A new indeterminacy-based quantum theory

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Abstract

I propose a novel (interpretation of) quantum theory, which I will call Environmental Determinacy-based or EnD Quantum Theory (EnDQT). In contrast to the well-known quantum theories, EnDQT has the benefit of not adding hidden variables, and it is not in tension with relativistic causality by providing a local causal explanation of quantum correlations without measurement outcomes varying according to, for example, systems or worlds. It is conservative, and so unlike theories such as spontaneous collapse theories, no modifications of the fundamental equations of quantum theory are required to establish when determinate values arise, and in principle, arbitrary systems can be in a superposition for an arbitrary amount of time. According to EnDQT, at some point, some systems acquired the capacity to have and give rise to other systems having determinate values, and where this capacity propagates via local interactions between systems. When systems are isolated from the systems that belong to these chains of interactions, they can, in principle, evolve unitarily indefinitely. EnDQT provides novel empirical posits that may distinguish it from other quantum theories. Furthermore, via the features of the systems that start the chains of interactions, it may provide payoffs to other areas of physics and their foundations, such as cosmology.

1 Introduction

The measurement problem[1] can be seen as arising from interactions in quantum theory (QT), which, without introducing some extra assumptions, can lead the quantum state of a macroscopic system to be in a superposition, where the latter doesn't correspond to a physical magnitude with determinate values. However, we know from classical physics and experimental evidence that this can't be the case at macroscopic scales.

In the search for a solution to this problem, as far as we know, a conservative approach should seek to fulfill the following desideratum:

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[1] See, e.g., Maudlin (1995) and Myrvold (2018).

*) A precise criterion for when determinate values arise that doesn't modify the fundamental equations of QT like spontaneous collapse theories or postulates a special force that causes such collapse like gravitational collapse theories.[2] This is because we currently have no clear evidence for that.

Similarly, given some adequate conditions, it's plausible to consider that any system could, in principle, evolve unitarily indefinitely regarding any physical degree of freedom. So, this conservative solution should also fulfill the desideratum of

**) Allowing for any system to, in principle, be in a superposition of quantum states associated with any physical magnitude for an arbitrary amount of time.

I will consider that an approach that fulfills *) and **), fulfills UT). A conservative strategy to fulfill UT) should aim to allow, in some circumstances, for any system to be placed in a superposition that corresponds to any physical magnitude for an arbitrary amount of time, even large target systems interacting with equally large systems. Then, perhaps consider that only interactions with specific systems lead a target system S to have determinate values, where these interactions are described quantum mechanically via decoherence.[3] Decoherence doesn't modify the fundamental equations of QT as stated by Dirac and von Neumann[4] and thus allows for a conservative approach. Furthermore, we have evidence that interactions between quantum systems involving decoherence play some role in giving rise to determinate outcomes. But interactions with which specific systems? Again, we could be conservative and appeal to interactions only with systems that were decohered shortly before the decohering interaction with S started, where these later systems were decohered by other systems that were also previously decohered, and so on. However, this idea seems to start giving rise to an infinite regress and some vagueness regarding the details of these interactions.

To deal with these issues, we could appeal to some plausible special systems that establish when these interactions began, a more precise structure that represents such interactions, and simple and conservative rules that establish how determinate values arise from them. Environmental Determinacy-based Quantum Theory (EnDQT) will pursue this strategy by introducing a network structure whose edges represent interactions between certain systems represented via decoherence, and that roughly establishes when these interactions give rise to them having determinate values. These interactions form what I will call stable determination chains (SDCs). Furthermore, SDCs started somewhere. As I will argue, the first systems with determinate values arose in the past through special systems. These systems started chains of local interactions over time and space, which are the SDCs. By interacting with these systems, a system acquires a determinate value of an observable during these interactions and the capacity

[2] See, e.g., Ghirardi & Bassi (2020), Oppenheim (2023), and Diósi (1995).

[3] See, e.g., Schlosshauer (2007) and references therein.

[4] See, e.g., Barrett (2019, Ch. 4).

to give rise to other systems having determinate values in interactions with them, which allows these later systems to lead other systems to have determinate values, and so on. So, these chains allow determinate values to propagate between systems and may persist over spacetime, where it is indeterministic which value will arise among the possible ones. These interactions are modeled via decoherence; thus, as I have said, they don't lead to any modification of fundamental equations of QT. The systems that don't belong to this network or don't interact with it at some point can, in principle, unitarily evolve indefinitely.

I will argue for one possibility for what these systems that start SDCs are via inflation, which is arguably the dominant paradigm in modern cosmology. This would provide a new role for the systems that start inflation. I will also argue that this assumption regarding these systems may have diverse philosophical advantages and possible payoffs to other areas of physics. For example, it might provide a more fundamental role to the inflaton field based on the fundamental features of quantum phenomena, as well as the universe's initial state that is often considered to be the source of temporal asymmetries (i.e., the Past-Hypothesis[5]). It might also provide further advantages to EnDQT relative to other quantum theories.

Furthermore, another important desideratum that a conservative approach to QT should achieve is

LC) In the domains where we know where to apply QT, not being in tension with relativity by not favoring a reference frame or leading to action at a distance like, for example, Bohmian mechanics,[6] and don't add hidden variables that lead to retrocausality or superdeterminism.[7]

For EnDQT to achieve LC), first, I will argue that it is able to deal with Bell's theorem by providing a local explanation of quantum correlations via Quantum Causal Models (section 3).[8]

Second, EnDQT will adopt a perspective on quantum states where they don't literally and directly represent some physical entity; instead, together with other elements of the theory, such as observables and networks representing SDCs, they help make inferences, gain knowledge about and indirectly represent how systems evolve and affect each other, how SDCs evolve, when systems acquire or not determinate values, how systems evolve outside interactions, etc.

So, contrary to spontaneous collapse theories, which reify the quantum state, there is no literal physical collapse of quantum states in a superposition. Instead, there is an epistemic local state update of the original state of the target system that can be implemented upon decoherence of this system by its environmental systems that belong to SDCs, under their local interactions. These interactions give rise indeterministically to these systems having a determinate value. So, given that EnDQT doesn't reify quantum states, in Bell-type scenarios, the

[5]Albert(2000).

[6]See, e.g., Goldstein (2021).

[7]See, e.g., Hossenfelder & Palmer (2020) and Friederich & Evans (2019).

[8]See, e.g., Costa & Shrapnel (2016), Allen et al. (2017), and Barrett et al. (2019).

measurements of Alice on her system don't non-locally affect the space-like separated system of Bob and vice versa.

This view on quantum states also considers that decoherence shouldn't be interpreted as representing a process of branching of the wave-function/quantum states but rather as a process in which, under local interactions, an environmental system that belongs to an SDC gives rise to another system having determinate values indeterministically. Furthermore, MWI-like views consider that decoherence in large enough regions of spacetime establishes criteria for systems to have determinate values of an observable. However, as we will see in the next section, EnDQT, in a sense, considers that such criteria form necessary but not sufficient conditions for determinate values to arise. This is because it matters if the environmental systems involved in this process belong to an SDC.

A common way to fulfill UT) and LC) is by adopting a relationalist interpretation in which the outcomes of Alice or Bob are relative to, for example, worlds, private perspectives, environments, simultaneity hyperplanes, etc.[9] However, for EnDQT these outcomes and all physical states will be absolute/non-relationalist. So, EnDQT,

NR) Doesn't adopt a relationalist interpretation of QT.

Given the well-known issue of probabilities of the MWI,[10] this might be deemed a desideratum and advantage of this view. Also, it's unclear if relationalism in a single-world is desirable. Furthermore, as I will argue (section 3), to my knowledge, EnDQT is currently the only QT that doesn't modify the fundamental equations of standard QT,[11] that is able to provide a local, non-hidden variable, non-relationalist common cause explanation of quantum correlations like the ones in Bell scenarios and the so-called extended Wigner's friend scenarios.[12][13]

So, EnDQT should be considered a conservative approach to QT because, as I have said, it doesn't modify the fundamental equations of standard QT, which I think is a virtue. Furthermore, it has the great benefit of fulfilling all of the above desiderata and providing other payoffs. I will start by explaining the basics of EnDQT, argue that it provides UT) and start building the case that it provides LC) and NR) (section 2). In section 3, I will argue that EnDQT provides LC) and NR) by showing that it provides a non-relational, local, and non-superdeterministic/non-retrocausal explanation of quantum/Bell-type correlations. In section 4 and throughout the text, I will suggest future

[9] See, e.g., Wallace (2012), Di Biagio & Rovelli (2021), Healey (2017), Dieks (2019), and Ormrod & Barrett (2024).

[10] See, e.g., Albert (2010) and Price (2010).

[11] It might be objected that quantum causal models modify the fundamental equation of QT. Note that I don't regard these models as a modification of equations of standard QT, but as a generalization or variation.

[12] I will focus on the scenarios from Bong et al. (2020) and Brukner (2018).

[13] Contrary to the suggestions by others (e.g., Cavalcanti & Wiseman, 2021, Schmid et al., 2023, and Yīng et al., 2023), we don't need to adapt QCMs to a relationalist approach, which might be considered as an advantage of this view.

developments. To simplify, I will mostly assume non-relativistic QT and the Schrödinger picture Hilbert space-based finite dimensional QT.

2 Main features: four conditions and two hypotheses

I will start by presenting the main features of this view and show why it fulfills UT). Also, I will begin building the argument for why it allows for LC) and NR). The main features of EnDQT presented here[14] involve four conditions and two hypotheses about how the capacity to have determinate values, and to provide other systems that capacity, spreads through interactions. I will start by explaining the four conditions, which will require that I give an account of the role of quantum states (which was already mostly given in the previous section), systems, interactions, decoherence, and how having a determinate value and allowing other systems to have determinate values propagate via interactions inferred via decoherence, where specific chains of interactions are formed. Afterward, I will present the two hypotheses that support EnDQT, where the second hypothesis involves an account of what the systems that start SDCs could be. I will mention some empirical predictions that EnDQT provides throughout this section.

