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Quantum relational indeterminacy

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ABSTRACT

The paper presents the first thorough investigation of quantum metaphysical indeterminacy (MI) in the context of the Relational Interpretation of Quantum Mechanics (RQM). We contend that the interaction between MI and RQM is mutually beneficial. On the one hand, MI provides a metaphysical framework for RQM that has been neglected in the literature, and that promises to undermine some objections that are often raised against RQM. On the other hand, RQM might serve as an example of fundamental quantum MI.

1. Introduction

In his recent paper *The Sky is Blue and Birds Flies Through it* (2018), the leading physicist Carlo Rovelli distinguishes three equally important kinds of development that can move us forward in understanding the quantum world. The first one is novel empirical content. For example, some interpretations lead to different, empirically distinguishable versions of quantum mechanics, and this might be reason enough to consider them different theories. The second kind of development is theoretical fertility, the ability to inspire original work. Rovelli himself, for instance, claims that his work on quantum mechanics is directly inspired by his work in quantum gravity. Finally.

> [T]he third manner in which progress can happen is how it does in philosophy: ideas are debated, absorbed, prove powerful, or weak, and slowly are retained or discarded. I am personally actually confident that this can happen for quantum theory. The key to this, in my opinion, is to fully accept this interference between the progress of fundamental physics and some major philosophical issues (Rovelli, 2018, p. 11).

The present work can be seen as an example of this third manner in which progress can happen. We shall provide the first thorough investigation of metaphysical indeterminacy (MI) in the context of the Relational Interpretation of Quantum Mechanics (RQM), an interpretation of quantum mechanics (QM) championed by Rovelli himself. We argue that the interaction between MI and RQM is mutually beneficial. On the one hand, MI provides a broadly philosophical—dare we say, metaphysical—framework for RQM that has been neglected in the literature, and that promises to undermine some objections that are often raised against this particular interpretation.[1] On the other hand, RQM might offer examples of fundamental (quantum) MI. This is not only interesting in and on itself. It also saves MI from a recent objection. We should immediately add an important disclaimer before we plunge into the depths of relational indeterminacy. *It is not the aim of the paper to defend either RQM or MI*[2]—its existence in general, or even the particular account of MI we are going to discuss. Rather the focus is on their interaction, so to speak. As we shall see, this interaction sheds light on both RQM and MI—or so we are about to argue.

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[1] We do not enter some *other* criticisms that have been leveled against RQM, e.g. the ones in Laudisa (2019). Furthermore, we only briefly touch on some recent worries in Dorato (2020).

[2] Though we may be admittedly sympathetic to one or both.

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2. Relational quantum mechanics

RQM was first presented in Rovelli (1996), and has been developed in Laudisa (2001), Smerlack and Rovelli (2007), Rovelli (2016), and Rovelli (2018).[3] Roughly, it consists of two parts[4]

- A re-interpretation of the usual quantum formalism;
- A derivation of this formalism from basic, general principles.

We will focus here only on the first part. For the sake of familiarity, we first present it in terms of quantum states. However, we should immediately register that Rovelli is extremely and explicitly skeptical[5] about the notion of quantum state.[6] Accordingly, when we will present the details of our own proposal to frame RQM in a broad philosophical perspective, we will refrain from using the notion of quantum state altogether, and focus only on observables and their values—as Rovelli (2018) suggests.[7]

RQM can be seen as a way to retain—and in fact, to generalize—the following tenets of the so-called Copenhagen interpretation of QM:[8]

Eigenfunction-Eigenvalue Link (EEL). A physical system s has a definite value v of an observable O iff the state of s is an eigenstate of O that belongs to v.

Schrödinger Dynamics. The state of s evolves according to the Schrödinger equation, i.e. it obeys $H(t)|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$.

"Collapse" Postulate.[9] At the time of measurement the state of s collapses in one of the eigenstates of O with probability given by the Born rule.

Roughly, the generalization of the Copenhagen interpretation stems from the fact that, according to RQM, it is not only particular physical systems, such as macroscopic systems or measuring devices, that cause the collapse and thus the acquisition of a definite value for a particular observable—as per the EEL. Rather, *all systems* and *all interactions* will do. Rovelli is explicit[10]

> [R]elational QM is Copenhagen quantum mechanics made democratic by bringing all systems onto the same footing (Rovelli, 2018, p. 11).
> [M]easurement is an interaction like any other (Rovelli, 2018, p. 5).

RQM is arguably best appreciated by focusing on what Rovelli calls The "Third Person" problem, which crucially depends on the tenets of the Copenhagen interpretation we mentioned above.[11] Suppose we have a physical system s_1, that, at t_1, is in a superposition of $spin_x$-state:

$$|\psi\rangle_{s_1} = (c_1|\uparrow\rangle + c_2|\downarrow\rangle)_{s_1} \tag{1}$$

and suppose now that another system,[12] s_2 performs a $spin_x$-measurement on—or, crucially, *simply interacts* with—s_1 and finds $spin_x = up$. Given the **Collapse Postulate** we have:

$$\begin{array}{l} t_1 \rightarrow t_2 \\ (c_1|\uparrow\rangle + c_2|\downarrow\rangle)_{s_1} \rightarrow |\uparrow\rangle_{s_1} \end{array} \tag{2}$$

The result of the quantum interaction between s_1 and s_2 is that s_1 *acquires* a definite value property, namely $spin_x = up$—this follows from the EEL. Now, suppose that a system s_3—the Third Person of the Third Person problem—describes the system s_{12}, i.e. the system composed[13] of s_1 and s_2. System s_3 does not interact with s_{12}. By the **Schrödinger Dynamics** we get:

$$\begin{array}{l} t_1 \rightarrow t_2 \\ ((c_1|\uparrow\rangle + c_2|\downarrow\rangle) \otimes |init\rangle)_{s_{12}} \rightarrow (c_1|\uparrow\rangle \otimes |up\rangle + c_2|\downarrow\rangle \otimes |down\rangle)_{s_{12}} \end{array} \tag{3}$$

It is easy to see that, in the presence of the EEL, the accounts given by the systems s_2 and s_3 of the very same events are different. For, according to s_2, at t_2, s_1 is in an eigenstate of $spin_x$, and therefore has a definite value of that observable, namely $spin_x = up$—as we already saw. According to s_3 however this is not the case: s_1 is not in an eigenstate of $spin_x$ and therefore does not have any definite value of it.[14] Rovelli claims that many of the extant interpretations of QM amount to either denying (2) or (3). RQM takes them at face value: both (2) and (3) are *correct accounts of the quantum phenomena*. This leads immediately to what Rovelli calls the **Main Observation** of RQM:

Main Observation. In QM different observers [i.e. systems] may give different accounts of the same sequence of events.

The acceptance of both (2) and (3) is partly motivated by the fact that Rovelli sees no physical reason to doubt the quantum formalism in its usual applications. This translates into what Rovelli calls **Completeness**:

Completeness. QM provides a complete and self-consistent scheme of description of the physical world.

[3] For a philosophical introduction, see Laudisa and Rovelli (2019).

[4] The similarity with Einstein's infamous 1905 special relativity paper is transparent and explicitly indicated by Rovelli himself as a motivation to develop RQM. Rovelli is also explicit about the limits of such similarity.

[5] See e.g. Rovelli (2018). He writes:

> [T]he *conceptual* step was to introduce the notion of wavefunction ψ, soon to be evolved in the notion of quantum state ψ, endowing it with heavy ontological weight. This conceptual step was *wrong, and dramatically misleading*. We are still paying the price for the confusion it generated (Rovelli, 2018: 2—italics added).

[6] Our presentation follows closely Rovelli (1996) and Brown (2009). They both use the notion of a quantum state.

