemently critical of metaphysicians' epistemic ambitions (van Fraassen 2002, ch. 1), and therefore accepts the proposition (2). He therefore uses the AMA.

Not only instrumentalists use the AMA, but this argument plays a central role in their argumentation. The AMA is even more fundamental than the two arguments that are usually regarded as the most central antirealist arguments: the pessimistic meta-induction argument and the underdetermination argument (Chakravartty 2007; Stanford 2006; Wray 2018).

The pessimistic meta-inductive argument starts with the enumeration of the theories that were first accepted by the scientific communities and then rejected. It concludes from these facts that it is probable that currently accepted theories will be rejected in the future (Putnam 1975; Laudan 1981a; Wray 2018).

The AMA explains why theoretical collapses happen. If AMA is correct, the cause of the fact that history of science is a graveyard of false theories is caused by the subordination of theoretical knowledge to metaphysical knowledge. Since history of metaphysics is a graveyard of metaphysical theories, the scientific theories will necessarily collapse one after another. On the contrary, since the history of mathematics is cumulative, the instrumentalist subordination of scientific theorization to mathematics will produce historically robust physical theories. Therefore, the MMA is an a priori pessimistic meta-induction: it

predicts that theoretical collapses will inevitably happen. Therefore, MMA is more fundamental than the pessimistic meta-induction.

The underdetermination argument holds that experimental evidence does not suffice to epistemically justify any theoretical choices. There are two reasons for this, and thus two versions of this argument, contrastive and holist (Stanford 2017). First, because several incompatible hypotheses can be compatible with the same data, these data cannot help to decide for one of these hypotheses. The contrastive character of theory confirmation excludes the existence of experimental proofs (Duhem 1991, 188–190). Second, because experimental data are not theoretically pure, a contradiction between a tested theory and experience does not necessarily result in the rejection of this tested theory. The holist character of theory confirmation excludes the existence of experimental proofs. As Duhem puts it:

> When certain consequences of a theory are struck by experimental contradiction, we learn that this theory should be modified but we are not told by the experiment what must be changed. It leaves to the physicist the task of finding out the weak spot that impairs the whole system. No absolute principle directs this inquiry, which different physicists may conduct in very different ways without having the right to accuse one another of illogicality. (Duhem 1991, 216)

As Duhem notices, if there were absolute principles directing the experimental inquiry, underdetermination would not happen. We will elaborate more on this point later. For now, let us notice the structure of the underdetermination argument. In order to do so, we must take into account an implicit premise of the argument. Duhem assumes that there are no 'absolute principle[s] direct[ing] [the] inquiry'. In other terms, he assumes that theoretical knowledge must be metaphysically pure, that is, that it implies the absence of metaphysical knowledge. Moreover, the context of the exposition of the underdetermination argument makes this premise clear, since this premise results from the AMA, and that the AMA is presented in the very first chapter of Duhem, (1991), whereas the underdetermination is only presented in the second part of the book. Therefore, Duhem's argument can be reconstructed as follows:

(~(1)) There is theoretical knowledge without metaphysical knowledge. *(metaphysical purity*)
(0a) If there is no metaphysical knowledge, theoretical choices are underdetermined.
(0b) If theoretical choices are underdetermined, there is no theoretical knowledge.
∴ Theoretical knowledge implies the absence of theoretical knowledge

The underdetermination argument can therefore be construed as a *reductio* demonstrating the first premise of the AMA. But the AMA could also be construed as a *reductio* demonstrating the first premise of the underdetermination argument. Therefore, these two arguments function together as an antinomy in Kant's (1781) sense: the AMA concludes to the falsity of the principle (1), and the falsity of this principle provides the principle (~(1)). of the underdetermination's argument. The underdetermination's argument concludes to the falsity of the principle (~(1)), and the falsity of this principle provides the principle (1) of AMA. Therefore, these two arguments can also be seen as forming a dilemma: if theoretical knowledge requires metaphysical knowledge, there is no theoretical knowledge; but if it is separated from metaphysical knowledge, there is also no theoretical knowledge. However, as the AMA makes explicit the first premise of the underdetermination argument, the former is arguably more fundamental than the latter.

3 Justification of the Indispensability Premise

Let us now undertake the analysis of the indispensability premise of the AMA.[4] Metaphysical knowledge is a necessary condition of theoretical knowledge if theoretical knowledge cannot be justified without metaphysical knowledge. Theoretical knowledge must be true and epistemically justified.[5] Knowledge is justified if given its justification it cannot be false. Epistemic justification can be direct or indirect. Theoretical knowledge is not directly justified since it is neither intuitive nor directly empirical knowledge. Indirect justification can be a posteriori or a priori depending on whether its premises are empirical evidence or metaphysical principles. Therefore, to prove that metaphysical knowledge is a necessary condition of theoretical knowledge, we need to prove that there is no rational procedure starting from empirical evidence and concluding that theoretical representations cannot be false. Five procedures can empirically justify a proposition: indirect observation, induction, method of hypothesis, crucial experiment, inference to the best explanation. Therefore, we must now examine each of these options.

We do not see unobservable objects *through* a microscope: what we really see then are images *in* the microscope. In order to conclude that these images are images of unobservable objects, an interpretation is required. In order to provide such interpretation, background theories are necessary. These theories must indicate the relation between the images observed in the microscope and the structures of unobservable objects. Therefore, the indirect experience of unobservable objects is theoretically laden. One must already know these objects in order to 'observe' them with a microscope. The reasoning is circular.[6] Indirect observation does not suffice to empirically justify theoretical knowledge.

Inductive generalization is the inference from the observation that a property is instantiated by a sample to the conclusion that is property is instantiated by an entire population. This inference rests on the presupposition that the sample is representative of the population. However, in the case of the unobservable, one cannot know whether observable objects are a representative sample of the population composed by observable and unobservable objects. In order to justify this assumption, one must already know the unobservable objects. Once again, the reasoning is circular.[7] Inductive generalization does not suffice to empirically justify theoretical knowledge.