To simplify, throughout this paper, I will employ the familiar view that what exists are systems; a system is characterized by a collection of observables, and an observable of a system sometimes has a determinate value, where its eigenvalues represent the latter. This leads systems to "have a determinate value." Or its observables sometimes have indeterminate values, leading systems to "have an indeterminate value." Interactions are represented via QT, and some of them (which are represented via decoherence) lead systems to have a determinate value of an observable.

Different ontologies can make the above view more precise and allow EnDQT to adopt a more robust realism. One may understand determinate values of systems as referring to flashes that arise or are produced under interactions, i.e., an ontology of local events in spacetime (but differently from spontaneous collapse theories and with a different interpretation of the quantum state), but there are other ways.[15] We could also view observables as representing determinables (e.g., position, energy, etc.) and determinate values as representing determinates of those determinables. Interactions give rise to a determinable with a determinate. Systems are collections of determinables, which at different moments of time, have determinates or not (e.g., having a spin-z with or without a determinate of spin-z) depending on their interactions like in the gappy version of quantum indeterminacy presented in Calosi & Wilson (2018). Quantum

[14]We will see that there are other versions of EnDQT if we vary these hypotheses and conditions, but we will see that this version so far is enough to fulfill the desiderata of Section 1.

[15]The flash ontology was first proposed by Bell (2004) and named by Tumulka (2006).

indeterminacy arises when we have a state of affairs constituted by a system lacking a determinate of a determinable.[16]

I will consider a (quantum) system as occupying local regions of spacetime and being represented at a moment in time by (an equivalence class of) quantum states and observables that act on the quantum states that belong to the Hilbert space of the system. Given the aim of not being in tension with relativistic causality, I will be interested in an ontology constituted fundamentally by local systems and their local interactions,[17] and hence on systems whose observables act on quantum states concerning a single region of space.[18] I will be very liberal about what constitutes a system. For example, an atom's internal degrees of freedom could constitute one.

Concerning the observables of a system S, for the sake of parsimony and for the purposes of allowing for a local theory (more on this in section 3), I will assume that:

Any observable O of S, including the non-dynamical ones, outside of specific interactions of S involving O, cannot have determinate values but rather have indeterminate values.[19]

A new feature that EnDQT introduces is the determination capacity (DC), which will have the great benefit of allowing for the formulation of some conditions that establish when systems have determinate values, but without modifying fundamental equations of QT and allowing for the fulfillment of the above desiderata. Below, I will explain these conditions, which will establish what it takes for a system to have a determinate value and transmit the DC to others and how the former and the latter are related. I will call them Conservative Determination Conditions (CDCs). There are other possible conditions, but I found these the simplest ones, and they will suffice for the current purposes.

CDC1) The determination capacity (DC) of system X concerning system Y (DC-Y) is the capacity that X has while interacting with Y,

i) to allow Y to have a determinate value under this interaction with X that

[16] Alternatively, we could have an ontology of quantum properties, and this is the one I prefer (see Appendix B).

[17] This assumption can be made more adequate under a quantum field theoretic treatment.

[18] For example, the larger system that forms a Bell pair would be a system localized in multiple regions of space. The quantum state of this system is an eigenstate of non-local observables.

[19] The eigenstates of the non-dynamical observables, which are never observed in a superposition, are typically considered to be subject to superselection rules (see, e.g., Bartlett et al., 2007). These rules can be regarded as prohibiting the preparation of quantum states in a superposition, which are eigenstates of some observable and assume a coherent behavior. Rather than postulating these rules, decoherence in a widespread environment in spacetime might be used to explain this superselection (see, e.g., Earman, 2008; Giulini et al., 1995). This is the perspective taken here. However, one may object to this perspective, and EnDQT can be adapted to allow nondynamical observables of systems to always have determinate values, even when they aren't interacting.

also leads X to have a determinate value and

ii) to provide the DC to Y concerning another system Z (DC-Z) if and only if a) Z starts interacting with X while Y is interacting with X, and b) Y has a determinate value due to X.

So, the DC propagates between systems via interactions because Z can then have the DC concerning a system K (DC-K), if and only if a) K starts interacting with Z while Z is interacting with Y, and b) Z has a determinate value due to Y, and so on for a system L that interacts with K while K interacts with Z, etc.

How does the DC propagates more concretely? The DC propagates between systems via local interactions over spacetime, so interactions only involve systems that aren't spacelike separated, where following the standard way,

For a system X to interact with system Y from time t to t', the quantum states of X and Y must at least be acted by the Hamiltonian of interaction representing the local interaction between X and Y from t to t'.

So, the reason I want X to have DC-Y while interacting with Y, and to provide the DC-Z to Y if and only if a) Z starts interacting with X while Y is interacting with X and b) Z has a determinate value due to Y is that, first, I want to provide clear criteria for systems to give rise to other systems having determinate values and to propagate that capacity to these systems. Without a criterion like CDC1), tracking when systems have the DC would be hard. Second, I also want clear criteria that establish that they can lose that capacity since, given the above desiderata, I want to allow for the possibility of arbitrary systems to be in a superposition for an arbitrary amount of time, even if they are interacting with other systems. So, we want these latter systems to lose that capacity. Third, I want to appeal *only* to (local) interactions represented by QT for systems to have the DC and not some other criteria (except in the case of some special and plausible systems, more on this below), hence a). Fourth, I want such criteria to be plausible in the sense that it is in agreement with what we have in decoherence models and measurement-like situations where system E (such as a measurement device) that gives rise to a system S having a determinate value, before interacting with S, has a determinate value of some observable like we seem to have in the *ready state* of a measurement device, hence b). Note that system Y could give rise to a measurement-like interaction when interacting with system Z. This condition will become clearer when we have all the conditions spelled out.

Now, which interactions give rise to determinate values? Since my aim here is to be conservative, I will use decoherence to represent those interactions because physicists standardly use it to represent measurement-like interactions. I will now briefly explain decoherence and some of the assumptions I will make. I will also highlight with numbers some of the assumptions made in decoherence models, which EnDQT will later justify. Let's consider a system S in the following state,

$$|\psi\rangle_S = \sum_{i=1}^{N} \alpha_i \, |s_i\rangle_S \tag{1}$$

and an environmental system E of S, constituted by many subsystems, interacting strongly with system S. For instance, $|\psi\rangle_S$ could be a superposition of spin-z eigenstates. Furthermore, S will be interacting strongly with the many subsystems with a spin in a specific direction that constitutes E, i.e., the Hamiltonian of interaction dominates the systems' evolution.[20] So, the dynamics will be driven by an interaction Hamiltonian, which governs or describes the interactions between systems that can affect specific observables (i^*)). For simplicity, throughout this article, I will assume this kind of evolution of systems under interactions with their environment.[21] Now, let's assume that S locally interacts with E, where their interaction is represented via the standard von Neumann interaction at least approximately by $|s_i\rangle_S \, |E_0\rangle_E \rightarrow_{\widehat{U}} |s_i\rangle_S \, |E_i(t)\rangle_E$ for all i and

$$\left(\sum_{i=1}^{N} \alpha_i \, |s_i\rangle_S\right) |E_0\rangle_E \rightarrow_{\widehat{U}} \sum_{i=1}^{N} \alpha_i \, |s_i\rangle_S \, |E_i(t)\rangle_E = |\Psi\rangle_{S+E}. \tag{2}$$

The distinguishability between the different states of E concerning its interactions with S can be quantified via the overlap between quantum states $\langle E_i(t) \mid E_l(t)\rangle_E$. The impact of this distinguishability of the states of E on S can be analyzed via the reduced density operator of S, obtained from tracing over the degrees of freedom of E in $|\Psi\rangle_{S+E}$,

$$\begin{aligned} \hat{\rho}_S(t) = \sum_{i=1}^{N} |\alpha_i|^2 \, |s_i\rangle_S \, \langle s_i| + \sum_{i,l=1, i\neq l}^{N} & \alpha_i^* \alpha_l |s_i\rangle_S \, \langle s_l| \, \langle E_i(t) \mid E_l(t)\rangle_E \, + \\ & \alpha_l^* \alpha_i \, |s_l\rangle_S \, \langle s_i| \, \langle E_l(t) \mid E_i(t)\rangle_E \, . \end{aligned} \tag{3}$$

Under a Hamiltonian of interactions describing the interactions between the target system and many systems), and systems having randomly distributed initial states and coupling constants (ii^*)), in decoherence models we obtain that $\langle E_i(t) \mid E_l(t)\rangle_E$ quickly decreases over time until $\langle E_i(t) \mid E_l(t)\rangle_E \approx 0$ when has E is constituted by many systems. The recurrence time of this term (back to not being significantly small in comparison with the other terms) in this case tends to be so large that it can exceed the universe's age, giving rise to a

[20] See, e.g., Cucchietti et al. (2005)

[21] This is the so-called quantum-measurement limit and is typically successful in describing many measurement-like interactions (Schlosshauer, 2007) In this case, the energy scales of the system-environment interaction are much larger than the energy scales associated with the self-Hamiltonians of the system and environment. More complex models of decoherence (see, e.g., Zurek, 2003, Zurek et al., 1993) where the system doesn't interact strongly with the environment, and self-Hamiltonian also has some weight in the evolution of the system, may give rise to different observables with determinate values depending on the initial quantum states. For simplicity, I will not talk about these more complex cases here or analyze how, in these cases, SDCs could be formed.

quasi-irreversible process mathematically speaking. Note that I will provide a distinct and "more pragmatic" sense of irreversibility below concerning other features of the environment that should be distinguished from this sense of irreversibility.