[7] We will come back to this in due course.

[8] We will come back to this in §4.

[9] As we shall see, the term collapse should be taken with caution in this context. As we said already, Rovelli favors a somewhat anti-realist attitude towards the quantum state: there can be no collapse, strictly speaking—hence the scare quotes. What happens is the acquisition of a definite-valued property of the relevant quantum system—exactly as it would happen if real collapse of the quantum state had taken place.

[10] Once again, we will come back to this in §4.

[11] This is somewhat reminiscent of Wigner-friends style arguments, as Brown (2009) already noticed. One such argument has been recently much discussed in the literature, namely the argument in Frauchiger and Renner (2018). The argument is in the form of a no-go theorem to the point that a theory that satisfies three different assumptions is inconsistent with quantum predictions. Going into the details of the argument is beyond the scope of the paper. Suffice to say that, as Frauchiger and Renner themselves recognize—see table 4 in the original paper—, RQM drops assumption *C*—for *Consistency*. This is because assumption *C* is equivalent to the claim that every observer ascribes the same state to each physical system. And this is clearly not the case in RQM.

[12] We can call this other system the observer if we remember that by observer we do not

> [M]ake any reference to conscious, animate, or computing, or in any other manner *special*, system (Rovelli, 1996, p. 1641).
> As a matter of fact, Rovelli explicitly holds that all systems are equivalent.

[13] We are not suggesting this *has* to be cashed out in purely *mereological* terms.

[14] We will return to this line of argument several times in the paper.

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It is not difficult to see that **Main Observation** and **Completeness** together lead to the basic tenet of RQM, namely the *relativization of states and observables of physical systems to other physical systems*:

> [Q]uantum mechanics is a theory about the physical description of *physical systems relative to other systems*, and this is a complete description of the world (Rovelli, 1996, p. 1650).

> [T]he actual value of *all* physical quantities of *any* system is only meaningful in relation to another system (Rovelli, 2018: 6—italics in the original).

The argument is straightforward: if both accounts (2) and (3) are *different* and *correct*, they have to be correct *relative to some relativization target*, which is simply taken to be another physical system. As Laudisa and Rovelli (2019) put it, RQM

> [A]dds a level of indexicality to the representation of the world (Laudisa & Rovelli, 2019, p. 2).

That is to say that when we describe states or observables of physical systems we should always include what we will call an *indexical cut* between different systems. This indexical cut serves to make the relativization explicit. We thus propose to amend the formalism so as to include such an indexical cut in the formalism itself.[15] Hence we will write:

$$\left|\psi\right\rangle_{s_i/s_j} \tag{4}$$

for "system s_i is in state $|\psi\rangle$ *relative* to system s_j". Here the indexical cut is explicitly represented by "/". The physical system on the left of the indixical cut is the system whose states and observables we are interested in, whereas the system on the right of the indexical cut is the relevant relativization target. Once this notation is in place, it is easy to see that in the Third Person problem, at t_2, we have:

$$\begin{aligned} &|\psi\rangle_{s_1/s_2} = |\uparrow\rangle_{s_1} \\ &|\psi\rangle_{s_{12}/s_3} = (c_1|\uparrow\rangle \otimes |up\rangle + c_2|\downarrow\rangle \otimes |down\rangle)_{s_{12}} \end{aligned} \tag{5}$$

Relativization to different systems thus ensures *consistency* and *correctness*.[16] Brown (2009) sums up the point of RQM nicely:

> [R]ovelli's interpretation amounts to complete acceptance of the principles given above [EEL, **The Schrödinger Dynamics** and **The Collapse Postulate**] specifying that measurement as *any system-metasystem*[17] interaction, and stressing that the Schrödinger dynamics applies only to the system (Brown, 2009, p. 684).

This should be enough in the way of presentation.

3. Quantum indeterminacy

MI is roughly indeterminacy *in the world*, as opposed to our description—semantic indeterminacy, or knowledge of the world—epistemic indeterminacy. It is usually thought to be a phenomenon that has to do with *indefiniteness*, and that elicits some sort of *no fact of the matter* response. For example, adapting from Barnes and Williams (2011), we can put forward the following biconditional: p is MI iff p is indefinite, and the source of this indefiniteness is the non-representational world.[18] It should be noted that this is not intended as a definition of MI. Rather it is supposed to give us an initial working understanding of the target notion. Now, standard QM, at least at first sight, violates the classical supposition of 'value definiteness', according to which the observables, or properties, of a system have precise values at all times. This is easily appreciated in the presence of the EEL. The general suggestion is that this failure of value definiteness is a case of MI. Let us focus simply on what Calosi and Wilson (2018) calls *superposition indeterminacy*. A superposition of eigenstates of an observable O is in general not an eigenstate of O. Hence, given the EEL, any physical system s in such a superposition will fail to have a determinate value of O. Equivalently, s will be indeterminate with respect to O. Several accounts of quantum indeterminacy as it is operative in the failure of value-definiteness have been proposed in the literature.[19] Here we want to focus on the so-called *determinable based account*, proposed in Wilson (2013), and developed explicitly for quantum indeterminacy in Calosi and Wilson (2018). There are different reasons behind this restriction, especially in the present context. First, alternative accounts are broadly supervaluationist in nature, and there is a compelling argument in the literature that such supervaluationist treatments run afoul of no-go results such as the Kochen-Specker theorem.[20] But, as Rovelli writes:

> [R]elational QM assumes seriously the Kochen-Specker theorem: variables take value only at interactions (Rovelli, 2018, p. 9).

Second, as we will argue in §4, RQM seems to fit perfectly within the determinable based account. As an introduction to the latter, let us quote from Wilson directly[21]

> *[D]eterminable-based MI*: What it is for a state of affairs to be MI in a given respect R at a time t is for the state of affairs to constitutively involve an object (more generally, entity) O such that (i) O has a determinable property P at t, and (ii) for some level L of determination of P, O does not have a unique level-L determinate of P at t (Wilson, 2013, p. 366).

It is clear that there are two ways in which an object can fail to instantiate a unique determinate of a determinable:

[15] We follow Brown (2009) here.

[16] For a detailed discussion see Wolf [Neé Wood] (2010).

[17] The metasystem in question is simply the physical system that appears on the right of our indexical cut/.

[18] Barnes and Williams (2011) argue at length that

> [A]ll parties should admit that they have a grasp on a generic notion of indefiniteness (…) as deployed in ordinary speech and used informally in philosophy (Barnes & Williams, 2011, p. 108).

[19] See Barnes and Williams (2011), Torza (2017), Calosi and Wilson (2018), and Darby and Pickup (2019) to mention a few.

[20] See Darby (2010), and Skow (2010).

[21] As a first stab,

> [D]eterminables and determinates are in the first instance type-level properties that stand in a distinctive specification relation: the determinable determinate relation (for short, determination). For example, *color* is a determinable having *red*, *blue*, and other specific shades of color as determinates; *shape* is a determinable having *rectangular*, *oval*, and other specific (including many irregular) shapes as determinates; *mass* is a determinable having specific mass values as determinates (Wilson, 2017, p. 1).

For an introduction, see Wilson (2017) and references therein.

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Gappy Metaphysical Indeterminacy. No determinate of the determinable is instantiated, hence *a fortiori* no unique determinate of the determinable is instantiated.

Glutty Metaphysical Indeterminacy. More than one determinate of the determinable is instantiated, such that no determinate is properly taken to be *the* unique determinate of the determinable.

