Quantum Metaphysics and the Foundations of Spacetime

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Abstract

The main research programs in quantum gravity tend to suggest in one way or another that most (if not all) spacetime structures are not fundamental. At the same time, work in quantum foundations highlights fundamental features that are in tension with any straightforward spacetime understanding. This paper aims to explore the little investigated but potentially fruitful links between these two fields.

1 Introduction

In recent years we have witnessed a novel tendency in the research on the metaphysical implications of quantum theory. Given the difficulties in providing a shared ontological picture of *how the world is like* if quantum theory is true—in large part due to the many ways in which we could address the measurement problem—researchers have attempted to focus on those features of the theory that can be considered to some extent *interpretation-neutral*, to use (Wallace 2019) expression. Phenomena such as entanglement and superposition, along with the mathematical features underpinning them, seem to be essential for how we define what a quantum theory is, and this is arguably true independently of one's preferred approach to the measurement problem. For instance, research in the metaphysics of quantum non-separability has shown that a certain *structuralist* (Lam 2017) or *holistic* (Miller 2016) attitude seem natural when it comes to understanding the phenomenon of entanglement. More recently, philosophers have suggested that the notion of *ontological indeterminacy* (a.k.a metaphysical indeterminacy) may provide an explanation of various features of quantum theory, and in particular it may explain the lack of value-definiteness affecting quantum systems in a state of superposition (Calosi and Wilson 2021).

These metaphysical strategies are not in the business of providing novel solutions to the measurement problem. Rather, the idea behind them is to refine the overall metaphysical understanding of the theory, which could then be implemented by specifying the many ontological alternatives inspired by the various solutions to the measurement problem. And in effect, there are now several concrete proposals on how to implement these strategies within the context of specific interpretations of the theory,[1] and under the overall assumption of scientific realism towards physics.

Once we grant that the relevant quantum features used to derive such metaphysical conclusions are essential to any quantum theory, it is natural to expect this claim to be true also in the context of the novel research programs in quantum gravity (QG). Our main working hypothesis is precisely that the aforementioned metaphysical strategies will prove insightful to better understand the world according to QG. And as a matter of fact, such an *interpretation-neutral* attitude is not just preferable in the context of QG, but may even seem necessary if we consider that no specific quantum interpretation is assumed or suggested at the current stage of research.

A common striking conceptual feature of many research programs in QG is that they suggest, in one way or another, that most (if not all) spatiotemporal structures are not fundamental (Huggett and Wüthrich 2013). Consequently, one should expect that those metaphysical and foundational results in quantum theory that are already in tension with certain spatio-temporal features (or that already point towards the existence of certain non-spatiotemporal features) may turn out to be particularly relevant. In this paper we are going to provide two such examples, and we will then consider how they may give us novel insights on the ontology of QG. The first of them, already well-known in the literature, concerns the metaphysical implications of quantum entanglement, whereas the second example pertains to some rather novel results in quantum foundations regarding the notion of causal non-separability. As we will show, each of these cases arguably forces us to reconsider some plausible and intuitive idea about the nature of spacetime, specifically as regards to the notion of locality, and of definiteness of the causal order among distinct events. If seen through the lenses of these recently proposed metaphysical views, the problematic implications of QG may perhaps seem more natural and acceptable, or so we will argue.

Roadmap. In §2, we focus on the metaphysical tools that have been developed to account for quantum entanglement and non-locality, as within the *structuralist* and the *holistic* metaphysical strategies. In §3, we first look at recent developments in quantum foundations about causally non-separable processes that do not assume a definite global causal structure. We then exploit the recently developed tools of *quantum indeterminacy* in order to provide an understanding of the notion of superposition of causal order. In §4 we show how the tools that we have introduced can help to articulate a coherent but not necessarily spatio-temporal worldview at the level of quantum gravity. In §5 we conclude.

2 The Metaphysics of Quantum Entanglement

This section provides an overview of some of the metaphysical tools that have been articulated within the framework of standard quantum mechanics (and quantum field theory) to account for the key features of quantum entanglement and non-locality. These metaphysical tools do not aim to provide a full ontology for quantum mechanics (or quantum field theory), since this would require addressing the measurement problem. Rather, they aim to capture central features that, to some extent, cut across (most of) the various realist interpretations of quantum mechanics; indeed, they can often be further specified within these interpretations. Since we are interested in exploring to what extent these metaphysical tools can be relevant in the quantum gravity context, we highlight their links to spacetime structures.

2.1 Entanglement and Non-Locality

In many ways, quantum entanglement and non-locality are central features of quantum mechanics—and, to some extent, of any quantum theory (such as quantum field theory). Within the

[1] For instance, see Calosi and Mariani (2020) for indeterminacy within the main realist interpretations of QM, and Esfeld (2017) for structuralism.

standard quantum formalism, entanglement is encoded in the ubiquitous entangled quantum states for composite systems. Quantum states can be represented by a vector in a Hilbert space, noted $|\psi\rangle$. A more general representation is provided by appeal to density matrices, noted ρ, which are linear operators acting on the Hilbert space assigned to the system under consideration. A density matrix encodes either pure quantum states, which can be described with a vector in a Hilbert space, or mixed quantum states, which express situations in which a system is in a probabilistic mixture of pure states. The latter case expresses a situation in which we describe a system in a probabilistic mixture of pure states. In the remainder of this work, we will appeal to density matrices to represent a system's quantum state, not only because this mathematical object more naturally connects with the discussions of section 3, but also because it provides a more generalised framework.

Let a composite system, labelled 1-2, be composed of two subsystems, labelled 1 and 2. The quantum states of the subsystems 1 and 2 are said to be *nonseparable*, or *entangled*, if the global quantum state of system 1-2 cannot be expressed as follows:

$$\rho_{1-2} = \sum_i q_i \ \rho_1^i \otimes \rho_2^i \tag{1}$$

where the index i sums over classical probabilities (q_i) to have the subsystem x in the (pure or mixed) quantum state described by ρ_x^i. This notion of entangled states is purely formal at this stage, and needs to be interpreted to get assigned a meaning. If one adopts a realist approach towards quantum mechanics, the quantum state is considered as pointing towards objective features of nature. Yet, there is a debate regarding the exact nature of these objective features (see section 2.2). Most accounts see the wavefunction as the mathematical object representing the objective content of the quantum state, while density matrices are seen as encoding a mere epistemic information about the quantum state. This is however debated, and previous work emphasises that there is no need for an epistemic interpretation of density matrices (Aharonov et al. 1993). Several authors have defended a view called *density matrix realism*, in which it is the density matrix that represents the objective content of the quantum state (Chen 2020).