So, when *this particular* quasi-irreversibility occurs for a system S interacting with E being modeled in the above way, I will consider that S was decohered by system E or the above states of S (also often called pointer states) were decohered by the states $|E_i(t)\rangle_E$ of E or by E.

Importantly, note that decoherence here does not necessarily mean the process of destruction of interference but whatever is represented via these models. As it will be clearer, it will only refer to that process when E has the DC. I will call the process that is modeled via decoherence in the sense that the environmental system has the DC, *fundamental decoherence*. More concretely, I will assume that when E has the DC, the reduced density operator $\hat{\rho}_S$ can be used to predict the determinate values and resultant statistics of the consequences of this interaction (i.e., the determinate values of S and E), as well as the timescale in which we can update the state of S to one of the $|s_i\rangle_S$ under decoherence iii*). Relatedly, as it will become clearer below when E has the DC, this model can directly account for the disappearance of interference effects due to S in situations where it interacts with E. So, in this case, when states of the environment become extremely distinguishable under interactions between S and E over time, we have,

$$\hat{\rho}_S \approx \sum_{i=1}^{N} |\alpha_i|^2 \, |s_i\rangle_S \langle s_i| \, . \tag{4}$$

From now on, I will call the states $|E_i(t)\rangle_E$ and $|E_l(t)\rangle_E$ for all i, j with $i \neq j$ when they are distinguishable, i.e., $\langle E_i(t) \mid E_l(t)\rangle_E \approx 0$, simply eigenstates of an observable O' of E because the projectors onto these states will approximately commute with the observable O' of E.

So, given the above, I will assume that

CSC2) Interactions between system X and a set of systems that form a larger system Y, which have the DC, lead system X to have a certain determinate value, where the distinguishability of the physical state of Y concerning the possible determinate values of X allows us to infer if X will have a determinate value among the possible ones and when that happens. Such distinguishability is inferred via the (fundamental) decoherence of X by Y, and where it's indeterministic the values that will arise among the possible ones.

The determinate value of X could be a measurement outcome and the one of Y could be a measurement device. Given the above assumptions and CDC2), we have that

In the simple situations that we will be concerned with here where the Hamiltonian of interaction dominates the evolution of the system, in order for system Y

to have a determinate value v of O, i) the observable O of Y that is monitored by system X that has the DC, and whose eigenstates are decohered by X in the sense above, has to at least approximately commute with the Hamiltonian of interaction representing the interaction between X and Y (commutativity criterion),[22] *and ii) where the eigenvalues of O include v.*

Thus, the determinate values that arise are the ones that are dynamically robust under interactions with certain systems that have the DC. Note that time instants such as t' above or time intervals around t', where a system has a determinate value due to interactions with environmental systems, from now on will be represented and inferred via the time that the overlap terms above go quasi-irreversibly to zero under decoherence due to a system having the DC (i.e., the decoherence timescale). So, the above overlap terms going quasi-irreversibly to zero will allow us to infer if the local interactions between S and the environmental systems that have the DC, succeeded in giving give to S having a determinate value of O. This success is inferred to occur at t' or around t'. Furthermore, it's indeterministic which value S will have among the possible ones, where the latter is given by the eigenvalues of O.[23]

The reader familiar with decoherence might have found the above description of fundamental decoherence as missing a sometimes cited ingredient of decoherence, which is that decoherence is associated with the openness of the environment or is associated with "the entanglement of the degrees of freedom of the system" with inaccessible or uncontrollable environments that make the state of the whole larger system hard/impossible to reverse. I will now relate this feature to fundamental decoherence models. First, let's call the models of decoherence where we don't know if the environmental systems have the DC or that is not specified, *pragmatic decoherence*. In contrast with fundamental decoherence models, pragmatic decoherence models involve other considerations that go beyond the model itself such as if the environment is open or not. *Pragmatic irreversible decoherence models* are models that involve situations where it's considered that is very difficult or impossible to reverse the process represented by them because they concern open environments (which we lack access to) and/or the interaction with many systems that are difficult to control. These are the extra considerations. The processes represented by the pragmatic irreversible decoherence models are the processes that we normally call decoherence. However, along with my explanation of the other CDCs, I will explain below

[22]See Schlosshauer (2007). In more complex models of decoherence (see previous footnote), note that this monitoring may be indirect, such as the decoherence of momentum in more complex models of decoherence than the ones mentioned here (Zurek et al., 1993), where there is direct monitoring of the position. The latter is contained in the Hamiltonian of interaction of the system (but not the former), and that's why it is considered that the decoherence of the momentum is indirect.

[23]For simplicity, I will not address here the case where we don't have maximum distinguishability of the states of the environment E, concerning the states of the target system. Roughly, this case can be inferred by the overlap terms of the environment not being zero or one stably over time. In these cases, the target system won't have a determinate value due to E. See Pipa (2024) for an ontology of quantum properties that addresses this case.

that the processes involving fundamental decoherence resemble, in important ways, the processes represented by the pragmatic irreversible decoherence models. Afterward, I will put the relation between these models in a clearer foundation.

Returning to the CSCs, we can now use CSC2) to spell out CSC1) in terms of fundamental decoherence.

CDC1*)The DC-Y of X is the capacity that X has while interacting with Y,

i) to decohere Y, which leads both systems to have a determinate value. Let's suppose that system S in eq.(2) is an instance of X, and system E is an instance of Y. The possible values of X are represented by the eigenvalues of the observable that the quantum states $|s_i\rangle_S$ of S in eq.(2) are eigenstates of. The possible values of Y are represented by the eigenvalues of the observable that the quantum states $|E_i(t)\rangle_E$ in eq.(2) are eigenstates of and

ii) to provide the DC-Z to Y if and only if ii-a) Z starts interacting with Y while Y is interacting with X and ii-b) Y is decohered by X.

We could suppose that while S in the example above interacts with E, it starts interacting with another system S', which would be an instance of Z. Then, when S is finally decohered by E, it could decohere S' and give rise to both S and E' having a determinate value. Such values would be represented like in the case of eq.(2), but now the target system would be S', and the environment would be S. So, S would have a determinate value when it interacts with E and another when it interacts with S'.

The criteria and some others will allow EnDQT to provide the great benefit of giving criteria for when determinate values arise, but without necessarily modifying the fundamental equations of QT like spontaneous collapse theories or adopting a relationalist view or hidden variables. As we can see, systems with the DC and determinate values propagate through interactions. I will call a chain of interactions between systems that propagate the DC, a stable determination chain (SDC). It is stable because it can be seen as a stable process that gives rise to the spread of determinacy between systems.

Note that, as we can anticipate, in order for a system E to decohere another S, it has to be interacting with other systems that have the DC. Those systems will have to interact with other systems with the DC, and so on. So, we will need many systems for a system S to be fundamentally decohered by E, giving rise to S having a determinate value. These systems will have to interact with S, as well as other members of the SDC. This process starts to resemble a process represented by a pragmatic irreversible decoherence model because we have here a great number of systems whose states will be very hard to control.

Returning to our conditions, given an SDC, we run the risk of an infinite regress because it's unclear where it starts. To circumvent these issues,

CDC3) I will consider that there are two kinds of systems that constitute an

SDC,

-Initiator systems or initiators, which are systems that have the DC concerning any system by default (i.e., they always have the DC-X for any system X), i.e., independently of their interactions with other systems. Because of this, initiators are the systems that start SDCs.

-Non-initiator systems are systems that don't have the DC concerning a system by default but have it due to their interactions with other systems that have the DC.

So, the (fundamental) decoherence of some system S by an initiator is necessary and sufficient to allow that later system to have a determinate value of some observable O of S. Also, S can acquire the DC concerning some other system S' if it interacts with this system while it interacts with the initiator. We will see further below a system that is a plausible candidate to be an initiator, and which is widely accepted in cosmology. I will argue that although initiators arose to address the measurement problem, they have the advantage of potentially addressing other problems in the foundations of physics, which is a good sign.

SDCs are represented by directed graphs, which represent the propagation of the DCs, or its potential propagation, which gives rise to systems that belong to it having determinate values. I will represent this interaction between X that leads Y to have a determinate value (together with X) and potentially leads Y to have the DC concerning some other system as $X \to Y$. When Y has the DC-Z, which leads some other system Z to have a determinate value, I will represent it as $X \to Y \to Z$.[24] In some DAGs that aim to depict the whole situation, the systems with only directed arrows towards them represent systems that have the DC but won't end up transmitting it to other systems. An SDC ends when it reaches these systems. The nodes with no directed arrows towards them represent the initiators.

Let's consider a simple and idealized example where, once again, we can neglect the intrinsic evolution of systems due to their strong interaction. This example will involve systems A, B, and C, where A is an initiator, in a toy mini-universe where the SDC that will be formed has the following structure, $A \to B \to C$. Let's assume that C starts interacting with B while B is interacting with A so that B has the DC-C, and B can end up transmitting the DC to C concerning some other system that C might end up interacting with.