Glutty metaphysical indeterminacy has been cashed out in at least two ways:[22] one where multiple determinates are instantiated, albeit in *relativized* fashion, and one where multiple determinates are instantiated, each to a *degree* less than one. In what follows we focus on the *relativization* variant. Wilson's case in point is that of an iridescent feather that has different determinate colors relative to different perspectives or spatial rays. She writes:

> [S]implifying a bit, it seems reasonable to take this account as suggesting that the determinate color of an iridescent hummingbird feather is relative to perspective. Moreover, the account suggests that multiple of these perspectives may be in place, and the associated determinate colors instanced, at a time: I can look at the feather and see red, you can look at the feather at the same time and see blue (Wilson, 2013, p. 367).

The question then is how this account applies—if it applies at all—to RQM. This is what the next section is about.

4. Relational indeterminacy

In this section we explore what MI can do for RQM, so to speak. First, we argue that indeterminacy can provide a neglected philosophical—once again, dare we say, metaphysical—framework for RQM (§4.1). We then go on to suggest that, as a matter of fact, RQM fits well with a determinable based account of MI. This also serves to tackle the so-called *Determinacy Problem* in Brown (2009) (§4.2).[23]

4.1. Indeterminate properties and non-interacting quantum systems

As we saw in §2 one of the main, if not *the* main tenet of RQM is that interacting quantum systems have definite value properties of the form Observable O has value v, $O = v$, only *relative* to other systems. Two questions naturally arise.

Non-Interacting Quantum Systems. What about non-interacting quantum systems? It follows that they do not have definite value properties. Does this mean they have *no* properties at all?

This leads to the second, related question.

Relevant Properties. Are definite value properties the only (meta)physically relevant properties?

This is where MI comes in. It provides a new, neglected answer to both the **Non-Interacting Quantum Systems** and the **Relevant Properties** questions above, an answer that promises to provide a somewhat general metaphysical framework for RQM. Before we provide more details let us briefly review some alternatives that has been presented in the literature.[24] Dorato (2016) distinguishes two answers to the **Non-Interacting Quantum Systems** question.[25]

Meaninglessness. It is absolutely *meaningless* to talk about properties of non-interacting quantum systems.

Dispositionalism. Quantum non-interacting systems have only *dispositional* properties.

These answers to **Non-Interacting Quantum Systems** seem to suggest also different answers to **Relevant Properties**. For instance, it seems natural to suggest that, according to **Meaninglessness**, only definite-value properties are metaphysically relevant, whereas according to **Dispositionalism** also *dispositions* more in general have metaphysical significance. Dorato contends that **Dispositionalism** has at least four advantages.[26] We are mostly interested in three of them[27]

> [T]he second is that to the extent that mass, charge, and spin, which are typically regarded as intrinsic, state-independent properties, can also be viewed as dispositional—and there are good reasons to take this stance—we gain a unified, dispositionalist account of both kinds of quantum states. The third advantage over claims of meaninglessness is to favor and even justify an entity-realistic account also of isolated quantum systems and not just of interacting ones. The fourth advantage of talking about dispositions in quantum mechanics is related to a well-known feature of the logical structure of quantum mechanics. This feature forbids the simultaneous attribution of definite properties to quantum systems whose dimensionality is greater than or equal to three (Dorato, 2016, pp. 241–242).

At this stage of the argument, we simply want to suggest that **Metaphysical Indeterminacy**, as it is accounted for in the determinable based account in §3, provides a new metaphysical framework to understand RQM. Recall that, in a nutshell, the determinable based account of MI has it that for a physical system to be indeterminate is for it have a determinable and not a unique determinate of that determinable. **Metaphysical Indeterminacy** understood along those lines can be used to give straightforward answers to both the **Non-Interacting Quantum Systems** and the **Relevant Properties** questions. Let us tackle these questions in the reverse order. First, definite value properties are not the only properties that are metaphysically relevant, for *determinables* are clearly relevant as well. In effect, they are the cornerstone of the determinable based account.[28] Second, non-interacting quantum systems have in fact some relevant physical properties, namely the determinable ones. **Metaphysical Indeterminacy** can claim the same advantages as **Dispositionalism**. Clearly, it can ground a realistic attitude towards non-interacting

[22] See Calosi and Wilson (2018).

[23] Brown (2009) suggests that another problem affects RQM, namely that there is no coherent global perspective on the quantum world. We agree that this is in fact the case. Yet, we are not sure why this should be thought of as a problem in the first place.

[24] Note that these are not the only accounts in the literature. Bitbol (2007) provides a neo-kantian reading of RQM, Van Frassen (2010) frames RQM against an empiricist background, and Candiotto (2017) suggests ontic structural realism as an explicit ontological framework for it. As a matter of fact, we believe some of these takes are compatible with the proposal put forward in this paper. We focus on other alternatives here, for they provide an explicit answer to some questions we will be interested in the rest of the paper.

[25] Dorato does not address the questions explicitly, but, in context, it is clear what his answers would be.

[26] Dorato elaborates this point further in Dorato (2020). See especially §5.

[27] The first one is the possibility of retaining some continuity with the ontology of the classical world. Admittedly, **Metaphysical Indeterminacy** departs from it, at least insofar as classical system are always *determinate* systems. However, we don't take this departure to be a problem: rather, we take it, it signals a substantive novelty of the quantum world.

[28] One can maintain the physical relevance of determinables even independently of MI. See e.g. French (2014).

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quantum systems. Relatedly, it avoids the radical consequences of **Meaninglessness**. The radicality of such consequences is best appreciated by focusing on particular properties. Take *position*. An isolated quantum system, according to RQM, does not have a definite position. But does this mean that it is in fact *meaningless* to talk about position for that system? Having position is just being in space. Clearly these quantum systems are in space. Where else could they be?[29] Or consider *energy*. If a quantum system fails to have a definite energy (relative to any other quantum system), does it follow that it has no energy whatsoever? That it is even *meaningless* to talk about it?As for the other two advantages, the unificationist view of quantum states and the compatibility with the foundational no-go theorems such as the Kochen-Specker theorem, we simply notice that the determinable-based account of MI was explicitly designed to provide a somewhat unified reading of the quantum state[30] that is compatible with such theorems. As a matter of fact, its compatibility with the latter has been one of the most significant argument in its favor.[31] In any case, as we pointed out already, at this stage of the argument, we want just to signal that **Metaphysical Indeterminacy** provides a neglected and potentially fruitful answer to some questions that naturally arise out of RQM. To appreciate that, consider, to start, the following idealization. There is a completely isolated quantum system s, that is, a system s that does not interact with any other system. Suppose s is in a superposition of O's eigenstates. Then, according to RQM, s does not have any definite value of O with respect to any other quantum system. This is very similar to what one finds in the Copenhagen interpretation outside a measurement context. It has been suggested that this idealized case involves indeterminacy, but the suggestion has been resisted.[32] Our point is that RQM is an interpretation of QM that *can* take the indeterminacy at face value by recognizing it in the metaphysics, rather than struggle to exorcise it as some other interpretations—e.g. Bohmian Mechanics. Presumably, at least part of the struggle against MI was due to the fact that the very notion seemed to be incoherent or unintelligible. Nowadays we have accounts of MI, such as the one we discussed in §3, that do provide an intelligible basis for it, so that the need to exorcise it is, if not eradicated, at least assuaged.[33]

Once this initial motivation is provided, in the remaining of the section, we spell out **Metaphysical Indeterminacy** in more detail. In the present context, it is useful to start with a characterization of **Metaphysical Determinacy**:

Metaphysical Determinacy. A quantum system s_1 is *metaphysically determinate* with respect to observable O iff, necessarily, for every other quantum system s_2, s_1 has a unique value v_2 of O relative to s_2. Or, equivalently: necessarily, s_1 has $O = v_2$ relative to every other quantum system s_2.[34]