Importantly, quantum entanglement can lead to empirically verified non-classical correlations violating Bell-type inequalities among spacelike separated entangled subsystems (Hensen et al. 2015). A Bell inequality, as famously defined in Bell's theorem (Bell 1964), is an algebraic inequality, the violation of which by any given probability distribution is commonly understood in terms of the violation of the premise called "local causality". This premise encodes the fact that causes precede their effects, and that causal influences travel continuously through spacetime at subluminal speeds. Such quantum correlations violating a Bell inequality are said to be *nonlocal*, and are not determined by and do not supervene on the states of the entangled subsystems[2] or by additional local variables not encoded in the entangled states, and are independent of the distance between the spacelike separated subsystems. In this context, quantum entanglement is naturally considered as involving some form of non-locality.[3] Since Bell inequalities can be defined in a purely operational way—i.e. by appealing exclusively to notions such as inputs and outputs of quantum operations treated as black boxes—nonlocal correlations are said to be model-independent.[4] For this reason, Bell nonlocality (i.e. the existence of nonlocal correlations) is naturally taken as reflecting some objective fact about the physical world that any quantum theory has to account for.[5]

[2]This failure of supervenience is often referred to as a form of non-separability in the philosophical literature (see recently Ismael and Schaffer 2020); in the physics literature, quantum non-separability often specifically denotes the non-factorizability of entangled quantum states, as it is reflected by Eq.1.

[3]Indeed, we here focus on entanglement leading to the violation of some Bell-type inequalities, and hence to some non-local correlations among the entangled subsystems—in particular, note that all pure entangled states lead to the violation of a Bell-type inequality, whereas mixed entangled states may not violate any Bell-type inequalities.

[4]In this context, a model-independent notion is one that does not appeal to any specific machinery, tool or apparatus; the experimental setup is reduced to a black box fed with some inputs and returning some output.

[5]By this, of course, we do not mean to argue that nonlocality is unavoidable. As a matter of fact, even within

2.2 Structuralism and Holism

Several metaphysical tools have been articulated to account for quantum entanglement and the related non-local correlations. Indeed, the fact that the modal connections that these quantum correlations exemplify cannot be understood in terms of intrinsic properties of the entangled subsystems (as encoded in their reduced density matrices or with the help of possible additional—'hidden'—variables)[6] provides a strong motivation for a structuralist interpretation in the sense of ontic structural realism (OSR). Indeed, in the context of quantum entanglement, a natural structuralist understanding takes the novel, experimentally verified non-local correlations among entangled subsystems as the manifestation of a new fundamental physical relation—often simply called 'entanglement relation'—connecting the subsystems (whatever these latter precisely are according to the quantum theory under consideration and the preferred quantum ontology). The metaphysical details of the relationship between relations (or structure) and relata within OSR can be articulated in different (and sometimes controversial) ways and have been much discussed in the literature (e.g. see the references in Lam 2017, §1). The *moderate* structuralist conception according to which the relations are on a par with their relata—forming together 'structures'—seems especially appropriate for many situations in (fundamental) physics, including the entanglement case. Most importantly, in this structuralist perspective, the entanglement relation connects the entangled subsystems such that these latter have no independent existence. On this view, the existence of the entangled subsystems (ontologically) depends on the entanglement structures they are part of, that is, on there being entanglement relations, but also on there being other subsystems to which they are entangled to—these latter being conceived as (ontologically) interdependent on one another. This characterization of entanglement in terms of (symmetric) ontological interdependence or mutual dependence has been recently nicely discussed in Calosi and Morganti (2018) within their coherentist conception—which, to us, constitutes a refinement rather than a departure from the moderate structuralism considered here and further detailed elsewhere.[7]

Leaving aside the metaphysical subtleties, what is important to highlight for our purpose in this paper is that, within this structuralist conception, the entanglement structures encoding the interdependence among the entangled subsystems are conceived as physical structures on their own right, without being necessarily tied to spacetime.[8] As we will see in section 4, this metaphysical feature may well prove very useful when trying to interpret the quantum gravity context where spacetime may not play its usual roles.

Another main metaphysical strategy to account for quantum entanglement is quantum holism (recently defended in Ismael and Schaffer 2020), which consists in arguing for the ontological priority of the quantum whole (that is, the total composite quantum system) over its entangled parts (the entangled subsystems). Such an interpretative move gets direct inspiration (and support) from the fact that the quantum state of the total composite system determines those of its entangled subsystems, while the converse fails. Beside this characterization in terms of ontological priority, various holistic aspects of quantum entanglement have been articulated for some time in the physics and philosophy literature (see Healey 2016 for a review), some of which

a broadly realist approach, there are accounts that may escape this conclusion. Examples include the acceptance of retrocausality (Price 2012; Leifer and Pusey 2017; Friederich and Evans 2019), versions of superdeterminism (t Hooft 2016), and perhaps some versions of the many-worlds approach to QM (Vaidman 2021). It is highly debated whether any of these strategies really help us avoiding nonlocality—see Myrvold et al. (2021) for discussion.

[6]Arguably, even within Bohmian mechanics, the non-local modal connections among Bohmian particles cannot be accounted for only in terms of intrinsic (and local) properties of the particles (Lam 2016).

[7]See for instance Lam (2013), who writes that the "interdependent existence of fundamental entangled quantum systems [is] one of the main morals of QM, which OSR aims to encode". As a matter of fact, while Calosi and Morganti (2018) critically analyse the standard version of OSR at length, they do not really discuss the *moderate* version in any depth. The relationships between *coherentism* and *structuralism* are obviously intricate, and yet we simply point out that in both views the main explanatory job is done by relations of *symmetric dependence*. Thus, we take it that the two views are not necessarily in conflict, *contra* what Calosi & Morganti seem to suggest.

[8]We believe that the question of what, if not spacetime, makes such structures physical (Lam and Esfeld 2013, §3) can be answered in functionalist terms (Lam and Wüthrich 2018).

more or less explicitly encode structuralist elements (to some extent, certain types of holism can be considered as precursors of the recent structuralist conceptions in the quantum context). However, it is not the place to discuss the commonalities and the disanalogies between quantum holism and structuralism (see Calosi and Morganti 2018 for a recent critical look).

What is especially interesting in our perspective here is the common ground argument recently put forward for quantum holism (Ismael and Schaffer 2020, §4). In many ways, the structure of this argument is similar to the familiar Reichenbach's common cause principle, which roughly states that two correlated events, where neither is the cause of the other, have a common cause that screens off the correlations between them. In view of the well-known difficulties of this principle in the quantum context (the issue is subtle though, see Hitchcock and Rédei 2021 for a recent review), Ismael and Schaffer (2020) articulate a common ground account of quantum entanglement, which relies on the principle that if "non-identical entities a and b are modally connected, then either (i) a grounds b, or (ii) b grounds a, or (iii) a and b are joint results of some common ground c" (4137)—where grounding is understood, in the way advocated by Schaffer (2009) as a (metaphysical) asymmetric dependence relation between more fundamental and less fundamental entities.[9] The application of this principle to entangled quantum subsystems then naturally leads to consider the total composite quantum system as their common ground, which clearly amounts to a form of holism since the whole (the total composite system) is then considered as ontologically prior to (more fundamental than) its parts (the entangled subsystems).