However, when B and C begin interacting, let's assume that we can neglect the evolution of the quantum states of B while A and B interact, such that we can idealize that B and C start interacting only when the interaction between A and B ends. Thus, we can just analyze the evolution of the quantum states of A while A and B are interacting, where this interaction ends approximately at

[24] For simplicity, here I will mostly not care about the distinction between a token network, which represents concrete interactions between systems, and type networks, which represent interactions between types of systems that exist in specific regions of spacetime.

t'. Let's put a subscript SDC on the quantum states of a system if that system is an initiator or has the DC relative to some system, belonging to an SDC. We then have the following interaction between A and B,

$$\begin{aligned} &|E_{\text{ready}}\,\rangle_{\text{A SDC}}\,(\alpha'\,|E_0'\rangle_B + \beta'\,|E_1'\rangle_B)\,(\alpha|\uparrow\rangle_C + \beta|\downarrow\rangle_C) \rightarrow_{t'} \\ &(|E_0\,(t')\rangle_{\text{A SDC}}\,|E_0'\rangle_B + |E_1\,(t')\rangle_{\text{A SDC}}\,|E_1'\rangle_B)\,(\alpha|\uparrow\rangle_C + \beta|\downarrow\rangle_C)\,. \end{aligned} \tag{5}$$

If $\langle E_0\,(t')\mid E_1\,(t')\rangle_{\text{A SDC}} \approx 0$ and $\langle E_1\,(t')\mid E_0\,(t')\rangle_{\text{A SDC}} \approx 0$ quasi-irreversibly when A and B end their interaction, we infer that B has a determinate value of the observable *monitored* by A at t' that arises from their interaction (i.e., let's assume that is either 0 or 1) and acquires the DC-C. Let's assume that B has a determinate value 0. Now, let's consider the interaction between B and C. Let's assume that, given their interaction Hamiltonian, it ends at t'',

$$|E_0\,(t')\rangle_{\text{A SDC}}\,|E_0'^{\uparrow}\,(t'')\rangle_B|\uparrow\rangle_C + |E_0\,(t')\rangle_{\text{A SDC}}\,|E_0'^{\downarrow}\,(t'')\rangle_B|\downarrow\rangle_C. \tag{6}$$

The evolution of the interaction between B and C could be analyzed via the reduced density operator $\rho_C(t)$. Their interaction will allow C to have a determinate value ($\uparrow$ or $\downarrow$) at t'' if $\langle E_0'^{\uparrow}\,(t'')\,|E_0^{\downarrow}\,(t'')\rangle_B \approx 0$ and $\langle E_0'^{\downarrow}\,(t'')\,|E_0^{\uparrow}\,(t'')\rangle_B \approx 0$ quasi-irreversibly when B and C end their interaction. B will have a determinate value at t'' that arises from its interaction with C where the possible values that it can have are represented via the eigenvalues of the observable that $|E_0'^{\uparrow}\,(t'')\rangle_B$ and $|E_0'^{\downarrow}\,(t'')\rangle_B$ are eigenstates of. Furthermore, C can have the DC concerning some other system D if it interacts with it before the interaction with B ends. Note that since system A is an initiator, it has the DC concerning any system. So its ability to give rise to other systems having determinate values and allowing them to have the DC doesn't depend on its interactions with other systems.

In decoherence models, the environment of a system is typically composed of many subsystems. So, it's more realistic and plausible to assume that

CDC4) For a system S to have the DC concerning some system S', its subsystems must have the DC concerning S' or its subsystems (value-mereology assumption).

For instance, let's consider that instead of S_2 above, we have a subsystem S_2^i of S_2 for some i where S_2^i is not able to decohere S_3 alone, but S_2 is. S_2 would just be able to give rise to S_3 having a determinate value, having the DC, if its subsystems S_2^i for all i interacted with subsystems of S_1, acquiring the DC, where S_1 and its subsystems have the DC. So, subsystems of a system, such as S_2^i for all i are spacelike separated from each other and are considered to form a "cause" for the "common effect," which is a system S_3 having a determinate value of one of its observables. Each subsystem of S_2 would also have another determinate value when S_3 has a determinate value. These interactions are represented by a directed graph with "colliders" (Figure 1). We can also simplify the structure of the above graph by treating S_2 as a whole, neglecting its subsystems (Figure 2).

CDC4) further constrains the structure and persistence of SDCs, whose elements already have to obey the other CDCs. It's plausible to consider that typically, a system will interact with many systems in spatiotemporal regions, which form a larger system E. In order for a system E with its subsystems to decohere another S, its subsystems will have to be interacting with other systems that have the DC concerning them, and those latter systems will have to be interacting with other systems, and so on. So, we will need many systems for a system interacting with a larger system E to have a determinate value due to E. Also, the more macroscopic S is, the more subsystems in principle has, and so more systems belonging to SDCs need to be interacting with S in order for it to have a determinate value and the DC concerning other systems. This process resembles, even more, a process represented by a pragmatic irreversible decoherence model because we will have many systems involved in the interaction that leads S to have a determinate value and the DC, and these systems will be hard to control. Also, the SDCs give rise to indeterministic processes, which make these interactions impossible to reverse unitarily.

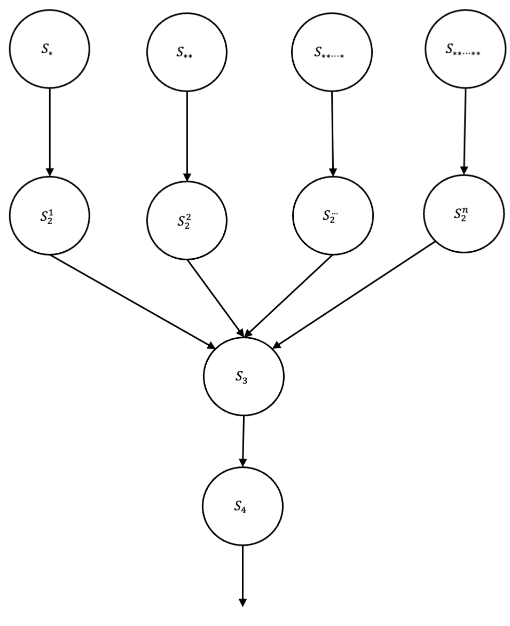

Figure 1: Directed graph that involves a common effect (i.e., a "collider") that represents the transmission of the DC between systems.

CDS1)-CDS4) constitute the CDCs. As we can begin to see more clearly, EnDQT has the benefit of providing a no-hidden-variable criterion for systems to have determinate values without modifying the fundamental equations of QT or appealing to relationalism.

Now, given the CSCs we can see how EnDQT justifies the assumptions i^*-iii^*) of decoherence models. Regarding i^*), it's important that the Hamiltonian of

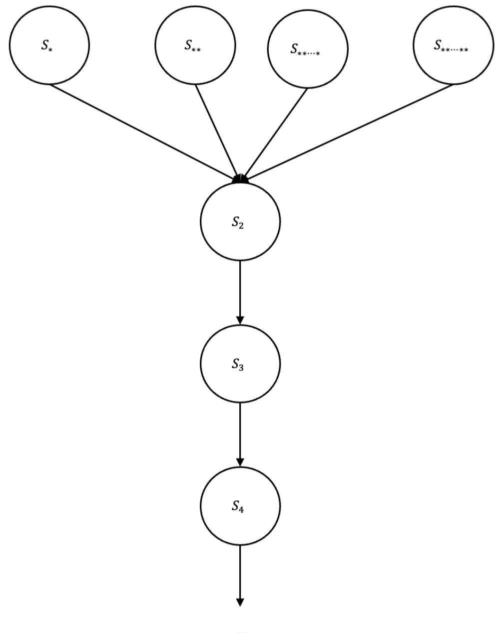

Figure 2: Directed graph involving common effects like the previous one, but just represents the whole system S_2.

interaction assumes a specific form to account for decoherence (given by the above commutativity criterion), which depends on the observables of the environment and the system because we regard it as representing the law-like dynamics of SDCs, which leads to determinate values. The observables of the environment E of S that appear in the Hamiltonian are also constrained by the interactions of the environmental systems of E with members of SDCs. Regarding ii^*), the initial states of the systems (and associated coupling constants) are randomly distributed (which gives rise to the overlap terms going quasi-irreversibly to zero in decoherence models) because the subsystems of E also need to belong to SDCs that indeterministically gave rise to them having determinate values before interacting with S and, hence, to a random distribution of their quantum states (and associated coupling constants). What about the distribution of the quantum states of the initiators? There are various possibilities, which will depend on what we regard initiators to be and speculations (more on this below). For example, that can be regarded as a brute fact of "the initial conditions of the universe" where initiators could be located. Or, given enough time, the quantum states of the initiators can achieve this overlap that triggers the process of propagation of the DC. Finally, regarding iii^*), what explains why and how systems (composed of many subsystems) that have the DC give rise to determinate values in this law-like way, where this is represented via fundamental decoherence, can be elegantly (as we will see) traced back to the initiators (which have the DC by default) that led them to have DCs and to give rise to systems having determinate values in this law-like way. So, one more benefit of adopting EnDQT with its CDCs is that it addresses some, perhaps, ad-hoc or strange features of decoherence by seeing it as a tool to represent the dynamics of SDCs.

I will now explain some natural hypotheses about initiators and the structure of SDCs that I will make to satisfactorily fulfill the goal of achieving UT), LC), and NR). These hypotheses will clarify some of the claims above and address some of the vagueness associated with models of decoherence.

I have been assuming that we can rely on fundamental decoherence to infer and represent how determinate values arise via SDCs. These represent the interactions between systems, starting with the initiators. The example above and CDC1)-CDC4) involve these models. So, fundamental decoherence represents interactions that render systems with determinate values in a certain situation involving an environment with a DC, given an appropriate and local Hamiltonian. Importantly, in order for a system S to have a DC and lead other systems to have determinate values, it's plausible that it will typically have to belong to an environment with many systems that propagate the DC, which seems to lead to a process that is hard to reverse/control due to these many systems that have determinate values indeterministically. Furthermore, the more macroscopic is S, the harder this seems to be. I also explained that fundamental decoherence models seem to represent phenomena that resemble those represented by pragmatic irreversible decoherence models. Remember that pragmatic irreversible decoherence models are models that involve situations where it's impossible to reverse the process they represent because they concern open/inaccessible environments or environments with many systems (but there is no reference to systems having the DC). However, it seems that we can use pragmatic irreversible decoherence models to infer when the processes represented by fundamental decoherence occur. But, as we will see, more needs to be said about the behavior of SDCs and fundamental decoherence to ground the typically used pragmatic irreversible decoherence models as a proper inferential tool for inferring when systems have determinate values in situations where we have not followed the interactions between systems since the beginning of an SDC.