Note that we did not use the notion of quantum state. This is because, as we noted in §1, Rovelli is extremely skeptical about this notion. It is thus important that MI in general, and the determinable based account in particular, do not need the notion of quantum state to get off the ground—even though the notion can be used to illustrate the latter account, should one want to use it. The only crucial notions at work here are the notion of observable—roughly, a determinable—and its value—roughly, a (maximal) determinate. Now, we do not want to claim that the bi-conditional above provides a *definition* of metaphysical determinacy in RQM. For one thing, we want to read the modal operator in terms of *nomological* necessity. Once we have this, we can simply provide the following characterization:

Metaphysical Indeterminacy. A quantum system s_1 is *metaphysically indeterminate* with respect to observable O iff it is not metaphysically determinate with respect to O.[35]

It should be clear that there are two ways in which a quantum system can be indeterminate with respect to a given O.[36] The first case is when there is a system s_2 such that s_1 has O, and has *no* value of O whatsoever relative to s_2. The second case is when there are systems s_2 and s_3 such that s_1 has different values of O relative to s_2 and s_3. Equivalently, there are s_2, s_3 such that s_1 has $O = v_2$ relative to s_2 and $O = v_3$ relative to s_3, and $v_2 \neq v_3$.We will see concrete examples in the next section.[37] Upon inspection, it is clear that the first case is a case of *gappy* MI, and the second case is a case of *glutty* MI, as they have been discussed in §3. As a matter of fact, the second case fits perfectly the *relativization* variant of *glutty* metaphysical

[29] To be fair, Rovelli has a complete relational understanding of space as well, so that the complaint in the main text might not apply. But non-relativistic quantum mechanics is often formulated having a somewhat implicit substantivalist understanding of space. In that context, the complaint has some bite. Or so it seems.

[30] Should one want to have such an account.

[31] See Calosi and Wilson (2018).

[32] Let us mention one example we will discuss later on. Glick (2017) quotes Gisin (2014, p. 44) as someone that, at least at first, proposes a reading of the idealized case in terms of indeterminacy. Glick himself goes on to propose an alternative reading that does away with said indeterminacy. We will return to this in §5.

[33] This discussion is indebted to some insightful remarks of two referees for this journal.

[34] It is a substantive question whether our reference to *every* quantum system requires to go beyond the original determinable based account in Wilson (2013). Answering such a substantive question goes beyond the scope of this paper. We should note that we are trying to stay faithful to the spirit, rather than the letter, of the determinable based account.

[35] One may have two worries in this respect. The first worry is as follows. As long as there is only one quantum system s_2 such that a system s_1 does not have a definite value $O = v$ relative to s_2, s_1 counts as indeterminate with respect to O. MI is widespread, too widespread in fact. We note two things. First, it is unclear why this is a problem in the first place. Once one recognizes that MI is not problematic, it should not constitute a problem if it is indeed widespread in the quantum domain. In effect, we believe this is exactly what happens in RQM. Second, one can always introduce a notion of (in)determinacy that is relativized not only to observables but also to systems, along the following lines: a system s_1 is determinate with respect to O relative to another system s_2 iff, necessarily s_1 has a value $O = v$ relative to s_2. The indeterminacy resulting from the failure of such relativized determinacy would not be as widespread. The second worry has it that one may endorse some variant of the so-called Einstein's criterion to the point that if one can predict with certainty the value of an observable of a system *given any one possible measurement*, then the system has that value. By contrast, metaphysical determinacy requires that a system has a determinate value if *all possible* measurements result in that value. And that is, once again, too strong a characterization of metaphysical (in)determinacy. First, we should note that the relativization strategy we mentioned before would work in this case as well, given that any characterization of (in)determinacy is always relative to a particular observable—note that in RQM one should arguably relativize the Einstein's criterion as well, for any ascription of definite-valued observables is meaningful only relative to other systems. Second, even the unrelativized characterization of indeterminacy seems to be in agreement with Einstein's criterion (at least) in the case that standard QM would describe as a system s being in eigenstate of observable O. In that case, we could predict with certainty the value v of O. Einstein's criterion yields that it s has $O = v$. But the same is true for our characterization of metaphysical determinacy. And this exhausts, one may add, the cases in which one should expect determinacy with respect to O. Thanks to an anonymous referee here.

[36] A referee suggested that in the case in which a system has a determinable but not a maximal specific determinate (a value) for that determinable, one can claim that the system has *indeterminate properties*. We see two options here: either having an indeterminate property O is —at least—co-extensive with being indeterminate with respect to O, or it is not. If it is, then we can indeed claim that the system in question has indeterminate properties. If it is not, one has to provide an account of what having an indeterminate property O is, so as to explore substantive connections—or lack thereof—between the two notions.

[37] Note that we had to specify that the system has the determinable O. We actually did not put this constraint in our characterization of **Metaphysical Determinacy**. This is because we believe it is redundant. We *assume* that if something has a determinate it has the corresponding determinable. In other words we assume that the determination relation obeys what Wilson (2017) calls Determinable Inheritance.

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indeterminacy.[38] As of now we spelled out some sort of general picture. In what follows we present worked out examples. In the end, we believe that the case for **Metaphysical Indeterminacy** as a possible metaphysical framework for RQM is a general case from *theoretical virtue*. It helps providing a clear picture of RQM, and at the same time, it helps responding to some criticism that has been leveled against the view. The so-called *Determinacy Problem* represents one such criticism. It is to that we now turn to.

4.2. Cases of relational indeterminacy and the determinacy problem

We want now to apply the general picture we canvassed in §4.1 to particular physical examples. We will take the lead from the Third Person problem of §2. The only difference is that from now on, we explicitly indicate the *indexical cut* that is relevant in the case at hand—the introduction of this indexical cut being, as we saw, the most crucial theoretical change brought about by RQM. Recall the structure of the problem.[39] We have at time t_1 a physical system s_1 in a superposition $spin_x$-state relative to another system s_2. System s_2 *interacts* with system s_1 by performing a $spin_x$ measurement on it, which results in, say $spin_x = up$. This is modeled as follows:

$$t_1 \to t_2 \\ t_1 \to t_2 (c_1|\uparrow\rangle + c_2|\downarrow\rangle)_{s_1/s_2} \to |\uparrow\rangle_{s_1/s_2} \tag{6}$$

There is also another system s_3 that describes the system s_{12} composed by s_1 and s_2. We furthermore suppose that s_3 does not interact with system s_{12}. We model this as:

$$t_1 \to t_2 \\ c_1|\uparrow\rangle + c_2|\downarrow\rangle)\otimes|init\rangle)(c_1|\uparrow\rangle + c_2|\downarrow\rangle)\otimes|init\rangle)_{s_{12}/s_3} \to (c_1|\uparrow\rangle\otimes|up\rangle + c_2|\downarrow\rangle)\otimes|down\rangle)_{s_{12}/s_3} \tag{7}$$

Now, consider s_1 at t_2. In standard QM we would calculate the reduced state of s_1 at the relevant time. In RQM we should also include the relativization target. It turns out that the state of s_1 relative to s_2 is an eigenstate of the spin-operator belonging to eigenvalue *up*, whereas the state of s_1 relative to s_3 is not an eigenstate of the spin operator—we saw that much already. It follows from the EEL that at time t_2, s_1 has $spin_x = up$ relative to s_2, but s_1 does not have $spin_x = up$ relative to s_3. If we concede that s_1 has the determinable $spin_x$,[40] this is enough to conclude that the case at hand is a case of MI, according to the determinable based account of §3. It also fits perfectly with the following explication by Rovelli[41]

> [T]hus, we have two descriptions of the physical sequence of events E: The description (1) [i.e., our equation (6)] given by the observer O and the description (2) [i.e., our equation (7)] given by the observer P. These are two distinct correct descriptions of the same sequence of events E. At time t_2, in the O description, system S is in the state $|1\rangle$ and the quantity q has value 1. According to the P description, S is not in the state $|1\rangle$ and the hand of the measuring apparatus does not indicate '1' (Rovelli, 1996, p. 1643).