Similarly to the structuralist case, we want here to highlight the fact that this holistic common ground strategy need not be tied to spacetime in any way. Indeed, for instance, Ismael and Schaffer (2020) explicitly consider wavefunction realism as a case where ordinary 3-dimensional space and entities located in 3-dimensional space are grounded in (and emerge from) a holistic common ground that is not 3-dimensional, namely the quantum wavefunction on (high-dimensional) configuration space.[10] In an analogous way, as we will see in section 4, this holistic common ground strategy can be naturally extended to full 4-dimensional spacetime, thereby helping to make sense of the non-spatiotemporal features suggested in many QG research programs.

3 Causal Non-Separability and Quantum Indeterminacy

The aim of this section is to introduce the recently discussed notion of *causally non-separable process*, and to discuss its metaphysical implications. We first introduce, in §3.1, the formal and technical details needed to understand causal non-separability, and we show how it is to be conceptually distinguished from quantum non-separability. In §3.2 we then suggest a way to understand the notion of causal superposition by exploiting the metaphysical tools developed within the debate on quantum indeterminacy.

3.1 Causally Non-Separable Processes

In the previous sections, the discussion focused on the theory of quantum mechanics in its standard form, i.e. as expressed in the formalism of Hilbert spaces. Yet, the theory has various formulations, on the basis of which different questions can be asked. More specifically, the field of quantum foundations also seeks to reformulate the theory within different formalisms in order

[9] Note, however, that *grounding* is more commonly understood as an explanatory relation between facts (Fine 2012; Correia and Schnieder 2012). On Schaffer's view, instead, *grounding* applies to every kind of entity (not just facts), which is also why his notion of grounding closely resembles that of *ontological dependence* (Fine 1994; Tahko and Lowe 2020).

[10] As a reviewer correctly points out, in order to get the holistic conclusion here we need the further claim according to which the 3D world is *part* of the wavefunction. This claim—recently defended at length by (Ney 2021*b*)—is not however straightforward and can be resisted.

to investigate the very structure of the theory, on the one hand, and inquiry about possible generalisations of the theory on the other hand. One of the formalisms used to reformulate quantum mechanics is that of operational theories. It offers an interesting framework, as it anchors the theory to a set of physical principles (from which the theory is recovered). Those principles select the probability distributions possibly correlating results of measurements performed on a given system (prepared in a specific way). Operational theories therefore widely appeal to the notions of preparation and measurement procedures, performed in isolated laboratories and in the context of given experimental setups. As discussed by Letertre (2021), the operational formalism, in spite of the instrumental connotation of its core concepts, does not need to be interpreted in an antirealist manner, and suits realist approaches as well.

There is one particular operational theory that not only recovers quantum mechanics, but generalises it by relaxing an important assumption according to which quantum events (which are, roughly, pairs of input and output systems connected via quantum operations) take place according to a definite (although possibly dynamical) causal structure. Such a theory, called the process matrix formalism, allows to investigate whether more general causal structures than those encountered in classical physics are allowed in the quantum realm. The connection between causal structures and spacetime geometries is tight, which makes this theory particularly relevant in order to study how quantum features can possibly impact the structure of spacetime (already at the non-relativistic level, and without taking gravity into account).

The process matrix formalism introduces the concept of quantum process, which is a function describing how n local quantum operations (noted A_j, with j being an integer ranging from 1 to n) are combined together to form a global operation. This notion is represented mathematically by a process matrix, noted W (see Fig. 1). A process matrix then describes the causal order among local quantum operations, by encoding how their respective inputs and outputs are connected to each others. Importantly, this description makes no assumptions about the spatiotemporal locations of the various interacting parties performing the local operations.

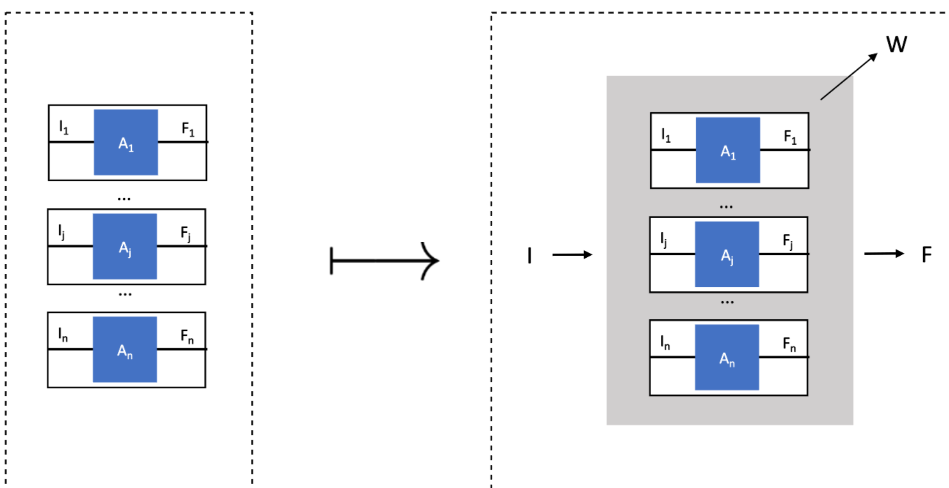

Figure 1: A generic quantum process. A quantum operation A_x sends some input quantum system described by a quantum state noted I_x on a final output quantum system described by a quantum state noted F_x. A quantum process W maps n such local quantum operations over a global operation noted A, of which the input is noted I and the output is noted F.

In some analogy with the notion of quantum non-separability, a quantum process can be causally non-separable, which means that it is incompatible with any fixed (although possibly dynamical) causal structure among the local operations involved. By definition, in the bipartite case,[11] a causally separable process $W_{A,B}$ involving the two parties A and B is a process that

[11] A generalisation to the multipartite case can be found in Oreshkov and Giarmatzi (2016) and Wechs et al. (2019).

can be expressed as a probabilistic mixture of processes compatible with a given fixed causal structure (Oreshkov et al. 2012; Oreshkov and Giarmatzi 2016):

$$W^{A,B} = q\ W^{A \preceq B} + (1-q)\ W^{B \preceq A} \tag{2}$$

where q is a number between 0 and 1 and $W^{X \preceq Y}$ represents a process for which signalling is only possible from X to Y.

For now, this notion of causal non-separability is purely formal. In a realist perspective, it is however natural to investigate to what extent this generalized concept may encode (possibly novel) physical features. We now first focus on this question, addressing subsequent interpretative issues in the next section.