As a reminder, I have called the models of decoherence that don't necessarily track the interactions involving systems with the DC pragmatic decoherence models. Another kind of pragmatic decoherence model is what I will call the *pragmatic reversible decoherence models*. These are models that represent a process that apparently involves decoherence in the sense that the overlap terms of the environment go quasi-irreversibly to zero. However, someone in some privileged position could reverse this process via operations on the system and environment, which is sometimes called recoherence. This reversible process often occurs inside isolated environments or situations where the environmental degrees of freedom don't become inaccessible to be reversed due to their in-practice isolation. Thus, the processes represented by these models aren't what we typically consider to be decoherence.

If we aren't careful, the distinction between a pragmatic reversible model and an irreversible one may be ambiguous in some situations. The Wigner's friend scenario[25] is an example of a situation. Suppose an isolated lab occupies an arbitrarily large spatiotemporal region with a human agent inside (a "friend"). The lab is isolated in such a way that Wigner outside the lab can unitarily manipulate the state of the friend plus their target system that the friend interacts with, treating both as being in an entangled state. So, in this case, we could have an enormous lab with many systems getting entangled with the friend and their target system S for a long time. However, if we were Wigner, we wouldn't consider that there was decoherence of S by the friend because Wigner could still unitarily reverse the state of the friend and their system. He would rather consider treating the friend plus target system interaction via a reversible decoherence pragmatic model. However, if the lab were open, he would treat their interaction via an irreversible decoherence pragmatic model. So, how do we exactly distinguish a reversible decoherence process from an irreversible one, since the reversible could also involve many systems? Let's call this problem the *Wigner's friend ambiguity problem.* As the discussion in the previous paragraphs suggests, if we want to address the measurement problem without changing the fundamental equations of QT, adding hidden variables to it, or adopting a relationalist view (more on this below), it seems that a way to deal with this problem is via paying attention to what constitutes an open environment and how it relates with SDCs.

I have pointed out how fundamental decoherence involving members of an SDC seems to lead to processes represented by the pragmatic irreversible decoherence models. The first hypothesis aims to deal with the above ambiguity problem and ground the success of the pragmatic irreversible decoherence models in helping account for determinate values arising via SDCs in open environment situations, as opposed to the reversible models. Thus, I will hypothesize that

The SDCs in our world are widespread in such a way that pragmatic irreversible decoherence models in open environments track the interactions between systems that belong to SDCs, but there can also exist processes represented via reversible decoherence pragmatic models, where the latter are tracking the interactions between systems that don't belong to SDCs (*SDCs-decoherence hypothesis*).

In other words, what the SDCs-decoherence hypothesis says is that the SDCs in our world are such that the open environments involved in irreversible decoherence pragmatic models will give rise to many interactions between the target system and systems that have the DC, in such a way that we can reliably approximate fundamental decoherence models by these pragmatic irreversible decoherence models. From now on, I will just assume that processes represented by pragmatic irreversible decoherence models occur in open environments.

On the other hand, it also hypothesizes that SDCs in our world are such that in isolated/controlled situations, we might be able to isolate the target system from interacting with members of SDCs, only interacting with systems that

[25] Wigner (1995).

don't have the DC. It all depends on the history of the SDCs that could interact with the target system in those situations and on our ingenuity in shielding the target system from interacting with SDCs (more on this below).

Furthermore, given EnDQT, if a pragmatic reversible decoherence model models specific situations SI with predictive success (like in the case of Wigner's friend), it allows us to infer the situations SI where a system is interacting with environmental systems that don't have the DC. Thus, we infer that in situations SI, no process that gives rise to determinate values occurs. Thus, note that isolated regions with macroscopic systems inside might isolate these systems from the influence of SDCs. Suppose this is done properly so that we can unitarily manipulate the contents of that region. In that case, we have a reversible process inside that region instead of an irreversible one. Then, suppose some situation, even involving interactions between macroscopic systems (like inside the friend's lab), is modeled by reversible decoherence with predictive success. In that case, we can infer that we have managed to isolate the systems from the influence of SDCs (more on this in the next section). This view is contrary to what is often assumed by relationalist views, such as the MWI,[26] which would consider that determinacy arises within a large enough isolated spatiotemporal region with systems decohering each other inside of it. It is in this sense that, as mentioned in the introduction, for MWI, decoherence is necessary and sufficient for determinacy, and for EnDQT, the interaction with SDCs matters.

So, to be clearer, according to EnDQT, the proper isolation of the friend's lab amounts to not simply the isolation of the lab but the isolation of the friend (and their system) from interacting with elements of SDCs. As I have mentioned, whether this isolation can be done in practice will depend on the particulars of the SDCs inside that lab and their history, represented by fundamental decoherence, going back to the initiators, and whether they will interact appropriately with the friend or not, giving rise to their decoherence. If there are enough members of an SDC inside an isolated lab, and assuming we know who the members are, the local processes represented by fundamental decoherence would be enough to model the process that leads the systems inside the isolated lab to have determinate values.

As I have mentioned above, a friend could be isolated by simply not allowing SDCs to interact with them. For example, suppose that the target system of the friend is system C in eqs.(5) and (6), and that the friend is system B. System B is just for a slight moment in a superposition. Furthermore, system A is now some system that previously interacted with other members of an SDC. We could isolate B from interacting with A. If this occurs, the friend would be unable to give rise to their target system C having a determinate value. The friend and their target system would just be in an entangled superposition with their target system, where both systems would have indeterminate values.

Relatedly, a friend could also be shielded from interacting with members of SDCs in the following way. Let's return to the original example involving

[26] Wallace(2012).

systems A, B, and C. As we can see via this example, in order for a system (like C) to continue having determinate values of an observable and giving rise to other systems having the DC and having determinate values ("destroying local superpositions"), interactions of the above kind should proceed at other times, i.e., C has to interact with other systems while interacting with B. This leads EnDQT to predict a phenomenon that I will call the *dissolution of an SDC*. If, during the evolution of an SDC, no system interacts with the system like C that is leading the expansion of that SDC, that SDC will disappear, not being able to give rise to further determinate values and the local destruction of superpositions.[27] Now, to isolate the friend from the influence of SDCs, we would *just* need to dissolve the SDCs that could interact with the friend. Note that this is different from isolating systems from interacting with target systems. It's instead not allowing the target systems to interact with systems with the DC. The phenomenon of dissolution of SDCs is a distinct prediction of EnDQT.

So, what the SDCs-decoherence hypothesis is doing is connecting the pragmatic decoherence models with the fundamental decoherence models, grounding the empirical success of the first on the phenomena represented by the latter. Accepting EnDQT the CDC1)-CDC4), we have good evidence that the SDCs-decoherence hypothesis holds, given the success of models of irreversible decoherence in accounting for measurement-like phenomena, and the success of reversible ones in not accounting for non-measurement-like phenomena.[28] Also, we have seen above how this hypothesis is plausible given that the CDCs lead to phenomena that resemble those represented by pragmatic irreversible decoherence models, which should even resemble them more if the environment is open since the latter will involve even more systems belonging to SDCs.

Contrary to what one may worry about, there is no future dependency or retrocausality for EnDQT in the sense that something giving rise to determinate values in the present depends on how some events turn up to arise in the future, i.e., the interactions turn out to give rise in the future to irreversible decoherence because they become uncontrollable (pragmatically speaking). Instead, given the above SDCs-decoherence hypothesis, our world is such that the pragmatic irreversible decoherence models (in open environments) are a reliable indicator to infer that determinate values arise via local interactions because the environmental systems that participate in this process are such that they have the DC. Also, we have seen how EnDQT justifies the features $i^{*}) - iii^{*})$ of fundamental decoherence models, which also justify their success in making inferences about how and when determinate values arise.

Now, it's time to address the elephant in the room, which is to specify what kind of physical systems initiators are and when we expect the SDCs to start, which corresponds to where initiators began to act. It seems to me that the hypothesis to establish when SDCs started should fulfill the following two desiderata: i') initiators should have a privileged position that allows them to give rise to widespread SDCs, so that they can explain the standardly assumed widespread

[27] Note that system C may also continue having determinate values if its states are decohered by other systems that belong to other SDCs that are expanding.

[28] See, e.g., virtual/reversible decoherence in Schlosshauer(2007).

existence of systems with determinate values across spacetime, including in the early universe. In other words, it should explain the widespread classicality that we observe or assume to exist. Furthermore, ii') it should support the SDCs-decoherence hypothesis in the sense that the systems that start SDCs should not be starting SDCs in arbitrary spacetime regions, so that it becomes plausible that sometimes we are able to isolate systems from the influence of SDCs (so that we are able, for example, to recohere the quantum states of a system). It's also undesirable if we manage to isolate a spacetime region to maintain the quantum systems inside of it in a superposition, and very likely, an initiator could likely manifest itself arbitrarily and destroy those superpositions. So, it's plausible to consider that initiators should manifest themselves mainly in the early universe since this is the earliest stage when we apply classical physics, in principle it's a stage that occurred in a clear spacetime region, and it's plausible to consider that in the early universe, something special happened (more on this below) and that systems in the early universe could be more influential than in the latter stages (more on this below too). So, given i') and ii'), it's plausible to assume the following general hypothesis,

At least most current SDCs in our universe started in the early universe, and initiators had a privileged role in this stage in terms of interacting with other quantum systems, which led to the formation of these SDCs (*SDCs-starting hypothesis*).