If we take another step further and we claim that at t_2 system s_1 does not have *any value* of $spin_x$ relative to s_3, what we have here is a (relativized) case of *gappy* MI.[42]

Now, we want to push the analysis a little further, for we believe the recognition of MI helps to undermine an objection that has been raised against RQM. Suppose we change the situation slightly. Suppose at t_3, system s_3 performs a measurement on s_{12}, which is modeled as:

$$t_2 \to t_3 \\ c_1|\uparrow\rangle\otimes|up\rangle) + (c_2|\downarrow\rangle\otimes|down\rangle)_{s_{12}/s_3} \to (|\downarrow\rangle\otimes|down\rangle))_{s_{12}/s_3} \tag{8}$$

On the other hand, nothing changes for s_1 relative to s_2.[43] That is, we have:

[38] A referee pointed out that RQM might provide examples of a more radical form of indeterminacy, that is *indeterminacy of determinables*. This is roughly when it is indeterminate which determinables a quantum system instantiates at t. And it is unclear whether determinable based MI is enough to account for such radical indeterminacy. A few things are worth noting. First, if the determinables in question turn out to be determinates of a less specific determinable—one needs to recall that the distinction between determinable and determinates is level-sensitive, in that a given determinable, say red, might be a determinate of another determinable, say color—then it is unclear why the determinable based account cannot be applied to such cases. It should be argued that the determinables that are operative in the radical indeterminacy at stake are *maximally unspecific determinables*, i.e. determinables that are not determinates of any other determinable. And this calls for substantive argument. Second, this would not undermine the main point of the paper, namely that RQM provides other cases of indeterminacy that can be accounted for in determinable terms.

[39] We reprise talk of quantum states here simply to mirror our discussion in §2. It is easy to translate the discussion solely in terms of observables and their values.

[40] This is the line we took in the paper. Arguably **Meaninglessness** will deliver that s_1 does not have the determinable $spin_x$. For an argument along the same lines, see Glick (2017). We respond to some of Glick's arguments in §5. Stephen French suggested to us that the determinable $spin_x$ could be attributed to s_1 on the basis of symmetry considerations.

[41] Translation manual: $S = s_1$, $O = s_2$, $P = s_3$, $|1\rangle = |\uparrow\rangle$, and, finally, $1 = up$.

[42] One may press the following worry. Suppose—as we do in the main text—that we have three quantum systems, s_1, s_2 and s_3. Suppose s_1 has $O = v_1$ relative to s_2 but no value of O relative to s_3. Therefore—so the thought goes—this is not a case of *gappy* MI, insofar as s_1 has a determinate, nor it is a case of *glutty* MI insofar as s_1 does not have more than one determinate. Hence, it is dubious this constitutes a case of MI after all. We contend that there is a more coarse-grained description of the case at hand that does show there is MI—modulo the conditional acceptance of the determinable based account. Here is such a description. There are at least two states of affairs, one that involves s_1, s_2 and O, and one that involves s_1, s_3, and O—we are being deliberately vague about the notion of involvement for we do not want to subscribe to any particular metaphysics of states of affairs. Now, focus on the latter: this is a state of affairs in which a system s_1 has a determinable O but no value of O relative to s_3. This is exactly (a relativized variant of) gappy MI. Thanks to an anonymous referee for pushing this point.

[43] We acknowledge this is physically unrealistic. Bear with us. If one wants, one can imagine that s_2 performs another $spin_x$ measurement on s_1 at t_2.

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$$t_2 \rightarrow t_3$$
$$|\uparrow\rangle_{s_1/s_2} \rightarrow |\uparrow\rangle_{s_1/s_2} \tag{9}$$

By the same argument above, at t_3 we have the following situation. We have one system s_1 such that s_1 has $spin_x = up$ relative to s_2, and s_1 has $spin_x = down$ relative to s_3.[44] This is almost *verbatim* a case of *glutty* MI in its *relativized* variant. As a matter of fact, it seems the RQM-counterpart of Wilson's iridescent feather case we mentioned in §2. Brown (2009) alleges something in the vicinity of the case we discussed is a problem for RQM. He labels it the *determinacy problem*. He does not see the *determinacy problem* as a knock-down objection to RQM but he sees it as a *genuine puzzle*[45]

> [N]othing said so far prevents it from being the case that *P* finds $|\downarrow\rangle$ at t_3, and thus *S* being spin-down for *P*, even though *S* was spin-up for *O*! (…) But here's the puzzle: we have parallel sets of consistent events relative to *O* and *P*, which nevertheless disagree (Brown, 2009, p. 690).

In general, it should be clear why MI could help with (some sorts of) determinacy problems, if the problem at hand is indeed a *lack of determinacy*. In effect, in the situation above Brown contends *it is not determined* which definite value properties a system has.[46] Clearly, determinacy, or better, the lack thereof is a problem only if one maintains that indeterminacy is not intelligible. But the very point of the accounts we mentioned in §3 is exactly that of providing an intelligible base for MI. Once we recognize that, failure of determinacy should not be regarded as a problem in the first place. In the particular case at hand, we contend, the sensation of puzzlement *should* indeed vanish. This is because, according to the metaphysical picture we are exploring, this is *exactly what we should have expected all along.* No puzzle here: our metaphysical theory *predicted* the situation correctly. Multiplicity of perspectives and disagreement among these perspectives are exactly the hallmarks of MI according to the view at hand. Now, we anticipate that someone will respond that *glutty* MI is *puzzling* in and on itself. That may be. But, it should be noted, it is not our purpose to defend *glutty* MI in its relativization variant here. The argument is conditional: *if glutty* MI provides a satisfactory account of quantum indeterminacy, *then* it will be helpful in the present context, as it will apply naturally to RQM.[47] Relatedly, it should be noted that no-charge of ad-hocness can be brought to bear. The determinable based account of MI was not developed just to save RQM from an embarrassment—if there ever was one. It was developed independently of RQM. In effect, it was developed independently of QM altogether.[48]

It is also instructive to see that the account we are pushing seems to get things right even when we should not expect any MI in the first place. Suppose we change the situation again. Suppose the situation at hand is one that we would usually describe as system s_1 being in eigenstate of $spin_x$. Then we will have—supposing the only quantum systems are s_1, s_2, and s_3 together with their composites:

$$t_1 \rightarrow t_2$$
$$|\uparrow\rangle_{s_1/s_2} \rightarrow |\uparrow\rangle_{s_1/s_2} \tag{10}$$

[44] Slight complication. Strictly speaking, we should say that s_{12} has $spin_x = down$, *down* relative to s_3. We claim that when s_{12} has that property relative to s_3, a sense can be made of s_1 having $spin_x = down$ relative to s_3. We overlook this complication for we are mostly interested here in discussing a problem in Brown (2009), and Brown himself overlooks this complication.

[45] Though he also writes that

> [T]he relational interpretation still results in a *paradox* (Brown, 2009, p. 680—italics added).

[46] As for a quick reply, one can simply observe that according to RQM, *s* has define value property $O = v$ is indeed not even truth-evaluable because it lacks a relativization target. We think this is as good a reply as any. However, Brown goes on to contend that it is really disagreement between different perspectives—so to speak—that generates the puzzle. We will use glutty MI to dispel such puzzlement.