There are at least some causally non-separable processes that have a rather straightforward physical implementation (Wechs et al. 2021). Among those, a particular process (see Fig. 2) called the *quantum switch* has been studied extensively these recent years (Chiribella et al. 2013; Oreshkov and Giarmatzi 2016; Araújo et al. 2015). Two parties, Alice and Bob, perform an operation in their respective closed local laboratory, on a shared system called the target system. This system is entangled with a control qubit,[12] the state of which determines the temporal order between Alice's and Bob's operations. More precisely, if the control qubit is in the state $|0\rangle$, the target system undergoes Alice's operation (noted A) before undergoing Bob's one (noted B), and vice versa if the qubit's state is in $|1\rangle$. A third party, Fiona, will perform an operation on the control qubit after Alice and Bob made their operations on the target, erasing the information about the causal order between Alice and Bob. If the control qubit is in a superposition of states $|0\rangle$ and $|1\rangle$, then the process involves a superposition of causal orders between Alice and Bob. It can be shown that the corresponding process describing the causal order among those parties is indeed causally non-separable, i.e. it is incompatible with any fixed causal order. In this case, we can say that the causal structure is indefinite.

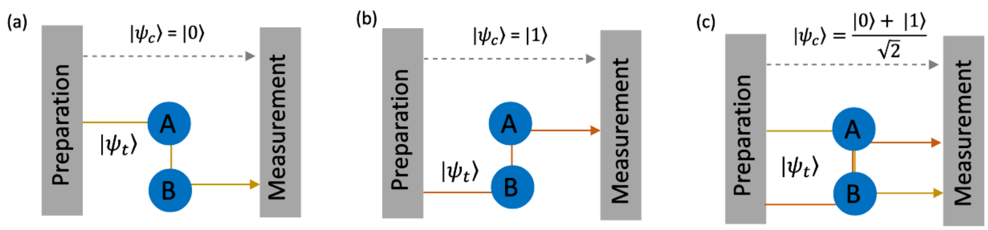

Figure 2: Diagram of the quantum switch. An initial preparation procedure prepares the initial quantum states of the target and control systems. $|\psi_t\rangle$ represents the quantum state of the control system. $|\psi_c\rangle$ represents the quantum state of the target system. A and B represent Alice and Bob's parties, respectively. A final measurement procedure is performed by third party Fiona. The state of the control system is entangled to the order between operations A and B. While scenarios (a) and (b) represents definite causal orders, the scenario (c), in which the control state is in a superposition of states, leads to a superposition of causal orders between A and B. This corresponds to the quantum switch.

The quantum switch has been experimentally implemented in a variety of ways (Procopio et al. 2015; Rubino et al. 2017; Goswami et al. 2018; Wei et al. 2019; Guo et al. 2020). Yet, objections have been raised against the idea that those implementations are physical realisations of a genuine indefinite causal order. The indefinite character of the causal order in the quantum switch indeed vanishes if we consider the possibility of causal cycles between A and B (MacLean et al. 2017). Yet, it is still possible, conceptually and experimentally, to imagine implementations of the quantum switch in which such cycles are not present. Another objection points out that only a gravitational quantum switch (i.e. involving an actual superposition of spacetime metrics) would constitute the only proper implementation of an indefinite causal order (Zych et al. 2019;

[12]A qubit is a quantum system of which the quantum state pertains to a two-dimensional Hilbert space, and that can be in any quantum superposition of two independent states forming a complete basis of this Hilbert space.

Paunković and Vojinović 2020). Indeed, it can be argued that the quantum switch, since it is defined within a classical non-relativistic spacetime, cannot guarantee a faithful description of spacetime at quantum scales. Yet, it can also be argued that the quantum switch, and more generally indefinite causal orders, point towards a tension between quantum features and classical spacetime. As such, their investigation can potentially lead to fruitful conceptual tools that could be of use in more advanced quantum theories of spacetime. Finally, some object that implementations of the quantum switch were not real processes, as each operation A and B were not performed once and only once (as is requested in the process matrix formalism). Oreshkov (2019) provides a technical argument against such worries, arguing that the formalism shows that operations within a process each takes place on specific input and output systems.

It seems therefore rather reasonable to consider that indefinite causal orders can possibly be found in physically implementable processes. The interesting question is now to articulate the interpretative implications of this generalized framework. Before doing so, and since the notion of causal non-separability has been defined in analogy with that of quantum non-separability, it is important to emphasize the extent and limits of this analogy in order to avoid potential unwarranted shortcuts or hasty conflations.

First, the notion of causal non-separability involves quantum processes, while quantum non-separability involves quantum states. These two notions are related, yet conceptually very distinct. A process links different operations, independently of the actual operations performed or of the actual systems undergoing those operations. A quantum state (mathematically represented by a density matrix) describes the state of a given physical system. In certain cases, a process can reduce to a density matrix, e.g. when a process describes separated operations (including the initial preparation procedure) performed on uncorrelated parts of a shared system, and of which we do not care about the outcomes. In that sense, processes generalize quantum states: a process can encode the same information as density matrices, but they usually allow much more, namely the encoding of correlations between different quantum operations. Because of these conceptually deep discrepancies, non-separability of quantum states and causal non-separability of quantum processes refer to different features. They characterize a certain kind of correlations between quantum states for the former, and between quantum events for the latter.[13] For this reason, causal nonseparability can encode relations among relata that are timelike separated, contrary to quantum nonseparability. Indeed, the various quantum events involved in a given quantum process, once embedded in spacetime, can be timelike separated, while the quantum states of entangled subsystems are (usually) spacelike separated. Yet, it is not the case that causal nonseparability is a mere extension of quantum nonseparability encoding correlations between quantum states at different times. Indeed, causal nonseparability is about correlations among quantum operations, while the initial quantum state for these operations can be left unspecified. To summarise, we have two distinct notions. On the one hand, quantum non-separability expresses that for some composite non-separable quantum state, the quantum states of the subsystems is indefinite. As discussed in section 2.2, various metaphysical theories can be applied to non-separable states in order to assign them a precise meaning. On the other hand, causal non-separability, by contrast, expresses that for some quantum processes, the causal order among the operational events involved are indefinite. Assigning a meaning to this formal feature will constitute the task of the next section.

Since all the currently known causally non-separable processes that are physically implementable can be described within standard quantum mechanics, their characterization within the process matrix formalism can be regarded as purely formal—i.e. not capturing any novel physical features. However, it remains an open issue whether there exist causally non-separable processes that are instantiated in nature, without being describable within standard quantum mechanics. Because such a scenario may well bring new physical and metaphysical insights, it

[13] We recall that process matrices do not encode quantum states *per se*. They only connect local operations to form a global one. As such, they correlate quantum events, which are distinct from the standard notion of events in relativity (namely spacetime points). Instead, in this context, a quantum event refers to a pair of input and output connected by a quantum operation.

is the one that will be explored in the next section.