As we will now see, the SDCs-starting hypothesis should be seen as a placeholder for more concrete hypotheses that obey the desiderata i') and ii') as the field of cosmology develops. Given the above desiderata, we can develop heuristics to establish which concrete systems started SDCs and seek a more specific hypothesis. Probably the simplest and most conservative one that is in agreement with these desiderata and EnDQT use of decoherence involves looking at the earliest occurring phenomena where it was necessary to postulate a (pragmatic irreversible) decoherence process.

Inflation is typically considered to have been driven by a scalar field, called the inflaton.[29] It's hypothesized that the zero-point fluctuations of the quantized inflaton scalar field and the associated energy-momentum fluctuations and gravitational field that it gave rise to, when amplified by the rapid expansion of inflation, attracted matter. Then, it's standardly hypothesized that these fluctuations served as a source that gave rise to the cosmic structure in our universe (e.g., galaxy, galaxy clusters, etc.).[30] The inflaton field is often treated classically, and the effects of these fluctuations are observed via slight temperature anisotropies in the Cosmic Microwave Background. The problem to solve is to explain how these quantum fluctuations became classical during the early stages of the evolution of the universe. To my knowledge, the earliest reasonably accepted decoherence processes involved the decoherence of these fluctuations and aimed

[29] Some models postulate multiple inflaton fields; for simplicity, here I will just consider that there is one field.

[30] Liddle & Lyth (2009).

to address this problem. Many decoherence models were formulated to describe this process.[31] In a toy model, each quantum state $|s_i\rangle_S$ in eq.(2) could be the field amplitude/fock state with momentum $\mathbf{k}$ of the inflaton field fluctuations S, and i would be the occupation number. E would be the environment (more on this below).[32] We could invoke decoherence plus the MWI to perhaps make these models more satisfactory. Alternative proposals appealed to spontaneous collapse theories to explain how quantum fluctuations become classical.[33] However, we can instead appeal to the more conservative approach proposed here.

Given the above heuristic, we can consider that the systems implicated in this process are the initiators, having a series of attractive features that fulfill the desiderata aimed by the SDCs-starting hypothesis. First, it fulfills the desiderata i) because of its influential position and role mentioned above that gave rise to the cosmic structure. Furthermore, the decay of the inflaton in the reheating stage is often hypothesized to have given rise at least to ordinary matter. Second, it fulfills the desiderata ii) given that the inflaton field doesn't seem to manifest itself in our present universe, we can, in principle, build arguments that consider that this field in the later stages of the universe didn't give rise anymore to SDCs or negligibly so. For instance, in the so-called reheating phase, it's standardly considered that the inflaton field, at least in our universe, reached the absolute minimum of its potential and stayed there (and has been staying there). If such minimum corresponds to the point where the field is zero or approximately zero (see Martin et al. (2014) for some empirically supported potentials by the Planck satellite that fulfill this requirement), and if we consider that the coupling of the inflaton field to all other fields/systems in the Lagrangian density that describes or governs our universe depends on the value of the inflaton field in such a way that the interaction terms are zero (or approximately so) when the field zero, we can consider that the inflaton field in the stages of the evolution of the universe after the reheating phase (which includes the phase where we are now) will at least rarely interact with other fields/systems. So, it will (at least) rarely give rise to SDCs in these later stages.[34]

Let's represent the Lagrangian density of our universe obeying the above desiderata, and whose initiator is the inflaton field, as $\mathcal{L}_{SDC}$. Since it ful-

[31]See, e.g., Boyanovsky (2015); Burgess, Holman, & Tasinato (2015); Burgess, Holman, & Tolley (2015); Burgess, Holman, Kaplanek; Kiefer, Lohmar, Polarski, & Starobinsky (2007); Kiefer & Polarski (2009); Liu, Sou, & Wang (2016); Martin & Vennin (2016, 2020, 2022); Martin, Vennin, & Starobinsky (2021); and Nath Raveendran, Parattu, & Sriramkumar (2022).

[32]See, e.g., Kiefer & Polarski (2009) and references therein for more details on these decoherence models.

[33]See, e.g., Perez et al. (2006).

[34]One may worry that in other stages of the evolution of the universe (to put it in very rough and intuitive terms), there may be the creation of virtual particles-antiparticles pairs from the vacuum occupied by the inflaton field. These particles may give rise to SDCs. This isn't, in principle, a problem. In many inflaton models (see, e.g., Binétruy & Dvali, 1996; Halyo, 1996; Lyth & Riotto, 1999; McDonald, 2000), the inflaton is considered to be very massive/energetic, and so those particles will be too short-lived (see Roberts & Butterfield (2020) for a rigorous explanation for why this is the case) to be able to give rise to SDCs at least significantly. Note that the particles that arise from the vacuum also have to be able to decohere other quantum systems to give rise to SDCs.

fills the desiderata i) and ii), I will call this hypothesis that appeals to inflation to explain the beginning of SDCs and the inflaton as the initiator, the *inflationary-starting hypothesis*. It could be stated in the following way,

Our universe is described/governed by the Lagrangian density $\mathcal{L}_{SDC}$.

This hypothesis is one concrete example of an SDCs-starting hypothesis.

How can we understand these initiators more concretely? For example, Kiefer & Polarski (2009) list various possible environmental systems that decohere the fluctuations of the inflaton field, such as some other quantum fields[35] or *parts* of the fluctuations themselves.[36] If we adopt the inflaton and its fluctuations as initiators, they will have the DC concerning any system and give rise to other systems with determinate values by interacting with (i.e., decohering) other fluctuations and so on, forming SDCs. Note that if we consider instead that other fields have the DC, being these fields the initiators, we would need to explain why these other fields aren't currently still giving rise to SDCs in agreement with the SDCs-starting hypothesis.

Instead of adopting the simple initiators I have been talking about, an alternative possibility involves postulating another kind of initiator, which I will call reactive initiators. Contrary to non-initiator systems,

Reactive initiators S are systems that, upon specific interactions with other systems E that don't have the DC, acquire the DC concerning any system due to E and a determinate value during interactions, where these interactions can be inferred via the pragmatic irreversible decoherence of S by E.

In this case, the inflaton field, with its fluctuations, would be a reactive initiator. The interactions with these perturbations represented via decoherence, where the environmental systems would be other fields, would give rise to the fluctuations having the DC.

As we can see, the SDCs-starting hypothesis offers resources to establish what initiators are. With the inflationary-starting hypothesis, I have pointed out that we already have models that agree with the above hypotheses and that simply appeal to the dominant paradigm in cosmology.

Furthermore, appealing to the inflaton as the initiator provides various advantages to EnDQT and possible scientific and philosophical payoffs. First, it perhaps shows that EnDQT is a more parsimonious theory than other interpretations of quantum theory. On top of their ontological or mathematical additions to physics and quantum theory, other quantum theories very likely need to postulate the inflaton field as belonging to the initial conditions of the universe and interpret it to address the problems that inflation is meant to address or as an instance of the so-called past hypothesis to explain the temporal asymmetries.[37] This hypothesis constrains the state of the early universe so that

[35] Possibly coming from string theory.

[36] E.g., an environment involving modes of the field with different momentum $\mathbf{k}$.

[37] Albert (2000).

the dynamics of the physical states in the future have the required temporal asymmetries, postulating a time-asymmetric boundary condition. Following Wallace (2023), he considered that "[t]he Past-Hypothesis, (...) is that the world came into being (or at least coalesced out of Planck-scale physics) in the local quantum vacuum state for a homogeneous, isotropic, inflationary spacetime." This vacuum state is also called the Bunch-Davies vacuum,[38] which is considered to be the initial state of the fluctuations of the inflaton field.[39] However, EnDQT doesn't need those additional mathematical or ontological postulates. They are already a part of how EnDQT regards the inflaton as an initiator and the interactions that arise from there, having a fundamental role in the theory.[40]

Second, it perhaps shows that EnDQT is also a more explanatory theory than other interpretations of quantum theory, or at least as offering a better scientific reductionist approach towards the above physical phenomena, which is often seen as valuable. More concretely, given the fundamental role of the inflaton mentioned above, EnDQT offers the possibility of explaining, or at least reducing the features of the initial conditions and the phenomena they aim to explain together with the laws of physics, in something more fundamental. Buying the EnDQT picture, the story would go roughly like this: fundamental features of quantum phenomena involving initiators and their behavior are arguably more fundamental than phenomena described by classical cosmology, particle physics, thermodynamics, and statistical mechanics. The consequences of inflation, which is believed to involve the homogeneity of (relativistically speaking) causally separated different regions of space, perhaps the different temporal asymmetries, the geometry of the universe to be nearly flat, the seeds of structure formation, etc., and perhaps the state given by the Past Hypotheses, would be seen as fundamentally arising from an initiator with certain features plus the laws of physics that describe/govern its behavior and interactions. These features allowed for SDCs to spread throughout the universe in a specific way but also led initiators to not manifest themselves anymore, not currently giving rise to SDCs (being in the absolute minimum of its potential). There is much more to say about this. Whether one should regard the initiators and their features as explaining some features of the initial conditions and their consequences, or at least successfully reducing this to a more fundamental mystery is a topic for future work. However, for now, note that for now it's plausible to consider that EnDQT offers this interesting possibility.

Third, and relatedly, EnDQT diminishes the at-first-sight ad hocness of the inflaton field by providing it with a more fundamental role. This role involves solving problems with the more fundamental theory, quantum theory, rather than just solving some less fundamental problems.

Fourth, the inflationary-SDCs hypothesis offers predictions, which might

[38] Bunch & Davies (1978).