[47] There might be some reservations about whether the situation at hand really constitutes a case of MI. We should notice that, as we explicitly admit in the main text, the argument is a conditional argument. One might be suspicious of the antecedent of the relevant conditional, and, as we pointed out in §1, it is not our aim in the paper to defend it. In effect, we can think of natural way of understanding the situation in which there appears to be no MI after all. The thought is that one could treat properties like $O = v$ as *relations* between two systems and then push the point that we only have two determinate yet relational states of affairs. But note that a reading in terms of *relations* and relational states of affairs is not mandatory. Here is another reading that seems to provide more leeway for the defender of MI. The thought would be that there are perspectival states of affairs, and the indeterminacy comes from the fact that there is no determinate state of affairs that these are perspectives of. Let us spend a few more words on this. In the case at hand, quantum systems s_2 and s_3 provide perspectives on an indeterminate state of affairs that involves—to use the deliberately vague notion we used already in footnote 38—only s_1 and $O = v_i$, with $i = \{1, 2\}$. We are well aware that, at this stage, this is mostly a vague suggestion in need of a fully fledged development. Such a development, we take it, goes beyond the scope of the paper. However we should signal that there is a renewed interest in the metaphysics of perspectival states of affairs—or perspectival facts—that could be wheeled in to support such a project. Recent contributions in the metaphysics and philosophy of science include Lipman (2016), Berenstain (2020), and Evans (2020). For example Berenstain characterizes a perspectival fact as a fact expressed by a proposition whose truth value depends on the perspective of a particular observer. Crucially, the fact expressed by the proposition in question needs not be a relational fact—what gets relativized is the truth value of the corresponding proposition. Lipman (2016) is even more explicit. The Determinacy Problem is exactly a case of what Limpman calls Perspectival Variance. And Lipman insists that one should not account for such perspectival variance by saying that the apparent properties or relations merely turn out to have higher adicity—that these cases simply reveal a hidden argument place (Lipman, 2016, p. 44). Finally, Evans (2020) explicitly suggests that it would be interesting to apply the notion of perspectival fact to RQM.

[48] Dorato (2020) suggests that there is a further problem beyond the one that we discuss. The problem is roughly that system s_3 *can* observe that system s_2 has observed that s_1 has $spin_x = up$, and observations cannot be relativized (Dorato, 2020, p. 11). He then goes on to suggest an Everettian reading of the situation that solves the problem. We concede that the Everettian solution might be a viable one. However, there could be other solutions as well. Note that at t_2, s_3 *does not* observe that s_1 has $spin_x = up$ relative to s_2. s_3 only observes that an interaction has taken place—given the correlation of superposition terms—not the result of such an interaction. Nor s_3 observes such a thing at t_3. Clearly, she *could*, in broad terms, observe it: s_3 could just ask s_2. But, as Rovelli himself notes:

> [I] believe that a common mistake (…) is to forget that precisely as an observer can acquire information about a system only by physically interacting with it, in the same fashion two observers can compare their information only by physically interacting with each other. This means that there is no way to compare the information possessed by O [s_2] with the information possessed by P [s_3] without considering a physical interaction between the two. Information, like any other property of a system, is a fully relational notion (Rovelli, 1996, p. 1644).

We admit this might be only the beginning of an answer to Dorato's worries. Given that—as we clarified—it is not our aim to defend RQM here, we will leave it at that.

$$t_1 \rightarrow t_2$$
$$(|\uparrow\rangle \otimes |init\rangle)_{s_{12}/s_3} \rightarrow (|\uparrow\rangle \otimes |up\rangle)_{s_{12}/s_3} \tag{11}$$

$$t_2 \rightarrow t_3$$
$$(|\uparrow\rangle \otimes |up\rangle)_{s_{12}/s_3} \rightarrow (|\uparrow\rangle \otimes |up\rangle)_{s_{12}/s_3} \tag{12}$$

$$t_2 \rightarrow t_3$$
$$|\uparrow\rangle_{s_1/s_2} \rightarrow |\uparrow\rangle_{s_1/s_2} \tag{13}$$

At t_3, necessarily, s_1 has $spin_x = up$ relative to all other interacting physical systems, s_2 and s_3. Thus, at t_3, s_1 is metaphysically determinate with respect to spin$_x$. Once again, this is what we should have expected. As we noted in §2, the source of quantum MI is *superposition*. And, in the case at hand, there is no superposition of $spin_x$ states.

5. Fundamental indeterminacy

In the previous section we argued that MI provides a philosophical framework for RQM, a framework that also helps undermining some objections against it. In this section we explore whether and how RQM can bolster the case in favor of MI. In a recent paper,[49] David Glick argues that there is no quantum indeterminacy. He provides several considerations in favor of the thesis. In what follows we focus on what we shall call the *argument from fundamentality*. In a nutshell, the argument is the following. According to the main live interpretations of QM—namely, according to Glick, Bohm, Everett, and GRW—there is no quantum indeterminacy at the fundamental level. Glick writes:

> [F]irst, and most straightforwardly, the Bohm theory endows particles with determinate positions and momenta at all times [...]. Second, the Everett interpretation, as developed by Wallace (2012), recognizes only the universal wavefunction in its fundamental ontology. The universal wavefunction is perfectly determinate at every time [...]. Finally, consider dynamical collapse theories such as versions of the GRW. The two versions of the GRW adopted by most contemporary defenders are the mass-density and flash-ontology varieties. Neither contain fundamental indeterminacy: the distribution of mass-density and the location of the flashes are both perfectly determinate (Glick, 2017, p. 205).

But, according to Glick, derivative, i.e., non-fundamental, indeterminacy is eliminable.

> [A]ny indeterminacy would occur at the non-fundamental level, and hence may be viewed as *eliminable* (Glick, 2017, p. 206).

Therefore, there is no quantum indeterminacy, Glick concludes. Given that quantum indeterminacy provides the best candidate for genuine MI, one might add, it is unclear whether there is any MI at all. It is important that we address the argument. If Glick is correct, it is suspicious at best that we resort to MI to provide a metaphysical framework for QM, RQM included. As we see it, in general, the *derivativeness* of quantum indeterminacy hardly supports its *eliminability*. In effect, eliminativism about derivative entities is highly revisionary. One of the crucial motivation, if not *the* crucial motivation, to endorse a substantive distinction between a fundamental and a derivative level is exactly to be realist about non-fundamental, derivative goings-on. If so, the argument from fundamentality is hardly compelling. Perhaps one can concede the point against eliminability, but still insist that derivative indeterminacy, even if not eliminable, is treatable in broadly representational terms. In a slogan, derivative indeterminacy is not metaphysical indeterminacy. There is indeed a long tradition of such deflationary approaches to indeterminacy. But quantum indeterminacy—even if derivative—is *prima facie* very different from the paradigmatic cases of representational indeterminacy. The latter usually involve vague predicates, compositional vagueness, or the problem of the many. Nothing of this sort is at stake here. Lewis (2016) recognizes this explicitly:

> But insofar as quantum mechanics does posit indeterminacy, that indeterminacy *has nothing to do with composition or even with familiar kinds of vagueness*, and hence quantum mechanics changes the nature of the debate over indeterminacy (Lewis, 2016, p. 75, italics added).