According to the method of hypothesis, a theoretical belief is justified if empirical phenomena can be derived from the postulated properties of unobservable entities (Laudan 1981b). However, in order to assert that the properties of observable objects can be derived from the properties of unobservable objects, one must already know what kind of relations relate observable and unobservable objects: are they constitutive

[4] There is a vast literature on the definition of indispensability arguments in philosophy of mathematics and mathematics. However, it is not necessary here to enter into these discussions: 'indispensability' does not refer to an argument, but to a proposition stating that metaphysical knowledge is a necessary condition of theoretical knowledge. I am indebted to the anonymous referee who has helped me to clarify this point.

[5] In order to take into account Gettier's counterexamples, I take these conditions to be necessary not jointly sufficient conditions of knowledge. I take these conditions as necessary since (at least *prima facie*) a reliabilist analysis of theoretical knowledge is not a very promising option.

[6] See Hacking (1983) for a more precise analysis of the use of microscopes.

[7] For a more thorough demonstration of this point, see Carnap (1995).

relations? Mereological relations? Instantiation relations? Causal relations? Processes? Mechanisms? Etc. Therefore, without antecedent metaphysical knowledge, the method of hypothesis cannot be used to justify theoretical knowledge. Moreover, it is logically trivial to say that the truth of $p \rightarrow q$ and the existence of q does not imply p. Since the method of hypothesis commits the converse fallacy, it does not suffice to empirically justify theoretical knowledge.

In order to avoid the converse fallacy, one could compare all the possible hypotheses with the already available or newly obtained experimental data. This method of the crucial experiment (broadly construed) rests on the 'Good Lot' assumption, that is, on the assumption that the unobservable world is conceivable (van Fraassen 1989; Wray 2018). This assumption presupposes metaphysical knowledge. Moreover, several incompatible hypotheses can be compatible with the same empirical evidence: theoretical choice can be logically and empirically underdetermined. Therefore, crucial experiments do not suffice to empirically justify theoretical knowledge.

In order to avoid the empirical underdetermination of incompatible theories and to overcome their empirical equivalence, one could take into account theoretical virtues (Schlindler 2018). Inference to the best explanation starts with a list of all possible explanations of the relevant phenomena, determines which one is the best, and concludes that the best is true. However, theoretical virtues imply substantial metaphysical commitments (Lipton 2004). Favoring simple explanations, for example, presupposes that the world is simple as well as a definite conception of simplicity, and thus presupposes metaphysical knowledge (van Fraassen 1989). Inference to the best explanation does not suffice to empirically justify theoretical knowledge.

As no purely empirical justification suffices to justify theoretical knowledge, there can be no theoretical knowledge without metaphysical knowledge.

It can be noted that the argument for the indispensability premise is also an argument for the claim that theoretical choices are empirically underdetermined. This identity is no happenstance: as already seen, since the AMA and the underdetermination argument form an antinomy, the underdetermination argument concludes to the falsity of its principle, and the falsity of this principle provides AMA's principle (1).

4 Justification of the Anti-Metaphysical Skeptical Premise

We must now turn to the arguments justifying the unknowability premise (2), that is, the anti-metaphysical skepticism.[8]

4.1 The Anti-Metaphysical Argument from Peer Disagreement

Metaphysical theories are necessarily rival theories, since they all share the same aim: they all try to model the most general and fundamental structures of reality (Paul 2012). Therefore, metaphysicians disagree with one another. These disagreements seem rationally

[8] The central text concerning skepticism towards metaphysics is obviously Kant (1781). The recent development of meta-metaphysics has given rise to a finer argument than the one presented here but whose subtleties are not relevant to our present purpose. For a contemporary and technical discussion of meta-metaphysical skepticism, see Wasserman (2009), Hirsch (2009), Chakravartty (2017).

irreducible, for no dominant theory emerges through the course of the discussions. Such inability to reach a consensus proves the inability to give a decisive argument and, therefore, the non-possession of such a decisive argument. As knowledge implies the possession of decisive arguments, metaphysician's persisting disagreements prove the inexistence of metaphysical knowledge.[9]

4.2 The Anti-Metaphysical Pessimistic Meta-Inductive Argument

The pessimistic meta-inductive argument can be turned against metaphysical epistemic ambitions. History of philosophy is the graveyard of metaphysical theories. Therefore, we are inductively justified to believe that current dominant metaphysical trends will be overcome at some point. As noted above, for the instrumentalist, the subordination of realist physics to metaphysics explains why scientific theories collapse: the instability of metaphysical theories is transmitted to the scientific theories. This gives a strong argument for practicing science as instrumentalists advise us to: 'saving the phenomena' heals scientific theories from their dependence, and therefore heals them from the contamination by metaphysical instability.

4.3 The Anti-Metaphysical Underdetermination Argument

It is easy to apply the underdetermination argument to metaphysical theories: one can always invent a set of principles from which experience or experimental knowledge or even the content of scientific theories can be deduced (Duhem 1996, 33). Therefore, the observable reality does not suffice to constrain metaphysical choices.

4.4 The Anti-Metaphysical Argument from the Structure of Explanation

Let us suppose that a metaphysical proposition describes the most fundamental structure of reality. This fundamentality is interpreted as the fact that everything in the universe is explained by the truthmakers of metaphysical propositions, while nothing in the universe explains these fundamental facts. Therefore, there are no other facts from which these facts could be deduced. Now, according to foundationalism, epistemic justification is the deduction of a proposition from other propositions. Therefore, the explanatory function of metaphysical propositions excludes their justification.[10] It follows that metaphysical principles must be petitions of principle or rely on a metaphysical intuition of the first principles.[11]

[9] The inference from disagreement to ignorance is discussed by the profuse literature on peer disagreements (*e.g.*, Christensen 2007; Elga 2007; Decker 2012). I take it here as a *prima facie* reasonable assumption.