[39] More concretely, it is the minimum energy eigenstate of the Hamiltonian for the primordial fluctuations infinitely back in the past.

[40] Even if one rejects inflation or the initial state of the inflaton as the past hypothesis, one needs to provide a substitute to these hypotheses that provide the same explanations, which is a tall order.

allow us to constrain the very permissive models of inflation further.[41] For instance, as was mentioned, one of the constraints on inflationary models is that the inflationary potential should have an absolute minimum when its value is zero in such a way that the Lagrangian *turns off* the interactions of the inflaton field with other fields/systems once the inflationary potential reaches its absolute minimum. This can be regarded as a prediction of EnDQT.

Fifth, as I have mentioned, instead of explaining how primordial fluctuations arose from quantum fluctuations of the inflaton field by appealing to spontaneous collapse theories (Perez et al., 2006) that modify the equations of QT, or MWI and decoherence, which leads to the problem of quantum probabilities, EnDQT provides a conservative solution that doesn't suffer from the above potential issues.

One might object that EnDQT, with its initiators, is built on top of speculative hypotheses. However, note that the above hypotheses are as speculative as any other hypotheses postulated by the currently popular interpretations of QT, and they turn out to be conservative in the sense that they don't involve any modification of standard QT.[42] Furthermore, given the benefits of achieving UT), LC), and NR) (as we will see), it's worth taking the above hypotheses of EnDQT seriously. Also, I have shown that the inflationary-starting hypothesis provides a series of philosophical and scientific payoffs. So, overall, EnDQT yields worthy payoffs. On top of that, the beginning of SDCs occurs in regions of spacetime where we expect special events to occur. Finally, I should emphasize that every approach to QT so far needs to appeal to special initial conditions for one reason or another. However, EnDQT does that while providing additional benefits.

One might also object that the inflationary paradigm has its problems, which places EnDQT in problematic foundations.[43] However, note that the SDCs-starting-hypothesis is a placeholder for current and future physics. Furthermore, whatever theory substitutes inflation, it should deal with the problems it pertains to solve. To solve those problems, it's plausible to consider that some features shared with the initiators will likely arise. This is because it's plausible to expect that in a future theory, it's likely that we will also have a rapid expansion of the universe in the early stages that doesn't occur anymore. Such rapid expansion is likely due to some set of entities E with a considerable influence that don't manifest themselves anymore or so much at least. Furthermore, the SDCs-starting hypothesis can also be supplemented with another hypothesis if it turns out that there are phenomena that need to be explained via widespread initiators. So, EnDQT, conceived more broadly, is a view whose correctness doesn't just depend on inflation.[44]

I have mentioned above some predictions that EnDQT provides, such as the dissolution of SDCs and those that are a consequence of the SDCs-inflationary

[41] Ijjas et al., (2013) and Dawid & McCoy (2023).

[42] MWI supporters might claim they make no speculative hypotheses, but a realist attitude to whatever lies beneath the multiplicity of worlds is itself a speculative hypothesis.

[43] See, e.g., Ijjas et al., (2013), Dawid & McCoy (2023) and references therein.

[44] It's conceivable that there are other alternative mechanisms beyond inflation, see Appendix C.

hypothesis. Another prediction is the following: as we have seen with the example above, adopting the conservative determination conditions (CDCs) generates constraints on how SDCs are formed and new predictions. Decoherence timescales roughly serve as an indicator for the timescale it takes for environments of a system to decohere that system on average, where that system ends up having specific determinate values (that are observed in the lab). Given the SDCs-decoherence hypothesis, the CDCs predict that the decoherence timescale that we empirically observe of a kind of system Z by a kind of system Y should be superior or of the same order as the decoherence timescale of Y by a kind of system X, where Y is typically decohered by X before Y decoheres Z, and where the interaction between X and Y starts first. Otherwise, contrary to what is assumed by the CDCs, we can have situations where Z will have a determinate value first (due to Y), then Y will have a determinate value due to X. Since the decoherence timescales can be empirically determined, a further analysis of the current empirically determined decoherence timescales is needed to see if they agree with the predictions of the CDCs.

The predictions of the CDCs are supported in the case that Y is a macrosystem (e.g., measurement devices), and Z is a microsystem. This is because macroscopic systems have decoherence timescales much shorter than the microscopic systems that they can decohere.[45] Furthermore, the conditions for a quantum system to be considered a classical controller of another quantum system support the CDCs, since our evidence for measurement-like interactions are based on these situations.[46] So, so far, the CDCs seem to be favored. It would be interesting if we find further evidence for or against them.

Before ending this section, I would like to mention two features of this view. First, we can see that EnDQT provides a new interpretation of Born probabilities. They allow us to predict how SDCs evolve. Second, given the above CDCs, how to build models of SDCs? One way is via what I will call the *recursive heuristic*: as we know, target systems of decoherence models can be environmental systems of other decoherence models. So, given this heuristic, we should consider that (pragmatic irreversible) decoherence models don't only model measurement-like interactions of the target system, but also how that target system can constitute an environment that gives rise to further measurement-like interactions. So, like in the above simple example involving A, B, and C that makes certain assumptions, we can then build models of the behavior of SDCs piecewise. If we had the following SDC, $X \to Y \to Z$, we should consider at least a decoherence

[45]The cross section for larger systems is larger than the one for smaller systems. Moreover, the decoherence rate of a quantum system, which is the inverse of the decoherence timescale, is proportional to their cross-section, as well as the flux of systems of the environment. See the collisional models of decoherence in, e.g., Joos & Zeh (1985), Kiefer & Joos (1999), and references therein.

[46]Milburn (2012) provided two examples of interacting quantum systems where one system serves as a classical controller for the other. The conditions necessary for this to occur are that, first, the controller must be open to the environment to establish a pointer basis for the controller coupled with the target system. Second, the dynamics of the controller, as an open system, must ensure that the approach to that pointer basis is much faster than the timescales of the system being controlled. All these conditions support the CDC.

model where X decoheres Y and another one where Y decoheres Z. Note that given the CSC4), SDCs have a certain structure. I have represented a toy example of such a structure via Figs. 1 and 2. So, ideally, given CSC4) we should also analyze the subsystems of these systems. Given the recursive heuristic and the fact that EnDQT doesn't modify the basic equations of QT, it should be possible to develop more realistic models of the evolution of SDCs.[47]

As we can see, EnDQT has the great benefit of achieving UT), providing criteria for absolute determinate values to arise in a single world without modifying the fundamental equations of QT. It only uses decoherence to assign determinate values to a system and the SDCs, whose description appeals to such equations. Furthermore, arbitrary systems can, in principle, be placed in a superposition for an arbitrary time duration concerning any observable as long as they don't interact with members of an SDC. Also, we have seen that EnDQT provides a series of benefits and predictions.

3 Why is EnDQT local?

In this section, I will argue that EnDQT achieves LC) and NR) by showing how it provides a local common cause explanation of quantum/Bell-type correlations without adopting non-local/action at a distance, relational, or superdeterministic/retrocausal strategies. In the EPR-Bell scenario, space-like separated Alice and Bob share a pair of quantum systems in an entangled state, and randomly perform measurements on those systems.

First, like in standard QT, the Hamiltonians of interaction, representing the interactions between the agents and their systems, (should) represent local interactions. Second, EnDQT doesn't modify the equations of QT, and so, in principle, it can be rendered Lorentz invariant, and thus, it can be rendered compatible with relativity and local in this sense.[48] I will assume this here.

[47] Note also that given the CDCs and EnDQT perspective on quantum states, we can't infer directly from a system whose quantum state is in an eigenstate of some observable that it has a determinate value of that observable. For instance, when Alice measures her system and assigns it an eigenstate of some observable, she can't infer that the target system of Bob is in an eigenstate of some observable since Bob might not have interacted with the local SDC. Also, we might assign out of convenience and idealization to a system an eigenstate of some observable, where the latter doesn't belong to an SDC, but that doesn't imply that it has a determinate value of that observable. This just implies that if it interacted with an SDC, it could have a determinate value with 100% of probability. Moreover, even upon a measurement of a local system "in an eigenstate of some observable," the system shortly after evolves into a superposition (modulo quantum Zeno-like measurements, which increase the probability of the system being found in the same quantum state in repeated measurements). That is also why I have been using decoherence to model measurement-like interactions in general. Furthermore, we can't always infer from a system that it's not in an eigenstate of some observable, that it hasn't a determinate value of such observable. For instance, entangled states that arise in decoherence don't correspond to eigenstates of some observable. These inferences based on EnDQT are in tension with both directions of the famous Eigenstate-Eigenvalue link because this link neglects the SDCs to make such inferences: A system S has a determinate value q of an observable O if and only if the quantum state of S is in an eigenstate of O with an eigenvalue q.

[48] Bracketing issues with relativistic symmetries that may arise if we aim for a quantum

Granting that EnDQT achieves these two senses of local, I will also argue that EnDQT deals with the EPR-Bell scenarios without violating relativistic causality, i.e., without forcing us to assume that the causes of the events involved in those correlations aren't in their past lightcone, and without invoking superdeterministic or retrocausal explanations. Furthermore, it provides a local common cause explanation of quantum correlations. Let's see how.[49]

A widely influential version of Bell's theorem[50] involves, together mainly with the no-superdeterminism assumption,[51] the factorizability condition,

$$P(AB \mid XY\mathbf{\Lambda}) = P(A \mid X\mathbf{\Lambda})P(B \mid Y\mathbf{\Lambda}). \tag{7}$$

The variables A, B, $\mathbf{\Lambda}$, X, and Y concern events embedded in a Minkowski spacetime. A and B represent the different measurement results of Alice and Bob, X and Y are the different possible choices of measurement settings for Alice and Bob. $\mathbf{\Lambda}$ represents some set of (classical) "hidden" variables in the past lightcone of A and B (see also Figure 3), representing the common causes of the correlations between X and Y.