Let us develop this line of argument. Quantum indeterminacy stems from patterns of instantiation of quantum observables by physical systems. This, we suggest, can hardly be treated as representational in nature. Representational accounts of indeterminacy can be broadly divided in two families, *semantic* and *epistemic*. According to *semanticism*, indeterminacy ultimately depends on the vague nature of different predicates. This phenomenon clearly affects natural language. Yet, there seems to be nothing semantically defective or vague in the language we used. In effect, we used the mathematical language of QM, with operators and eigenvalues. No language is arguably more precise and unambiguous than mathematical language. According to *epistemicism*, indeterminacy boils down to a lack of knowledge either about the correct use of predicates or about the external world. In the first case, we fail to see how it could be argued that quantum indeterminacy emerges from a lack knowledge about the correct use of the quantum vocabulary. As a matter of fact, RQM takes quantum formalism—as we saw in §2—at face value. In the second case, the idea would be that there is quantum indeterminacy because we lack some relevant knowledge about the external world. The world itself is completely determinate, but sometimes we are simply ignorant about which determinate way it is. However, the complete determinateness of the world conflicts with many important foundational results, such as the Kochen-Specker theorem, which RQM takes seriously. There might be another way in which quantum indeterminacy as operative in the failure of value definiteness of quantum observables can be considered as epistemic. It boils down to a claim that any attribution of observables to certain physical systems does not represent something physical about the system, but rather, it represents our knowledge of it. Attributions of positions, energy, spin would not represent anything physical about quantum systems. This seems to be dangerously close to a radical anti-realism in QM. Note that this is far more radical than anti-realism about the quantum state—which Rovelli endorses. This is anti-realism about *observables*—and, arguably, systems. For one, Rovelli is explicit that RQM is decisively realist in this respect:

> [R]elational QM (...) is *realist* about quantum events, systems, interactions ... (Rovelli, 2018: 9—italics added).

[49] See Glick (2017).

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We contend that these are reasons enough to shift the burden of the proof on those who endorse a representational account of quantum indeterminacy in the context of RQM.[50]

We will briefly return to this, but, as of now, we want to shift the focus on the other claim, namely that according to the main live interpretations there is no fundamental quantum indeterminacy. Glick simply does not consider RQM. So, the question becomes: is there a reading of RQM according to which there is fundamental quantum indeterminacy? In the rest of the section we provide reasons to think this is the case.

Interacting quantum systems seem to be the fundamental item in the RQM ontology. As a matter of fact, the fundamental ontology of RQM is presented by Rovelli (2018), and Laudisa and Rovelli (2019) as a *sparse flash-ontology* of quantum events, which *actualize*—their word—at quantum interactions. Here are some relevant passages:

> [A] good name for the actualization of the value of a variable in an interaction is quantum event. The proper ontology for quantum mechanics is a sparse ontology of (relational) quantum events happening at interactions between physical systems (Rovelli, 2018, p. 7).

> [T]he ontology of RQM is a sparse (flash) ontology or relational quantum events, taken as primitive, and not derived from any underlying representation (…) RQM gives no deeper justification or underlying dynamical representation of the main process: the actualization of quantum events at interactions (…) The core discreteness of the quantum event actualization is not explained in RQM: it is understood as the picture of how nature works according to quantum theory (Laudisa & Rovelli, 2019, pp. 19–20).

We take it that passages like the ones above—if taken at face value—are enough to conclude that quantum interactions, or quantum events are fundamental in RQM. This is clearly not the place to enter into a substantive metaphysical question about the priority relations between events and their participants. However, we shall notice that there seem to be two major views: either participants depend on events—perhaps because they are abstractions from those events as Whitehead would have it—and thus events are more fundamental than participants, or events depend on their participants.[51] If events depend on their participants—so the thought goes—those participants are at least *as fundamental as* the events they participate in. In this case, both non-interacting and interacting quantum systems would be part of the fundamental ontology. Let us call this the *conditional argument*, for it is conditional on the acceptance of substantive principles about dependence and fundamentality.[52] The argument for non-interacting quantum systems requires some unpacking.[53] Suppose s_1 is a system that interacts with a system s_2, in such a way that s_1 acquires a determinate value property $O = v$—relative to s_2. By the conditional argument above s_1 is fundamental—given that it is a participant in a fundamental event. Now, suppose there is another system s_3 such that s_1 and s_3 do not interact. s_1 will not have any value v of O relative to s_3. It will be indeterminate with respect to O—relative to s_3. There is a sense in which this indeterminacy is fundamental in that it consists in the obtaining of an indeterminate state of affairs that has a fundamental constituent, namely s_1. The thought is that, once a system interacts with another, it is fundamental in the light of the conditional argument. But that system arguably does not interact with many other systems. Thus, it is a constitutive part of indeterminate states of affairs. The indeterminacy of those state of affairs inherits its fundamental status from the fundamentality of (one of) its constituents.[54]

But RQM might provide other examples of fundamental quantum indeterminacy. Go back to the final case in §4.2, the one according to which there is a system s_1 that has $spin_x = up$ relative to s_2, but has $spin_x = down$ relative to s_3. These are exactly two examples of quantum events according to Rovelli himself—as per the quotations above. And these are fundamental in RQM. But, we argued in §3.2, these provide examples of glutty MI. Thus, in this case, RQM *provides* an example of fundamental quantum indeterminacy.

As a matter of fact, the fundamentality of quantum indeterminacy in RQM should not come as a surprise even for those who believe that the only right place to look for fundamental indeterminacy is the Copenhagen interpretation.[55] They include Glick himself:

> [S]o, what interpretation of QM do advocates of quantum indeterminacy have in mind? The usual reply is the 'standard', 'orthodox' or 'Copenhagen' interpretation (Glick, 2018: 205).

The reason why RQM is naturally hospitable to fundamental indeterminacy, we contend, is the fact that Rovelli's explicit aim is to design an interpretation that is, in spirit, as close as possible to the Copenhagen interpretation. Indeed, as we pointed out in §1, Rovelli is explicit throughout his work about this desideratum:

> [RQM] is essentially a refinement of the textbook 'Copenhagen' interpretation, where the role of the Copenhagen observer is not limited to the classical world, but can instead be assumed by any physical system (Laudisa & Rovelli, 2019, p. 1).

[50] We do not consider the sort of radical anti-realism about quantum observables and systems at length simply because we think of the paper as squarely placed within a mild realistic attitude towards QM. Thanks to two anonymous referees here.

[51] It should be noted that this discussion is rough at best. It *assumes* there are dependence relations between events and participants, and that dependence tracks relative fundamentality. Both assumptions are substantive and in need of independent support.

[52] One might object that no non-relativistic quantum system can be fundamental. And we agree. It is however clear, in context, that the discussion Glick engages with is a somewhat conditional discussion: insofar as one takes non-relativistic quantum mechanics to be fundamental, then any MI regarding non-relativistic quantum systems should be considered fundamental as well—see e.g. Glick's discussion of the Copenhagen interpretation that we quote later on. We should also point out that, as we said, we find the inference from derivativeness to eliminability neither compelling nor plausible. Any argument to the point that non-relativistic quantum systems are not fundamental will therefore not affect our claim that there is quantum indeterminacy, if only at the derivative level.

[53] We believe that distinguishing between fundamental interacting quantum systems, and derivative non-interacting ones might be traced back to **Meaninglessness**. And we are skeptical about **Meaninglessness** in general. We will not pursue this line of argument here.

[54] It should be noted that if all quantum systems were to be completely isolated systems—and thus indeterminate with respect to at least some of their observables—then indeterminacy would not qualify as fundamental, not even in the light of the conditional argument. Thanks to an anonymous referee here.

[55] See e.g. Skow (2010), Bokulich (2014), and Wolff (2015). Here is, for instance, Bokulich:

> [I]n this paper I am taking a realist attitude towards the standard interpretation, and asking what the world would be like if this interpretation were true (Bokulich, 2014, p. 460).

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As we briefly saw in §2, the crucial difference between the Copenhagen interpretation and RQM, is that the latter aims to extend the role of measurements beyond the classical world. According to Rovelli, any quantum interaction counts as a measurement, so to speak:

> [I]n the Copenhagen view, it is the interaction with a classical object that *actualizes* properties. A different solution has been suggested in this paper: interaction with any object, but then *actualization* of properties is only relative to that object. (Rovelli, 1996, p. 18, italics added).