[10] If one proposition can be deduced from another provided that all the truthmakers of the first one are included in all the truthmakers of the second, then metaphysical propositions, describing sets of facts that include all the other facts, cannot be deduced from anything.

[11] Inwagen (1994) or Plantinga (1993) support the existence and legitimacy of such an intuition. Intuition is then conceived as a kind of perception without eyes or as a kind of revelation without mediating angels.

5 The Neo-Experimentalist Argument

As already mentioned above, an instrumentalist is a philosopher for whom only the empirically verifiable content of scientific theories is true and justified, while its non-empirical content is only a computational tool for synthesizing empirical knowledge. For instrumentalists, the cognitive content of theories does not come from theorization but from experimentation. Theoretical principles are not discovered, but invented, and they are invented post hoc: they are chosen only for their ability to make it possible to compute the already gained experimental knowledge in a given field (Hempel 1958). This pre-existing empirical knowledge is produced by experimental work. Therefore, instrumentalists accept the existence of *experimental knowledge*, *i.e.*, of experimental data and of experimentally established empirical laws. As scientific realists also admit that such knowledge exists, the acceptance of experimental knowledge provides a common epistemic ground for instrumentalists and realists.

Experimental knowledge has been investigated by neo-experimentalist philosophers (Mayo 1996). The motto of these philosophers is Hacking's phrase: experiment has a 'life of its own' (Hacking 1982, 71). In other words, experiments should not always be conceived in relation with theories. But experimental knowledge should also be distinguished from empirical knowledge. Neo-experimentalists show that experimenters reason on experiments, but that these reasonings do not necessarily appeal to scientific theories. Instead, experimenters appeal to more general principles such as 'If I can spray them, then they are real' (Hacking 1983) or, more generally 'causality implies reality' (see, *e.g.,* Suarez 2010, 146). Such general principles are not empirical, but precede any possible experience: they are a priori. Moreover, they describe general features of reality. These principles should therefore be classified as metaphysical principles.[12]

Let us now elaborate on that suggestion, and address the question: *What metaphysical knowledge is presupposed by the endeavor to produce experimental knowledge? What are the* a priori *principles without which experimental knowledge would not be possible?*

Experimentation is an activity. The goal of this activity is to describe nomological regularities in general in the form of equations. Any activity relies on a set of beliefs. Let us start by making explicit a few beliefs of the experimenters without which their endeavor would not make sense.

(a) Admitting experimental knowledge forces us to admit the external and independent existence of the objective reality. It is not enough to think of one thing to make it happen.[13] The results of the experimental process do not depend on our minds. It is not the mind of the experimenter who manipulates the objects, but his body. Accepting the existence of experimental knowledge implies, by recursivity, the acceptance of the existence of experiments. The existence of experiments implies the existence of experimenters, research laboratories, and all the things that these laboratories contain.[14]

[12] For a distinction between an epistemological and a metaphysical reading of Hacking's view, see Morrison (1990).

[13] The experience of measuring is first of all that of space, and the effort to travel in it: we compare the efforts that would be required to travel between two distances by asking ourselves how many steps separate them.

[14] On all these points, there is no difference between scientific realists and instrumentalists, except that the realists accept the possibility that theoretical models can serve as a guide for experimentation: theories can be constructed prior to experimentation.

Therefore, it seems impossible to take the experimental activities seriously without being a metaphysical realist.[15]

(b) The elements of an experimental device are spatially distinct. The body of the experimenters is included in the same space as that of things. In order to cross the distance that separates one thing from another, an effort is necessary, etc.

(c) It is possible to quantitatively vary a measured property.

(d) The objects on which the physical or chemical experiment is carried out are devoid of intentions.

(e) Experimentation, defined in a very general way, is an activity consisting of the interaction of natural or artificial substances to induce and observe processes. Therefore, it is impossible to perform an experiment without accepting the objective existence of causal relationships: the experimenter acts on the experimental device, which acts on the test substance, which acts on the measuring devices (Woodward 2005).

The following experimental metaphysical principles can be deduced by existential generalizations:

(A) There are differences between the properties of physical objects that do not depend on human physical and cognitive capabilities.
(B) There are numerically distinct realities.
(C) There are continuous properties.
(D) There are realities that do not act intentionally.
(E) There are objective causal relationships.

Without such ontological commitments, the possibility of experimental practices and knowledge is not conceivable. If instrumentalists accept the existence of experimental knowledge and if experimental knowledge involves metaphysical knowledge, instrumentalists should accept the existence of metaphysical knowledge. This reasoning can be captured by the following argument:

The neo-experimentalist argument (NEA)
(4) Experimental knowledge implies metaphysical knowledge. *(Neo-experimentalism)*
(5) There is experimental knowledge. *(Instrumentalism)*
∴ (6) There is metaphysical knowledge. *(Meta-metaphysical anti-skepticism)*

We will refer to this argument as the neo-experimentalist argument for the existence metaphysical knowledge (from now on: NEA). The proposition (6) of the NEA is the negation of the proposition (2) of the AMA. If the instrumentalist position commits to the existence of metaphysical knowledge, the instrumentalists' use of the AMA is incoherent.

[15] There is nothing inconsistent about scientific instrumentalists being metaphysical realists. First, they may very well consider that only the observable world is a mind-independent reality. Second, because even if they accepted the existence of unobservable realities, it would not follow that they would have to accept the possibility of knowledge of these unobservable realities. Instrumentalists do not necessarily deny that the unobservable realities exist, or even the possibility of forming true representations of these realities. They deny that we can epistemically justify these representations, and, therefore, that we can *know* that these unobservable exist, and what they are.