Before doing so, it is worth noting that, in the same way that quantum nonseparability has a model-independent counterpart, namely nonlocal correlations, causal nonseparability has such an equivalent too. Indeed, causal nonseparability leads to correlations that may violate the causal equivalent of Bell inequalities, i.e. causal inequalities (Oreshkov et al. 2012; Branciard et al. 2015). Their violation necessarily indicates that the correlation is incompatible with any definite causal structure. Causal nonseparability is necessary but non-sufficient for noncausal correlations (i.e. correlations violating a causal inequality) (Oreshkov et al. 2012; Wechs et al. 2019; Oreshkov and Giarmatzi 2016; Araújo et al. 2015). No empirical protocol that generates noncausal correlations has been found so far (Wechs et al. 2021).

3.2 The Metaphysics of Causal Non-Separability

If we adopt a realist attitude towards causal non-separability, the nature of the related indefiniteness of causal orders will very much depend on the exact meaning assigned to the process matrices characterizing causal non-separability. In the case of metaphysically indefinite causal orders, the world itself is such that causal order among events is ontologically indefinite, independently of any observer. This claim needs to be further clarified, e.g. by relying on already existing metaphysical tools developed by previous work in the field of metaphysical indeterminacy (Wilson 2013; Barnes and Williams 2011), and in particular on its application to quantum theory (Calosi and Wilson 2019; Calosi and Mariani 2020; Calosi and Wilson 2021). Quantum theory seems to violate a rather standard principle regarding the way in which properties are instantiated by physical systems. Contrary to what happens in classical physics, where every quantity gets assigned a definite value at all times, quantum theories are affected by what has been called *lack of value-definiteness* (LVD). In short, LVD indicates that quantum observables do not always possess precise values. LVD can be easily grasped by looking at the standard way of assigning values to physical systems given the quantum formalism, the so-called Eigenstate-Eigenvalue Link (EEL):

EEL. A physical system s has a definite value v of an observable $\mathcal{O}$ *iff* s is an eigenstate of $\mathcal{O}$.
Following Calosi & Wilson (2018), we can provide the following threefold classification of cases of LVD in quantum theory:

Superposition. A linear combination $|\psi\rangle = q_1 |\phi_1\rangle + q_2 |\phi_2\rangle$ of different eigenstates $|\phi_1\rangle$ and $|\phi_2\rangle$ of an observable $\mathcal{O}$ is not always an eigenstate of $\mathcal{O}$. If a system S is in $|\psi\rangle$ it does not have a definite value of $\mathcal{O}$.

Incompatible Observables. Consider two observables $\mathcal{O}_1$ and $\mathcal{O}_2$. The observables commute *iff* $[\mathcal{O}_1, \mathcal{O}_2] = \mathcal{O}_1\mathcal{O}_2 - \mathcal{O}_2\mathcal{O}_1 = 0$. If they do not, they are *incompatible*. If two observables are incompatible, they do not share all the same eigenstates. Thus if S is in one such non-shared eigenstate of $\mathcal{O}_1$ ($\mathcal{O}_2$), it follows that it does not have a definite value for $\mathcal{O}_2$ ($\mathcal{O}_1$).

Entanglement. Consider an *entangled* system S_{12} composed by S_1 and S_2 with corresponding Hilbert space $\mathcal{H}_{12} = \mathcal{H}_1 \otimes \mathcal{H}_2$. S_{12} might be in an eigenstate $|\psi\rangle$ of $\mathcal{O}_{12} = \mathcal{O}_1 - \mathcal{O}_2$ that is neither an eigenstate of $\mathcal{O}_1$ nor an eigenstate of $\mathcal{O}_2$—with $\mathcal{O}_1$ and $\mathcal{O}_2$ defined on $\mathcal{H}_1$ and on $\mathcal{H}_2$ respectively. Both S_1 and S_2 will therefore lack a definite value for the corresponding observables.

Consider that, in each of the above, applying the EEL entails that one or more observables do not always possess a definite a value. Such lack of definiteness has been taken at face value as to indicate the existence of an ontological kind of indeterminacy (a.k.a. *metaphysical indeterminacy*, henceforth MI), namely one that we cannot explain away as due to our ignorance or to semantic indecision. According to Calosi and Wilson (2019), MI is pervasive in quantum theory, and affects in one way or another every interpretation of quantum theory. We shall notice, however, that this claim is not so straightforward, and requires many details that we cannot enter here. For one, consider that the argument leading from LVD to the existence of quantum indeterminacy is essentially based on the EEL. The EEL, however, is rejected by any interpretation of quantum theory other than the Orthodox one. Therefore, in order to establish the existence of quantum indeterminacy in the context of other interpretations of the theory it seems that much more needs to be said. For our purposes, however, we simply notice that similar arguments have been put forward in recent years in many of the existing interpretations,[14] thus showing that, if not forced upon us, MI is at least to some extent suggested by quantum theory, and could then be a useful explanatory tool.[15]

One of the major problems with accepting the existence of quantum MI is that the very notion of ontological indeterminacy has been considered for many decades incoherent. Lewis (1986) was famously against this notion, claiming that "the only consistent account of indeterminacy is one that locates it in either our thought or our language". Moreover, Evans (1978) has influentially argued that indeterminate identity is contradictory, and many philosophers believed that indeterminate identity is required to make sense of MI. For all these reasons, philosophers have long been sceptical towards MI. This situation has started to change in the last decade, when several proposals have been developed as consistent ways to make sense of this idea. Two quite distinct families of approaches should be mentioned: the *meta-level* views, and the *object-level* views. Very roughly, the distinction between them is the following. According to the former, indeterminacy is understood as wordly unsettledness between fully precise alternatives. Therefore, on this view, there is MI when it is indeterminate which determinate state of affairs obtain. According to the latter, the *object-level* view, indeterminacy is understood as the obtainment of an indeterminate state of affairs. Thus, on this view, there is MI when an indeterminate state of affairs (determinately) obtains. Both approaches to MI have been exploited in order to make sense of the lack of value-definiteness in quantum theory, although it is fair to notice that the *object-level* view seems to be preferred (see Calosi and Mariani 2020 for discussion).

Quantum MI has been so far discussed only in the context of non-relativistic quantum theory. Nonetheless, notice that the main arguments for its existence rely on certain features of the theory that we expect to find in any quantum theory, quantum gravity included. The major reason for such a pervasiveness of quantum MI is arguably that this view proposes an ontological account of superposition states. Consequently, it also seems quite natural to apply these tools to the case of a superposition of causal orders emerging in the PMF. To that end, we shall first require that *every* causal order expressed (or represented) by a given process matrix is to be taken as objective, i.e. independent from observers (in some standard sense). This assumption is largely justified if we consider that realism towards the PMF basically means, if anything, that this formalism gives us a language for expressing causal claims in the most generalised way (as input-output physical operations).