> [W]hen and how a probabilistic prediction about the value of a variable a of a physical system S is resolved into an actual value? The answer is: when S interacts with another physical system S' (…) *Any* interaction counts, irrespectively of size, number of degrees of freedom, presence of records, consciousness, degree of classicality of S', decoherence or else, because none of these pertain to elementary physics (Rovelli, 2018, p. 5).

In §4 we put forward a proposal that can be seen as a way of cashing out the distinction Rovelli draws in the passages above between definite-value *actualized* properties, and *non-actualized* properties, and we did it in terms of the determinable based account of MI. Roughly, the key would be to identify *actualized* properties with maximal determinates, and *non-actualized* properties with determinables. Such a distinction is shared by both RQM and a certain understanding of the Copenhagen interpretation. It should thus be expected that our understanding of RQM could shed some light on the Copenhagen interpretation as well. Let us spend few more words on this. In his Gifford Lectures from 1955 to 1956, later published as *Physics and Philosophy*, Heisenberg puts forward his own understanding of the Copenhagen interpretation, that differs substantially from Bohr's. According to Heisenberg, we should conceive of systems in superposition states that have not yet interacted with a measuring apparatus as something

> [S]tanding in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality (Heisenberg, 1956, p. 12).

To describe the ontology of the systems before measurements, Heisenberg uses interchangeably the terms possibility, tendency, potentiality, and even, explicitly referring to Aristotle, the Latin term *potentia*. The main conceptual challenge of QM, according to Heisenberg, is to provide an explanation of the

> [T]ransition from the possible to the actual (Heisenberg, 1956, p. 23)

that occurs when systems and measuring devices interact. According to Kistler (2018), we could interpret Heisenberg's view in two distinct ways:

> [O]n the first interpretation (…) quantum mechanical system that is in a superposed state has, before measurement, only potential existence. It only becomes actual, or real, upon measurement. On a different interpretation (…), the system itself is actual or real even before the measurement. However, it has some of its properties only potentially, i.e. properties that correspond to physical observables, with respect to which the system is not in any eigenstate but rather in a linear superposition of eigenstates (Kistler, 2018, p. 363).

While the Copenhagen interpretation is more often associated with the former view,[56] the latter seems closer to the approach we defended throughout this paper with respect to RQM. The crucial issue is how we should understand the idea that systems in superposition possess properties only *potentially*. Kistler (2018) proposes a dispositional understanding of potentiality, which is close in spirit to Dorato's **Dispositionalism**. We suggested that **Dispositionalism** is not the only candidate on offer. **Metaphysical Indeterminacy** is another candidate. It delivers an understanding of systems in superposition states as *metaphysically indeterminate systems*. If we push this line with respect to Heisenberg's own understanding of QM, we could find significant similarities with Rovelli's view.[57,58]

Most crucially for our purpose here, we shall notice that both approaches seem to provide the very same case of fundamental indeterminacy. We saw that, in the case of RQM, in order for the indeterminacy to be fundamental, we would need to assume the fundamentality of quantum systems along with their properties—and their interactions. We should register here that, even if the claim of fundamentality is not upheld, the *reality*—and thus the *non-eliminability*—of quantum (interacting) systems and their properties is explicitly retained all along, as per the previous passage we quote again here:

> [R]elational QM (…) is *realist* about quantum events, systems, interactions … (Rovelli, 2018: 9—italics added).

This would be enough to undermine Glick's argument from fundamentality. Be that as it may, while discussing what is the correct understanding of the Copenhagen interpretation for there to be fundamental indeterminacy, Glick (2017) claims that

> [C]harity recommends consideration of a version of standard [Copenhagen] QM in which physical properties are non-derivative (Glick, 2017, p. 206).

Therefore, in both cases, fundamental indeterminacy derives from the fundamentality of quantum (interacting) systems and their properties, and from taking the EEL at face value. However, to be clear, a large part of the disagreement with Glick generates from what one takes the correct ontology of fundamental quantum systems to be. According to him, something in the vicinity of what

[56] See e.g. Howard (2004). Howard stresses that, on a closer inspection, the Copenhagen interpretation has been invented and propagated by Heisenberg alone, starting in the '50s. Be that as it may, we shall at least notice that a large part of historians agree that Bohr and Heisenberg views were very different, and thus should not be discussed as a coherent whole—see Chavally (1994), Cushing (1994), and Beller (1999), and Faye (2019) to mention a few.

[57] It is arguably no coincidence that Rovelli (2018) discusses Heisenberg's understanding of QM at length.

[58] More generally, we might note that different answers to the **Non-Interacting Quantum Systems** and **Relevant Properties** questions above will deliver distinct background metaphysical frameworks whose applicability goes beyond RQM. We already argued that it can be used to distinguish different ways of understanding Heisenberg's view. Nothing prevents us to extend a similar result to other somewhat neglected interpretations of quantum mechanics. A similar classification based on different possible answers to the **Non-Interacting Quantum Systems** and **Relevant Properties** questions can be given for the Modal Hamiltonian Interpretation (e.g. Lombardi, 2019), to mention but one—thanks to Juha Saatsi for pointing this out. The exploration of the possible role of MI in the Modal Hamiltonian Interpretation is something we leave for future work.

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we called above the **Meaninglessness** view—and that he calls the **Sparse View**[59]—is the most straightforward option, precisely because it avoids talking about indeterminacy.[60] By contrast, we contend that an account of MI can be perfectly intelligible, and this fact alone is enough to undermine some of the motivations for a view in the vicinity of **Meaninglessness**.

In general, we take the discussion in this section to undermine Glick's argument against the existence of quantum indeterminacy. It is not true that in all the main live interpretations of quantum mechanics there is no fundamental indeterminacy. Naturally, this conclusion rests on taking RQM as one of the main live interpretations of quantum theory. We do not see why it should not be. As Brown remarks:

> [T]he view has its attractions. Unlike realist-collapse theories it takes the prediction of the formalism with full seriousness (…) Unlike ordinary no-collapse theories, it gives us determinate measurement records without adverting to a dualistic solution to do so, for the theory posits no extra entities beyond what the formalism requires, nor it requires any quantum minds or divergent worlds, actuality-makers or Bohmian particles, or any such contrivances (Brown, 2009, p. 693).

This absence of such contrivances, we believe, is reason enough to consider RQM as a serious contender among other serious contenders. And if there is indeterminacy according to RQM, so be it. We *can* face it. We *should* face it. This also concludes the paper: RQM and MI together provide a substantive and fascinating account of the quantum world, an account that is physically accurate and philosophically profound.

Credit author statement

The present co-authored manuscript is fully co-equal, with authors listed in alphabetical order.

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[59] Glick characterizes the **Sparse View** as follows:

> [W]hen the quantum state of A is not in an eigenstate of O, it lacks both the determinate and determinable properties associated with O (Glick, 2017, p. 206). There are obvious differences between this and the **Meaningless** view. However, we notice that the very same considerations we advanced in §3.2 against the **Meaningless** view apply to the **Sparse View** as well. This is reason enough to discussing them together in the present context. To be fair, the argument against **Meaningless** needs to be slightly modified if it is to count as an argument against the **Sparse View**. In particular, the argument works only under the following further assumption: Having Position—that is, once again, being in space—is a determinable with Having Precise Positions as determinates. If this is the case, no matter how many levels of determinables and determinates one introduces between the two, the **Sparse View** entails that a system without any precise position is not in space either. We take that the further assumption in question is fairly plausible—at least insofar as one accepts the determinable/determinate distinction to begin with. But we agree that it is a further assumption that can be challenged. Given that it is not our interest in this paper to provide a critical assessment of the **Sparse View**, we shall leave it at that. Thanks to an anonymous referee here.

[60] We thank David Glick for suggesting this.

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