6 Instrumentalists' First Way Out: Minimally Metaphysical Instrumentalism

Instrumentalists are not bereft of responses to this charge of incoherence. They can partially accept and partially reject the proposition (4): this proposition could be considered as true with respect to one kind of metaphysics and false with respect to the other. This move would overcome the apparent contradiction between (2) and (6), since instrumentalists could argue that the expression 'metaphysical knowledge' in each of these propositions does not actually refer to the same realities. This strategy thus requires a conceptual distinction between two kinds of metaphysics. This distinction should be conceived in such a way that one kind of metaphysics simultaneously satisfies the proposition (1) and (2), and the other kind simultaneously satisfies the propositions (4) and (6).

The central challenge for this strategy is to articulate such a conceptual distinction. As a proposition is all the more certain that it is less informative, instrumentalists should link experimental knowledge with minimally informative metaphysical principles, and theoretical constructions with maximally informative metaphysical principles. Minimally metaphysical principles should be sufficiently metaphysical to justify experimental knowledge, and sufficiently minimal to avoid the risks of error.[16]

In order to see how to satisfy these two conditions, it is necessary to examine the definition of metaphysics. Metaphysics is usually conceived as 'the search for fundamental and general truths about the world' (Paul 2012, 4). But this definition is too narrow, for it associates two features that could be separated without losing its *definiendum*: The search for fundamental but non-general truths is still metaphysical; the search for general but non-fundamental truths is still metaphysical. The metaphysical principles of experimental knowledge mentioned in the previous section can be classified as general but not fundamental principles: they describe general features of nature and they can be accounted for by a multiplicity of accounts in terms of fundamental entities or properties. On the opposite, theology is a metaphysical inquiry about a fundamental but not necessarily general entity: not every theologian believes that God and nature are identical. Therefore, metaphysics should not be defined by a list of jointly necessary conditions but by a disjunction of sufficient conditions.

General features of nature can be known without knowing its fundamental features. As these features are general, they are instantiated by any object, and therefore by the objects of our experiences and experiments. On the opposite, fundamental natural entities must either instantiate the general features of reality or explain them.[17] In each of these cases, fundamental knowledge implies general knowledge, but not the reverse. Therefore, general metaphysical knowledge is less informative, and more certain. We will therefore cash out the opposition between minimally and maximally metaphysical principles in terms of the opposition between general principles and fundamental principles.[18]

[16] See Chakravartty (2017) for a similar position.

[17] For example, the existence of objective causal relationships can be explained both by assuming the existence of laws of nature associated with categorical properties and by assuming the existence of dispositional properties (Bird 2007).

[18] There are several possible ways to articulate more precisely the opposition between maximally and minimally metaphysical principles. One could use the Kantian distinction between transcendental and transcendental metaphysics (Kant 1781; Friedman 2001), or Chakravartty's model of levels of metaphysical 'epistemic risk' (Chakravartty 2017). But for the purpose of the present paper, this distinction suffices.

Minimally metaphysical instrumentalism is the position according to which experimenters can admit minimally metaphysical principles without admitting maximally metaphysical principles. Such instrumentalist view is held by Pierre Duhem in his paper 'Physics and metaphysics' (1893).[19]

Duhem distinguishes knowledge of essences and knowledge of phenomena. Essences are internal to substances; they are the things in themselves, whereas phenomena are external to substances; they are the objects of experience. According to Duhem, essences are the causes of phenomena; phenomena are the effect of essences. He also distinguishes direct and indirect knowledge. Therefore, there are theoretically four possible kinds of knowledge: direct knowledge of essences, indirect knowledge of essences, direct knowledge of phenomena, indirect knowledge of phenomena.

The first kind of knowledge, the intuition of essences, is humanly unattainable: 'the human intellect does not have direct knowledge or immediate vision of the essence of external things' (Duhem 1996, 31). It belongs to, 'according to the teachings of the theologians, an angel's intellect' (Duhem 1996, 31). The third kind of knowledge is empirical and easily accessible: 'What we know directly of these things are the phenomena that arise from them and the sequence of these phenomena' (Duhem 1996, 31). The fourth possibility, testimonial knowledge for instance is not really considered by Duhem. Remains the theoretical possibility of indirect knowledge of essences. This is what Duhem calls 'metaphysics'.

Then, Duhem introduces a distinction between 'truths established by metaphysics' and 'metaphysical systems'. The truths established by metaphysics are 'negative in form' and obtained 'in ascending from observed phenomena to the substances which cause them'. As they are epistemically minimal, they are certain. But they are 'too general and little determinate' to justify knowledge of the essences of the things, *i.e.*, to justify theoretical knowledge. On the opposite, metaphysical systems are sets of propositions accounting for metaphysical truths and justifying theoretical knowledge. As they are empirically underdetermined and conflictual, they are uncertain (Duhem 1996, 33).[20]

The concept of 'metaphysical systems' definitely fit the definition of maximally metaphysical knowledge, for it satisfies the propositions (1) and (2). But it is not certain that the 'truths established by metaphysics' are equivalent to what we have called minimally metaphysical principles. Contrary to the latter, the former has a negative form. More importantly, we cannot see how to derive experimental knowledge from these negative principles, and thus satisfy the proposition (4).[21]

However, a page later, Duhem introduces another kind of metaphysics which fits the concept of minimal metaphysics:

> The experimental method rests on principles evident in themselves and independent of metaphysics. It does not follow from this that the foundations of the experimental method escape the grasp of metaphysics and cannot become objects of study for that science. Apart from any metaphysical investigation, we have the concept of body and the concept of law in manner distinct enough to be able to make a legitimate use of these concepts in physical investigation. Apart from any metaphysical investigation,

[19] See also Miranda Vilchis (2018).