As we have shown, causally non-separable processes that are physically implementable display superpositions of indefinite causal orders which result from the entanglement of the causal structure with an ancillary system's state. Despite some technical differences between this case and that of indeterminacy in standard QM (differences that do not concern us here), this situation could be analysed according to the same rationale found in Calosi and Mariani (2021), namely by interpreting such superpositions as instances of metaphysical indeterminacy. To recall, in the standard case a given observable may lack a *unique* determinate property, say *spin up* or *spin down*, while still instantiating the relevant determinable, say $spin_x$. In the case at hand, instead, we would take the determinable to be something like *event E being causally connected with event F*, and the corresponding determinates to be *E causing F* and *F causing E*.

[14] In particular, notice that in the context of spontaneous collapse interpretations of QM, indeterminacy can arise even by revising the EEL. See, e.g.: Lewis (2016); Albert and Loewer (1996); Mariani (2022). For a critique, see Glick (2017).

[15] A reviewer points out—we think correctly—that appealing to indeterminacy here does not provide a further explanation as to why the indeterminacy occurs. In a way, the existence of the indeterminate states of affairs is to be taken as a brute fact. However, what the accounts of metaphysical indeterminacy can do is to elucidate and explain what *it means* for a state of affairs to be indeterminate, and to to distinguish indeterminate from determinate states of affairs. It is in this sense that we contend the accounts can be useful tools. We thank the reviewer for inviting us to say more on this.

As we have shown, causally non-separable processes instantiate the above determinable while they do not uniquely instantiate the corresponding determinates.[16] As a result, superposition of causal orders can *in principle* be interpreted as an instance of metaphysical indeterminacy in the same way as it is the superposition of values for standard quantum observables. The crucial assumption we are making for such an analogy to hold is obviously that there is a genuine *determinable-determinate* relation involved when we think of a causal relation between two distinct events. Notice however that, if the existence of a certain determinable property is to be taken seriously whenever there exists a physical observable that corresponds to it, our assumption looks justified since in the case of causally non-separable processes there is indeed an observable corresponding to the causal order.[17]

The main conceptual difference between indeterminacy of quantum states and that of causal orders is that in the standard case the indeterminacy affects the *state* of a given system and its properties. Here, instead, the indeterminacy affects the causal relations among systems. This difference is quite crucial for our purposes. Indeed, consider that metaphysical indeterminacy in the objective causal order between events seems to point towards indeterminacy in the spacetime structure itself (given some plausible assumptions concerning how causal structures relates to spacetime structures). Thus, the result of applying the tools of quantum MI to the PMF, along with the assumption that this formalism faithfully represents the objective causal structure of the world, seem to suggest that the spacetime structure is itself indeterminate. Of course, the

[16] It seems safe to presume that the resulting indeterminacy would be of the *glutty* kind, with both determinates instantiated at the same time. The *gappy* version seems ruled out by the simple fact that, if neither E *causes* F nor F *causes* E are instantiated, the whole causal structure displayed by a causally non-separable process could not be empirically tested in the first place.

[17] The order in which the transformations A and B are applied on the target system can be seen as a quantum property of the particular process that describes the quantum switch (for which, by definition, the initial quantum state of the control system is fixed in a superposition of states (in the $\{|0\rangle, |1\rangle\}$ basis)). We note that property q, such that $q = 1$ means "The target system has gone through laboratory A and then laboratory B", and $q = 2$ means "The target system has gone through laboratory B and then laboratory A". By construction of the QS, the observable corresponding to the property q can be measured by measuring the state of the control system (in the $\{|0\rangle, |1\rangle\}$ basis). The corresponding observables $\mathcal{O}$, $\mathcal{O}_{\mathcal{AB}}$ and $\mathcal{O}_{\mathcal{BA}}$ are mathematically expressed as follows:

$$\mathcal{O} = \mathcal{O}_{\mathcal{AB}} + \mathcal{O}_{\mathcal{BA}} = |0\rangle\langle 0| + |1\rangle\langle 1| = \mathbb{1} \tag{3}$$

$$\tag{4}$$

with

$$\mathcal{O}_{\mathcal{AB}} = |0\rangle\langle 0| \tag{5}$$

$$\mathcal{O}_{\mathcal{BA}} = |1\rangle\langle 1| \tag{6}$$

The observables $\mathcal{O}_{\mathcal{AB}}$ and $\mathcal{O}_{\mathcal{BA}}$ can be applied on the process $|W_{QS}\rangle$ itself, acting as a measurement of property q. First, it can be showed that $|W_{QS}\rangle$ can be expressed as follows:

$$|W_{QS}\rangle = \frac{1}{\sqrt{2}}(|\psi\rangle^{A^I}|\mathbb{1}\rangle\rangle^{A^O B^I}|\mathbb{1}\rangle\rangle^{B^O F^t}|0\rangle^{F^c} + |\psi\rangle^{B^I}|\mathbb{1}\rangle\rangle^{B^O A^I}|\mathbb{1}\rangle\rangle^{A^O F^t}|1\rangle^{F^c}) \tag{7}$$

with $|\psi\rangle^{A^I}$ ($|\psi\rangle^{B^I}$) being the quantum state of the target system at the entrance of laboratory A (B), $|0\rangle^{F^c}$ and $|1\rangle^{F^c}$ are the quantum states of the control system at the entrance of the third party's laboratory (Fiona's), and $|\mathbb{1}\rangle\rangle^{XY}$ is the Choi vector of the identity channel sending the output quantum state of laboratory X on the input of laboratory Y.

If we apply, say the observable $\mathcal{O}_{\mathcal{AB}}$ on W_{QS}, we indeed "project" the process W_{QS} on the process W_{QS}^{AB} which instantiate a definite causal order in which A causally precedes B:

$$\frac{\mathcal{O}_{\mathcal{AB}}|W_{QS}\rangle}{\sqrt{\langle W_{QS}|\mathcal{O}_{\mathcal{AB}}\mathcal{O}_{\mathcal{AB}}|W_{QS}\rangle}} = |\psi\rangle^{A^I}|\mathbb{1}\rangle\rangle^{A^O B^I}|\mathbb{1}\rangle\rangle^{B^O F^t}|0\rangle^{F^c} = |W_{QS}^{AB}\rangle \tag{8}$$

Similarly, applying the observable $\mathcal{O}_{\mathcal{BA}}$ on W_{QS} will project the process on W_{QS}^{BA} which instantiate a definite causal order in which B causally precedes A.

most natural reaction to this is simply to see in the above arguments a *modus tollens*, and so to reject one of the premises. However, as we will argue in the next section, the notion of *indeterminate spacetime* may be useful in the context of QG as well. If we are right, this would not only show that this notion should be taken seriously, but would also indirectly reinforce the argument just given by suggesting a certain continuity between PMF and QG.