[20] I am grateful to one of the anonymous referees who has suggested this option to me.

[21] Moreover, it could be argued that the metaphysical principles Duhem has in mind when he writes *The Physical Theory. Its aim, its structure*, are the negative principles, since each theoretical school rejects a property that the other accepts (Duhem 1906, 10-18).

> we know that the phenomena arising from matter are subject to fixed laws, and this principle is so certain that we are able, without hesitation, to dedicate our life to the discovery of these laws. But from the fact that we have knowledge of these concepts and sufficient confidence in this principle to make us use these concepts and this principle in the course of our experimental investigation, it does not follow that this knowledge is absolutely clear and complete, or that the foundations on which it rests are known to us, or that we have nothing to learn about these questions. (Duhem 1996, 34-35)

Duhem opposes here a common sense and implicit metaphysical knowledge, necessary to guide experimental practices, and 'metaphysical investigation[s]' aiming at making truths of metaphysics explicit and at building metaphysical systems. This distinction exactly fits the distinction between minimally and maximally metaphysical principles.

7 Knowledge of the Existence of the Unobservable

Let us now argue that minimally metaphysical instrumentalism is not a coherent option. The strategy is to establish that the minimally metaphysical principles necessary to account for experimental knowledge are sufficient to yield a minimal knowledge of the unobservable reality.

We will first show that, if experimenters know experimental laws, they must also know that there are unobservable realities whose properties are pretty much similar to those of observable things. The gist of the argument is that minimally metaphysical principles necessary to ground experimental knowledge also imply the existence of unobservable entities ontologically commensurable (*i.e.,* with similar properties, determinable by quantitative variations) with observable entities. Therefore, if experimenters must accept these principles, they also must believe that unobservable objects exist.

The premises of this proof will be the aforementioned experimental metaphysical principles. But we also need a general characterization of the threshold between observable and unobservable. Unobservability and observability are not intrinsic, but dispositional properties. If an object does not have the power to modify human minds through the modification of human bodies, it is unobservable. Conversely, if the human mind does not have the power to be modified through its body by an object, this object is unobservable. Therefore, the observability threshold depends both on the properties of the object and on human physical and cognitive capabilities:

> (O) The unobservability threshold depends on human physical and cognitive capabilities. (*Metacognitive Axiom*)

We wish to prove that, if (O) and (A) are true, it is very unlikely that all differences between the properties of physical objects depend on the difference between the observable and the unobservable. Indeed, if there are such properties, there is no reason to believe that the same properties we observe do not also exist at the scale of the unobservable.

Suppose that *all* differences in the properties of physical objects depend on the threshold of non-observability. If we also assume that the relationship of dependence is transitive, it would follow that *all* differences in the properties of physical objects would depend on the human mind. However, this contradicts the proposition (A). Therefore, if the indispensability relationship is transitive, accepting propositions (O) and (A) implies that there

are differences between the properties of physical objects that do not depend on the non-observability threshold.

Let us introduce the proposition (D) to determine whether it is legitimate to believe that the boundaries of the unobservable and of the ontologically immeasurable coincide. It would mean that the objects of experiments would cease to behave as usual as soon as the unobservability threshold is crossed. Such a view seems to be based on both a form of animism and anthropocentrism. However, according to (D), reality exists independently of us and indifferently to us. It must therefore behave in the same way, whether or not it is observed.[22] To say otherwise would amount to say that there is a multiplicity of Cartesian evil demons who have nothing more to do than play tricks on us. In other words, if nature is truly devoid of intentions, it is indifferent to human beings, and if it is indifferent to humans, it does not hide—nor does it show itself.[23]

Let us now address the proposition (C). Experimenters have ordinary or mathematical knowledge of continuous properties. However, a continuous property has parts. These parts have parts, etc. We know that the parts that divide a whole are smaller than the whole. Finally, we know from experience that our perceptual capacities are limited, i.e., that their sensibility has a given threshold. If we combine these three types of knowledge, it follows that experimenters know that unobservable parts of natural substances and experimental devices exist; that unobservable objects have the same kinds of measurable properties as the measurable properties of observable objects.

Certainly, these unobservable parts can be of various kinds and some of them can even be empty spaces. This cannot be known a priori. Nevertheless, the affirmation of the existence of an unobservable reality is the consequence of metaphysical realism, whose acceptance is necessary to take into account experimental practice.

The previous reasoning precedes experimental knowledge. It provides a minimal knowledge of the unobservable reality that is not yet scientific theoretical knowledge. To prove that theoretical knowledge is made possible by the minimally metaphysical principles, it is necessary to show that taking into account minimally metaphysical principles at least partially undermines the aforementioned underdetermination arguments.[24]

The contrastive underdetermination relies on the assumption that the only information permitting the scientists to judge the truth of a theory is ‘the comparison between the consequences of this theory and the experimental laws it has to represent and classify’ (Duhem 1991, 180). Minimally metaphysical principles introduce a third kind of constraint in the situation. As constraints narrow down theoretical options, taking them into account should help to narrow down the theoretical options. Moreover, minimally metaphysical principles justify at least some of the background assumptions of the empirical justification procedures examined in the Sect. 3 of this paper.

[22] One might object that according to Heisenberg’s principle of indeterminacy, the uncertainty concerning the measurement of the velocity of particles is inversely proportional to the uncertainty of the measurement of their positions. We would answer that 1. the Heisenberg principle applies to the level of elementary particles, and that the unobservable world is not reduced to this level. 2. The Heisenberg principle does not concern observations, but the manipulation of phenomena. It formulates the relationship between the particle and the manipulation and measuring instruments. 3. This objection is only valid if scientific realism is true. 4. There are several interpretations of quantum mechanics.

[23] This argument is an experimentalist reworking of Smart’s (1963) argument of cosmic coincidence.

[24] I am very grateful to to anonymous referee that has pointed to me that the underdertermination arguments are not ‘totally’ (to use her/his word) undermined, and that I should therefore qualify my claim.

Minimally metaphysical principles also undermine the holist underdetermination claim. Duhem's argumentation intermingles two claims: the claim of the necessary recourse to interpretations to use experimental data and the claim of the necessary recourse to scientific theories to interpret experimental data. If minimally metaphysical principles exist, the truth of the former claim does not imply the truth of the latter claim. Duhem rightly rejects what came to be called 'the myth of the given'. Background interpretative principles are necessary to make sense of experiments. However, Duhem assumes that these principles are necessarily science-theoretical principles. But such principles can also be minimally metaphysical principles. The inference from the rejection of the 'myth of the given' to theoretical overdetermination of the data and correlatively to the holist underdetermination of theoretical choices is not legitimate.

It could even be argued that Duhem implicitly accepts that the existence of minimally metaphysical principles undermines the underdetermination arguments. In the excerpt quoted in the first section of this paper, Duhem suggests that admitting 'absolute principles direct[ing] [the] inquiry' concerning the value of scientific theories would enable scientists to make empirically determined theoretical choices. Let us now follow up on that suggestion. In the last subsection of the Chapter 6 of the *Physical theory*, Duhem argues for the possibility and even the historical occurrence of reasonable choices of hypotheses. For instance, at some point, it was no longer rational for Biot to support the Newtonian theory of light:

> After Foucault's experiment had shown that light traveled faster in air than in water, Biot gave up supporting the emission hypothesis; strictly, pure logic would not have compelled him to give it up, for Foucault's experiment was not the crucial experiment that Arago thought he saw in it, but by resisting wave optics for a longer time Biot would have been lacking in good sense. (Duhem 1991, 218)

Duhem's arguments for *reasonable* theoretical choices rest on two distinctions. First, Duhem dissociates here crucial experiments and choices of hypotheses. The impossibility of crucial experiments does not imply the impossibility of a motivated choice of hypotheses. The ideal of a crucial experiment implies that when there are two competing hypotheses, the organization of *one* crucial experiment suffices to *immediately* settle the problem. For Duhem, rejecting this illusion does not imply that no hypothesis can ever be eliminated. It implies that rejecting a hypothesis and justifying another takes more than one experiment: it takes time. Second, Duhem distinguishes two sources of normative constraints that weigh on theoretical choices: logic and experience, on the one hand, what he calls 'good sense', on the other. To say the same thing with other words, he distinguishes between rational choice and reasonable choice. According to him, rational theoretical choice only is underdetermined, but not reasonable theoretical choice.

These two distinctions work together since the 'good sense' needs to consider an entire research tradition in order to decide whether or not this tradition should be abandoned:

> The day arrives when good sense comes out so clearly in favor of one of the two sides that the other side gives up the struggle even though pure logic would not forbid its continuation. (Duhem 1991, 218)

Therefore, according to Duhem, a reasonable choice between theories is possible. Now, it has often been noted that the definition of 'good sense' is rather mysterious (Ivanova & Paternotte 2012). If it is reasonable to explain 'good sense' as the result of the use of minimally metaphysical principles, it is also reasonable to support that minimally metaphysical principles enable scientists to arbitrate between competing hypotheses. Acceptation of minimally metaphysical principles has exactly the same effect as good sense. And it is not as mysterious: minimally metaphysical principles can be seen, in a Lakatosian way, as the 'hard core'

of a family of research programs. The case of Biot's ultimate rejection of the Newton theory should then be explained by the minimally metaphysical principles.

8 Second Possible Way Out: Algebraic Instrumentalism

The second response to the neo-experimentalist argument is to entirely reject the proposition (4), that is, to reject the necessity of relying on metaphysical premises to yield experimental knowledge.

Abandoning his previous minimally metaphysical instrumentalism, Duhem (1894; 1906) has provided a description of the experimental work that seems to autonomize it from minimally metaphysical principles. To put it in a nutshell, experimental knowledge is, according to Duhem, *algebraic*: by giving an algebraic form to experimental knowledge, physicists subordinate it to an intellectual enterprise that is epistemically solid, socially consensual and metaphysically neutral (algebra being conceived as a purely linguistic device).

Duhem's argument for this view is that, without prior scientific training, no observer will be able to understand what they would observe in an experimental physics laboratory. To show this, Duhem uses a kind of ethnographic description of laboratory life:

> [A]ny experiment in physics, involves two parts. In the first place, it consists in the observation of certain facts; in order to make this observation, it suffices for you to be attentive and alert enough with your senses. It is not necessary to know physics; the director of the laboratory may be less skillful in this matter of observation than the assistant. In the second place, it consists in the interpretation of the observed facts; in order to make this interpretation, it does not suffice to have alert attention and practiced eye; it is necessary to know the accepted theories and to know how to apply them, in short, to be a physicist. (Duhem 1991, 145)

Experiments that can be understood by laymen are not physical but biological experiments, such as those described by Claude Bernard to build his theory of the experimental method (Duhem 1991, 180–182). To support this distinction between biological and physical experiments, Duhem draws a distinction between two types of experimental devices: purely qualitative experimental devices and measuring devices. The experimental laws obtained with measuring devices do not describe the working of the observable substances, but the numbers indicated by these measuring devices. Therefore, experimenters do not observe experimental devices: they read it.

In order to explain how experimenters can make sense of experiments, Duhem claims that experimental results are theoretically overdetermined: background scientific theories enable experimenters to translate the data in theoretical terms. This description of experimental interpretations provides the premise not only of the holist underdetermination argument (Stanford 2017) but also of the algebraic conception of experiments.