4 Quantum metaphysics and quantum gravity

The aim of this section is to explore the relevance in the quantum gravity context of the quantum metaphysics tools and the recent work in quantum foundations we have discussed in sections 2 and 3. The main research programs in quantum gravity (QG) tend to suggest in one way or another that most (if not all) standard spacetime structures are not fundamental but emergent (Huggett and Wüthrich 2013). This radical suggestion raises two main (sets of) philosophical issues (which, to some extent, run in parallel with the main physical and technical issues in QG). The first concerns the sense in which spacetime features can emerge from non-spatiotemporal structures, while the second is about the very characterization of a non-spatiotemporal physical ontology. A functionalist perspective has been recently articulated in order to elucidate the emergence issue: the idea is that spacetime functionally emerges from the non-spatiotemporal in the sense that under the right circumstances, the quantum gravitational structures can play the relevant spatio-temporal roles (Lam and Wüthrich 2018).

It is interesting to note that, if functionalism has a wide range of applications in philosophy of science, this spacetime functionalism strategy that aims to provide a conceptual framework for the emergence of spacetime in QG is partly inspired by quantum metaphysics, more precisely by the functionalist understanding of standard 3-dimensional situations within wavefunction realism (see Lam and Wüthrich 2018, 41 as well as references therein). To a certain extent, this case exemplifies a fruitful link between quantum metaphysics and QG.

Similarly, the metaphysical tools of structuralism, holism and indeterminacy we have discussed in section 2 can help to characterize a physical ontology in non-spatio-temporal terms.[18] Indeed, to the extent that approaches to QG aim to be quantum theories, it is largely expected that quantum entanglement and Bell-type correlations remain a central feature at the QG level. For instance, quantum entanglement plays a central role in loop quantum gravity (LQG) and group field theory, where there is a precise sense in which quantum entanglement constitutes a glueing relation among fundamental non-spatiotemporal degrees of freedom (e.g. see Baytaş et al. 2018 and Colafranceschi and Oriti 2021). More broadly, quantum entanglement is also

[18] In the light of our discussion, it looks quite natural to consider in more details how the metaphysics of structuralism, holism, and coherentism interact with the hypothesis of quantum indeterminacy. This is an intricate issue, and although we do not aim to provide a systematic view in this paper, we believe it is important to provide a few lines on our own perspective on this. What is common to the various metaphysical strategies for interpreting entanglement is the attempt to provide an *explanation* to some peculiar relations of dependence between distinct systems. It is in fact no surprise that the discussion on entanglement gets intimately connected to the issue of *fundamentality*, which is seen in contemporary philosophy as a way of regimenting the notion of explanation itself. On the other hand, it seems quite natural to interpret much of what goes on in the literature on quantum indeterminacy as an attempt to indicate an inherent lack of completeness in our explanations of certain physical facts, for instance the systems in a superposition state. But more importantly, if we consider the indeterminacy which affects entangled systems, it appears immediately clear that by adding (indeterminate) facts about the component systems we do not get to a full explanation of the dependence relations exhibited by the composite system. Therefore, one would expect that the lack of completeness in the explanation one finds with quantum indeterminacy could be supplemented by the specific metaphysics of entanglement. The details will then depend on the specific metaphysics one has in mind among the ones on the market. For instance, take structuralism, according to which (very roughly!) entanglement can be explained by positing fundamental relations on top of (or along with) the physical objects. By adding quantum indeterminacy to the picture, one could expect that the fundamental relations of entanglement (instantiated by the composite system) provides an explanation to the existence of the indeterminacy affecting the component systems. We thank an anonymous reviewer of this journal for a very insightful discussion and for inviting us to say more on this important issue.

expected to play a role in the very emergence of spacetime, as suggested for instance in the context of the AdS/CFT string duality by the Ryu-Takayanagi relationship between entanglement entropy (in the boundary) and area (in the bulk).[19]

Now, to the extent that the structuralist and holistic accounts of quantum entanglement do not depend on spacetime, they can be articulated in the context of quantum gravity, and so may help to characterize its non-spatio-temporal ontology. Within the structuralist perspective, this latter is then understood in terms of entanglement structures, that is, in terms of networks of entanglement relations among (entangled) quantum gravitational subsystems, which are interdependent on one another. Since, in this context, quantum entanglement is the glueing relation holding things together—a kind of Lewisian worldmate relation that would be non-spatio-temporal (see the discussion in Darby 2009; more recently, see Jaksland (forthcoming), who uses the notion of 'world-making' relation)—quantum gravitational subsystems are entangled, and hence interdependent, in virtue of being part of the same world (or in virtue of giving rise to the same spacetime).[20] This is an interesting metaphysical implication of the structuralist perspective, suggesting some non-trivial insight into the nature of the physical world as described by some prominent current QG approaches.

The holistic account of quantum entanglement provides a slightly different (but not necessarily incompatible) perspective, emphasizing the ontological priority of the whole entangled quantum gravitational structure (over its entangled parts or subsystems). Following Ismael and Schaffer (2020)'s common ground strategy (see §2.2), it can then be argued that the quantum gravitational whole (e.g. the total, entangled spin network or spin foam structure in LQG) is best understood as the common ground of its quantum gravitational subsystems, some of which corresponding to spacetime regions. This naturally leads to consider the total, entangled quantum gravitational structure as the common ground for spacetime itself. This view does not necessarily clash with the functional emergence mentioned above, but can be seen as capturing an additional aspect of the relationship between the emergent spacetime and the underlying quantum gravitational structure.

The recent work in quantum foundations discussed in section 3 also connects to certain suggestions from research in QG. In order to articulate this potential link, we start by emphasising the connection between spacetime and causal structures.

The link between causation and spacetime has been extensively discussed in several theories, both in metaphysics and in philosophy of science. To make but one prominent example, consider that in the standard Lewisian supervenience picture causation emerges from the mosaic of actual events plus spatiotemporal relations among them. In a way, Lewis starts from spacetime to get to causation, but in principle the converse can be done too. For instance, in the context of QG, causal set theory aims to recover spacetime, as described by (sectors of) general relativity, from fundamental, non (fully) spatio-temporal causal structures.[21] No matter what the priority relation between spacetime and causation is—or whether there is such a relation, or whether they are best conceived as being metaphysically on a par—nobody would deny that there is an intimate connection between spacetime and causation.