The algebraic conception of experiments is a crucial piece of Duhem's constructive argument for instrumentalism. For Duhem, the construction of a physical theory involves four steps. First, using measuring devices, the experimenter translates qualitative data into quantitative data. Then, he gathers and compares the different measurements thus obtained. Then, he tries to summarize these correlations in algebraic forms. Finally, the search for theoretical hypotheses capable of synthesizing all the algebraic formulations previously developed (Duhem 1991, 21–23; Gueguen & Psillos 2017). To illustrate (in a

very schematic way) this view, let us take the case of thermodynamics and, more precisely, the scientific study of gas behavior. As a first step, the implementation of an experimental system for a scientific study of gases requires the ability to measure different properties of the gases: volume, pressure, temperature, and therefore to 'graft' measuring devices onto the different gases. A qualitative study of gases then shifts to a quantitative approach to the phenomenon. The experimental study of the gas then consists in varying the value of one of its properties to observe how the other parameters evolve. Or, more precisely, to vary one of its properties by keeping the other fixed. The experimenter then draws measurement tables, draws a curve and, by linear regression, looks for the algebraic formulation of the general relationship between these properties. This approach allows him to discover several laws: Boyle-Mariotte's law, Charles' law, Gay-Lussac's law. According to Duhem, the production of authentic knowledge stops there. The scientific theoretician then asks how these different laws could be summarized. Theorists then use algebra to discover a general formula from which particular laws can be deduced. In our example: the law of perfect gases, from which we can deduce the laws of Boyle-Mariotte, Charles and Gay-Lussac. But this invention does not bring any information about the world. It only makes it possible to more economically formulate already available knowledge.

Apparently, Duhem's description of the experimental work makes it possible to conceive its result as a purely positive knowledge, that is, knowledge devoid of any metaphysical commitment. However, this conception relies on a confusion between the two claims distinguished in the previous section: experiments need interpretations; interpretations need scientific theories. Metaphysical minimalism accepts the first claim, but rejects the second. To support this position, we will first examine an alternative ethnographical interpretation of scientific practices, and then show that Duhem's conception leads to an infinite regress over the history of science.

Ronald Giere (1988) has directly responded to ethnographic arguments against the direct intelligibility of experimental settings. He draws on a distinction between three ways of understanding what takes place in a laboratory: direct observation, theoretical interpretation, and observation mediated by spatial diagrams. Ronald Giere notices that a careful and reflective look at the map of the Indiana University particle accelerator suffices to get a general idea of what is happening there: it is possible to guess that this experimental device is a path (Giere 1988, 116). And, therefore, to conclude, from the causal relation between the production of the beam and the modification of detectors that there are unobservable objects following this path. The idea is that the geometrical layout of the laboratory and of individual experiments is an essential part of physicists thinking: 'just as many people cannot talk without gesturing, experimental nuclear physicists cannot discuss their work without drawing pictures' (Giere 1988, 133). And according to Giere, laymen have the ability to reason spatially. Therefore, Duhem's distinction between the physiological experimental method and the experimental physicist method, as well as the concomitant disqualification of profane expertise, are not legitimate. And if theoretically uninformed people are nonetheless able to interpret physical experiments, it must be because they rely on other kinds of principles. They must be minimally metaphysically equipped to interpret what's going on in a laboratory.

Another argument against Duhem's algebraic conception of experiment is that it leads to an infinite regress. Theories are tested by experiments. Any experiment involves measurement apparatus whose interpretation requires a theory. These theories must have been tested, etc. Therefore, either the existence of physical experiments is inexplicable or one must posit the existence of experiments that could be interpreted without any previous scientific theory. But to interpret, experimenters such as Galileo, Priestley, Pascal, Faraday or

Thompson must have relied on some other principles. Minimally metaphysical principles explain the interpretive take-off of experimental history.

9 Conclusion

In this paper, I have made two claims. First, I have claimed that the anti-metaphysical argument is more fundamental than the underdetermination argument and the pessimistic-meta-induction. Second, I have claimed that the instrumentalists' use of the anti-metaphysical argument is incoherent. Instrumentalists try to reconcile anti-realism and deference towards science. If my argument is correct, they cannot have it both ways: they should either adopt a minimal scientific realism or subscribe to anti-scientific anti-realism. The gist of my argument is that the same minimally metaphysical principles which are a necessary condition for experimental knowledge are also, if combined with empirical knowledge, a sufficient condition for a minimal theoretical knowledge.

From these two claims, it follows that the existence of minimally metaphysical knowledge must help to also undermine the underdetermination and the meta-inductive arguments. The first of these consequences has already been confirmed in this paper, for we have seen that the existence of minimally metaphysical principles undermines both the holist and the contrastive underdetermination of theoretical choices. The second consequence remains to be tested.[25]

References

Bird, A. (2007). *Nature's metaphysics*. Oxford: Oxford University Press.
Carnap, R. (1995) [1966]. *An Introduction to the Philosophy of Science*. New York: Dover.
Chakravartty, A. (2007). *A metaphysics for scientific realism: Knowing the unobservable*. Cambridge: Cambridge University Press.
Chakravartty, A. (2017). *Scientific ontology. Integrating naturalized metaphysics and voluntaristic epistemology*. Oxford: Oxford University Press.
Chalmers, D., Manley, D., & Wasserman, R. (Eds.). (2009). *Metametaphysics*. Oxford: Oxford University Press.
Christensen, D. (2007). Epistemology of disagreement: The goods news. *Philosophical Review, 116*, 187–217.
Decker, J. (2012). Disagreement, evidence, agnosticism. *Synthese, 187*, 753–783.
Duhem, P. (1892a). Notation atomique et hypothèses atomistiques. *Revue des Questions Scientifiques, 16*(31), 391–454.
Duhem, P. (1892b). Quelques réflexions sur les théories scientifiques. *Revue des questions scientifiques, 16*(31), 139–177.
Duhem, P. (1894). Quelques réflexions au sujet de la physique expérimentale. *Revue des Questions Scientifiques, 18*(36), 179–229.
Duhem, P. (1905). Physique de croyant. *Annales de philosophie chrétienne* 77(4), translated in Duhem (1991): 273–311.
Duhem, P. (1991) [1906]. *La théorie physique. Son objet, sa structure*, trans. by Wiener, P. *The Aim and Structure of Physical Theory.* Princeton: Princeton University Press.
Duhem, P. (1917). Notice sur les travaux scientifiques de Pierre Duhem. *Mémoire de la Société des Sciences Physiques et Naturelles de Bordeaux* 7: 41–169. English translation of parts 2 and 3 in Duhem 1996.
Duhem, P. (1996). *Essays in History and Philosophy of Science*, ed. and translation by Roger Ariew and Peter Barker. Indianapolis: Hackett.
Elga, A. (2007). Reflection and disagreement. *Nous, 41*, 478–502.

[25] I want to express my gratitude to the three referees of this paper for their thorough and thought-provoking critiques of previous versions of this paper: they tremendously helped me to improve it.

Friedman, M. (2001). *Dynamics of reason*. Chicago: University of Chicago Press.
Giere, R. (1988). *Explaining science: A cognitive approach. Science and its conceptual foundations*. Chicago: University of Chicago Press.
Gueguen, M., & Psillos, S. (2017). Anti-skepticism and epistemic humility in Pierre Duhem's philosophy of science. *Transversal: International Journal for the Historiography of Science, 2*, 54–72.
Hacking, I. (1982). Experimentation and scientific realism. *Philosophical Topics, 13*(1), 71–87.
Hacking, I. (1983). *Representing and intervening*. Cambridge: Cambridge University Press.
Hempel, C. G. (1951). The concept of cognitive significance: A reconsideration. *Proceedings of the American Academy of Arts and Sciences, 81*, 61–77.
Hempel, C. G. (1958). The theoretician's dilemma: A study in the logic of theory construction. *Minnesota Studies in the Philosophy of Science, 2*, 173–226.
Hirsch, E. (2009). Ontology and alternative languages. In D. Chalmers, D. Manley, & R. Wasserman (Eds.), *Metametaphysics.* (pp. 231–259). Oxford: Oxford University Press.
Inwagen, P. (1994). Quam Dilecta. In T. V. Morris (Ed.), *God and the philosophers.* (pp. 30–60). Oxford: Oxford University Press.
Ivanova, M., & Paternotte, C. (2012). Theory choice, good sense and social consensus. *Erkenntnis, 78*, 1109–1132.
Kant, I. (1970) [1781]. *Kritik der reinen Venunft*. Berlin: Walter de Gruyter.
Ladyman, J., Douven, I., Horsten, L., & van Fraassen, B. (1997). A defence of van Fraassen's critique of abductive inference: Reply to psillos. *The philosophical Quaterly, 47*(188), 305–321.
Laudan, L. (1981a). A confutation of convergent realism. *Philosophy of Science, 48*(1), 19–49.
Laudan, L. (1981b). *Science and hypothesis: Historical essays on scientific methodology*. Dordrecht: D. Reidel.
Lipton, P. (2004). *Inference to the best explanation*. London and New York: Routledge.
Mayo, D. G. (1996). *Error and the growth of experimental knowledge*. Chicago: University of Chicago Press.
Morris, T. (1996). *God and the philosophers*. Oxford: Oxford University Press.
Morrison, M. (1990). Theory, intervention and realism. *Synthese, 82*(1), 1–22.
Paul, L. (2012). Metaphysics as modeling: The Handmaiden's Tale. *Philosophical Studies, 160*, 1–27.
Plantinga, A. (1993). *Warrant and proper function*. Oxford: Oxford University Press.
Putnam, H. (1975). *Philosophical papers 1. Mathematics, matter, and method*. Cambridge: Cambridge University Press.
Schindler, S. (2018). *Theoretical virtues in science. Uncovering reality through theory*. Cambridge: Cambridge University Press.
Smart, J. (1963). *Philosophy and scientific realism*. London and New York: Routledge.
Stanford, K. (2006). *Exceeding our grasp: Science, history, and the problem of unconceived alternatives*. Oxford: Oxford University Press.
Stanford, K. (2017). Underdetermination of Scientific Theory, *The Stanford Encyclopedia of Philosophy*, Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/win2017/entries/scientific-underdetermination/>
Suarez, M. (2010). Experimental realism defended: How inference to the most likely cause might be sound. In S. Hartmann, C. Hoefer, & L. Bovens (Eds.), *Nancy Cartwright's philosophy of science.* London: Routledge.
Van Fraassen. 2008. *Scientific Representation*. Oxford: Oxford University Press.
Van Fraassen, B. (1980). *The Scientific Image*. Oxford: Clarendon Press.
Van Fraassen, B. (1989). *Laws and symmetry*. Oxford: Clarendon Press.
Van Fraassen, B. (2002). *The empirical stance*. New Haven and London: Yale University Press.
Vicker, P. (2015). Understanding the selective realist defense against PMI. *Synthese, 194*, 3221–3232.
Vilchis, R. M. (2018). The distinction between physics and metaphysics in Duhem's philosophy. *Revista Portuguesa de Filosofia, 74*(1), 85–114.
Wasserman, R. (2009). Introduction: a guided tour of metaphysics. In D. Chalmers, D. Manley, & R. Wasserman (Eds.), *Metametaphysics: new essays on the foundations of ontology.* (pp. 1–38). Oxford: Oxford University Press.
Woodward, J. (2005). *Making things happen: A theory of causal explanation*. Oxford: Oxford University Press.
Wray, B. (2018). *Resisting scientific realism*. Cambridge: Cambridge University Press.