From this consideration, and under the assumption that the causal orders encoded in causally nonseparable process matrices are objective, indefinite causal orders can be seen as reflecting indefiniteness in the spacetime structure itself. In this regard, as discussed in section 3.1, Zych et al. (2019) introduced a thought experiment called gravitational quantum switch, for which

[19] See for instance Ryu and Takayanagi (2006) and Van Raamsdonk (2010). See Jaksland (forthcoming) for a philosophical discussion of how distance can be recovered from quantum entanglement, and Ney (2021*a*) for a critical perspective. The Ryu-Takayanagi formula is expected to generalize beyond the AdS/CFT correspondence, such as within the framework of LQG and group field theory, see Chirco et al. (2018).

[20] There may well be sectors of QG that do not give rise to any classical spacetime, and in particular that may not be entangled with anything else. This then raises the question of what makes them part of the same world.

[21] A strong motivation for causal set theory is provided by a series of important results in general relativity basically showing that the geometry of spacetime is fixed by its causal structure (up to a conformal factor—and assuming the condition of past and future distinguishability; see Huggett and Wüthrich (forthcoming, ch. 2) for a recent philosophical discussion of causal set theory, as well as references therein).

indefiniteness of causal order would arise from an actual superposition of spacetime regions in a quantum gravity context.[22] This clearly resonates with the idea, present in many approaches to QG, that spacetime itself could be in a quantum superposition. It also shows that, while indefinite causal orders point towards a tension between a classical background spacetime and quantum features such as superposition and entanglement, the implications of indefinite causal orders should be considered within the context of a fully gravitational theory.

The route leading from causal indefiniteness to spacetime indeterminacy is not straightforward, yet it may give us some initial motivations for exploring the possible role (and nature) of indeterminacy in approaches to QG. First, recall from §3.2 that one of the three instances of quantum indeterminacy individuated in the literature concerns the *non-commutativity* of the algebra of operators. This feature is an essential component for any quantum theory, QG included. A working hypothesis consists in individuating first the relevant operators in the theory that arguably describe spacetime properties. By doing so, and having shown that these do not commute, we would get an initial grasp on how superposition of spacetime regions could emerge. In a recent paper, Cinti et al. (2021) consider in detail two cases of non-commutative operators, one in string theory (ST) and one in LQG, that can both lead to spatiotemporal superpositions. In both cases, it can be shown that the operators describing geometric properties (the centre of mass position/momentum in ST, and the minimal length in the case of LQG) do not commute. By analogy with the standard argument given by Calosi and Wilson (2019), we could take these properties, along with the systems instantiating them, as instances of metaphysically indeterminate states of affairs. Of course, such a line of reasoning is to be developed further. For one, consider that the standard argument for quantum indeterminacy is based on the EEL (as shown in §3.2). Clearly though, nothing like the EEL is explicitly endorsed in the approaches to QG we have mentioned. Although this is an interesting issue *per se*, it has to be noticed that even in the case of QG, we would likely need to provide a way to ascribe values to physical properties. It may be expected that at least in some way of doing so, the argument based on the EEL could then be given.

Allowing for indeterminacy in the fundamental spacetime structure of QG may also provide a novel, rather provocative perspective on the most debated philosophical issue in the QG context. Indeed, as we mentioned, it is widely argued that spacetime is not fundamental in QG. This conclusion often relies on the assumption that quantum superpositions of (spacetime-like) structures at the fundamental level cannot be understood in any spatio-temporal sense. For instance, quantum superpositions of spin networks (or spin foams) are generic in LQG, and this is often taken as indicating that spacetime vanishes at this level, and so is not fundamental (see e.g. Rovelli 2004, § 6.7.1 in the physics literature, and Huggett and Wüthrich 2013, § 2.3 in the philosophy of physics literature). Up to now, and to the best of our knowledge, the interpretative and metaphysical strategy of considering (certain) spacetime structures as being indeterminate in QG (in some appropriate sense) has not been seriously investigated (at least in the current philosophy of physics literature). In certain cases, it seems that spacetime fundamentality is rejected because spacetime indeterminacy is rejected.[23] We notice that such a rejection of spacetime indeterminacy is only justified if we have good reasons to believe that this notion does not make sense, or even that it is inconsistent. However, there are now various proposals to make sense of metaphysical indeterminacy, and this notion has been argued to be

[22]Zych et al. (2019) emphasize that spacetime in the standard quantum switch is classical, in contrast to the gravitational quantum switch. Indeed, indefinite causal order in the quantum switch is the result of a temporal order entangled with some ancillary system, while the spacetime background is classical. This leads to several differences with the gravitational version, in which one has an explicit superposition of spacetime regions, originating from a mass superpositions linked to spacetime via the principles of general relativity. In the standard quantum switch, only very specific causal orders escape to a classical description, and the time of the events depends on their temporal order. This is not the case in the gravitational quantum switch, in which an entire region of spacetime is non-classical (in a quantum superposition), and within this region, the time of events does not depend on their temporal order.

[23]The situation is actually more subtle than that: as we have mentioned earlier, there may well be sectors of QG that do not give rise to any classical spacetime (e.g. in some limit), and so that are not spatio-temporal in a way that is not directly related to quantum indeterminacy (thanks to Daniele Oriti for highlighting this point to us).

explanatory useful already in the context of non-relativistic QM. This points to the intriguing suggestion that what is taken as the non-fundamentality of spacetime (or of certain spacetime features) in the QG context could also be understood in terms of some spacetime indeterminacy. Articulating this suggestion in details and its implications for the debates around the emergence of spacetime thus constitutes a worthwhile project that may shed an interesting new light on spacetime in QG.

5 Conclusion

A great deal of the recent philosophical discussions on non-relativistic quantum mechanics can be seen as an attempt to provide an *interpretation-neutral* understanding of the most crucial features of this theory, namely *entanglement* and *superposition*. The line of reasoning we developed in this paper starts by considering how pervasive these features are, even once we look well beyond quantum mechanics and we start taking into account the recent approaches to QG. As we have shown, and despite QG being in its early stage of development, these key aspects of non-relativistic quantum mechanics, instead of being erased or overcome, will likely remain crucial for our understanding of the natural world. The main suggestion of this paper is that we should look at the metaphysical views that have already been developed within the philosophy of quantum mechanics to provide a more systematic understanding of these features, and we apply similar approaches to QG. In that spirit, we first reviewed two stances, holism and structuralism, as strategies to interpret quantum *entanglement*. We argued that, to the extent that these views are already meant to describe non-spatiotemporal features of reality, they can be used as a conceptual basis for developing an ontology for QG. Second, we have shown how the notion of quantum indeterminacy has been articulated in the context of standard quantum mechanics as an explanation for *superposition* states. Similarly, this notion has proven useful, as we have argued in details, to make sense of the notion of *causal superposition* within the process matrix formalism. This can arguably lead, as we suggested, to a form of spacetime indeterminacy which may provide a novel perspective on the thorny issue of the emergence of spacetime in QG.

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