This condition is seen as a consequence of two assumptions:[52]

-The causes of an event are in its past lightcone,

-The classical Reichenbach Common Cause Principle (CRCCP).

Briefly, the CRCCP states that if events A and B are correlated, then either A causes B, or B causes A, or both A and B have common causes $\mathbf{\Lambda}$, where conditioning on $\mathbf{\Lambda}$, A and B are decorrelated, i.e., $P(A, B \mid \mathbf{\Lambda}) = P(A \mid \mathbf{\Lambda})P(B \mid \mathbf{\Lambda})$. However, it's unclear whether we should accept that these probabilistic relations given by the CRCCP should, in general, represent a causal structure involving quantum systems, given the exotic features of the latter. The CRCCP can be seen as a consequence of the Classical Markov Condition (CMC), assumed by classical causal models (CCMs).[53]

The CMC connects the causal structure provided by some theory represented by a DAG with probabilistic statements. The CMC is the following,

let's assume we have a DAG G, representing a causal structure over the variables $\boldsymbol{V} = \{X_1, \ldots, X_n\}$. *A joint probability distribution* $P(X_1, \ldots, X_n)$ *is classical Markov with respect to* G *if and only if it satisfies the following condition: for all distinct variables in* $\boldsymbol{V}, P$ *over these variables factorizes as* $P(X_1, \ldots, X_n) =$

theory of gravity, but this goes beyond the desideratum LC).

[49]Future work will enter into more details about this strategy (Pipa, forthcoming).

[50]Another widely influential version is considered to rule out the existence of local deterministic hidden variables (Bell, 1964). On the other hand, the version presented here is often considered to rule out indeterministic hidden variables. Since EnDQT is an indeterministic theory, this version is more relevant.

[51]This assumption states that any events on a space-like hypersurface SH are uncorrelated with any set of interventions subsequent to SH. This theorem also assumes that there is a joint probability distribution for the outcomes of Alice and Bob.

[52]Bell (1976, 1995, 2004). See also, e.g., Myrvold et al. (2021) and references therein.

[53]I will not derive it here, but see Hitchcock & Rédei (2021).

$\prod_j P(X_j \mid Pa(X_j))$, *where* $Pa(X_j)$ *are the "parent nodes" of* X_j, *i.e., the nodes whose arrows that start from these nodes point to* X_j.

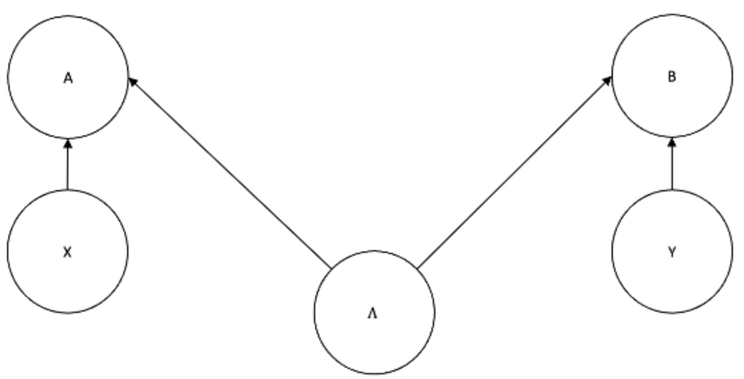

Figure 3: DAG of the common cause structure of Bell correlations, which respects relativity. This causal structure respects relativistic causality because X or A doesn't influence Y or B, and vice-versa, where these events are spacelike separated. Moreover, no other variables influence the variables A, B, X, or Y, or they don't influence anything else. So, there are no retrocausal or superdeterministic causal relations.

The CMC for the above DAG, which respects relativity, allows us to derive the following equation (I will denote regions of spacetime, the related nodes, and variables whose values may be instantiated in those regions using the same letters),

$$P(AB \mid XY) = \sum_{\Lambda} P(\Lambda)\mathrm{P}(A \mid X\Lambda)\mathrm{P}(B \mid Y\Lambda). \tag{8}$$

The acceptability of the CRCCP can be supported by the empirical success of the application of the CMC via CCMs (e.g., Pearl, 2009).[54] EnDQT responds to Bell's theorem by rejecting that the CMC can be applied in general to accurately represent causal relations between quantum systems, and hence it rejects the applicability of the CRCCP and the factorizability condition to make such accurate representation.[55]

There are at least two complementary ways of justifying the rejection of the CMC. One way is by looking at a precise justification of the CMC involving structural equations: they involve relationships between endogenous variables V_j (i.e., variables whose values are determined by other variables in the model) that

[54]There is also a way of deriving the factorizability condition, as well as the no-superdeterminism condition directly from CCMs and the CMC. See Khanna et al. (2023).

[55]So, note that EnDQT also rejects outcome independence and parameter independence that can be used to derive factorizability condition (Jarrett, 1984) by rejecting their applicability to represent causal relations between quantum systems.

depend on their endogenous parent variables $\mathrm{Pa}(V_j)$ plus exogenous variables U_j (i.e., variables whose values are determined from outside the model) establishing a directed deterministic relationship $V_j = f(Pa(V_j), U_j)$. Pearl and Verma (1995) proved that if we have a DAG G' representing the causal structure on V_j, the probability distribution $P(V_j)$ that results from the marginalization of the noise sources, if U_i are probabilistically independent in P, will respect the CMC concerning G.[56]

The above justification invokes features rejected by EnDQT. First, the systems assumed by these equations have, in general, determinate values in the sense of not having indeterminate ones represented by QT, such as via subsystems of entangled states. Second, the origin of the probabilities of the CMC is in the ignorance about some underlying determinate values. Furthermore, note that these systems with quantum indeterminate values, according to EnDQT, that travel to each wing don't even have a probabilistic model independently of the measurements of Alice or Bob. So, we can't have a probability over the common causes independently of their interactions, as it's assumed by this proof. Third, the above causal relations between systems aren't described by QT. More precisely, they don't involve unitary evolutions, decoherence, and quantum indeterministic processes.

We could assign a determinate value to the whole state $|\Psi\rangle$ of the entangled systems that would correspond to the eigenvalues of the observable that this state is an eigenstate of. However, Alice and Bob rather act on the subsystems of these systems. So, we should consider that it is not the whole state $|\Psi\rangle$ that determines the outcomes, but its subsystems. Each subsystem of this entangled state influences locally the outcomes of Alice and Bob, and there is no way to assign a determinate value to each subsystem.

There are at least two possible objections to this justification for rejecting the CMC. First, there could be some other justification for the CMC that doesn't assume determinate values but quantum indeterminate ones, although it's difficult to see which one would be. Second, this justification makes it unclear whether a causal explanation of quantum correlations can be provided, and this deficiency could press us to reject other assumptions instead of the CRCCP.

However, we can go further in terms of presenting evidence for why CCMs are inappropriate and justify the rejection of the CMC that improves over the above one. A way of finding the limitations of the domain of applicability of the CCMs is by examining the more general models that putatively represent causal relations in the quantum domain, i.e., quantum causal models (QCMs).[57] I will analyze how QCMs make some assumptions that CCMs don't make, and that that these assumptions concern the quantum domain according to EnDQT. QCMs are, in principle, more general because they reduce to classical ones in a "classical limit." Like we found what is wrong with classical mechanics when we examine the more general theory, QT, which reduces to classical mechanics in some limit; we find what is wrong with the CCMs, when we adopt QCMs

[56] See, e.g., Pearl (2009), Pearl & Verma (1995), and Hitchcock (2022).

[57] Costa & Shrapnel (2016), Allen et al. (2017), and Barrett et al. (2019).

interpreted via EnDQT.

As I will explain, QCMs will have the role of showing how EnDQT provides a local causal explanation of Bell-type correlations. Note that QCMs currently are only formulated for finite-dimensional Hilbert spaces. However, this isn't as far as we can tell, in principle, a fundamental limitation.[58] I will thus pose the following argument,

> P-1) QCMs, which assume the quantum Markov condition (QMC) that is a generalization of the classical one, according to EnDQT, explain locally Bell-type/quantum correlations.
>
> P-2) Quantum causal models interpreted by EnDQT explicitly consider that systems that participate in those causal relations i) can assume indeterminate values represented via QT, ii) only assume determinate values when they interact with an SDC, and iii) where those relations are described via QT. i)-iii) are appropriate assumptions for EnDQT.
>
> P-3) On the other hand, CCMs and the CMC, which arise in a specific limit from QCMs,[59] don't make, in general, the same EnDQT-appropriate assumptions as QCMs.
>
> C) Hence, according to EnDQT, CCMs, with their CMC, are inappropriate to provide an account of quantum causal relations contrary to QCMs. The latter provides an appropriate causal explanation of Bell-type/quantum correlations, which is local.

Let's turn to the justification of P-1). QCMs consider that each node in the causal DAG concerns a possible locus of interventions on the properties of a system. More concretely, each node is associated with a set of CP (completely positive) maps $\tau_{A_1}^{k_{A_1}|x_{A_1}} \otimes \ldots \otimes \tau_{A_n}^{k_{A_n}|x_{A_n}}$,[60] also called quantum instruments, instead of random variables as in the CCMs case. This set gives the "possibility space" that can be associated with the different ways the properties of a system with its quantum state can change under local interventions x, which correspond to the preparation of quantum systems, transformations, measurements on them, etc., each leading to different outcomes k.

The QMC is defined through the causal DAG where the edges of the DAG are associated with quantum channels/completely positive trace-preserving (CPTP) maps.[61] Examples of a quantum channel are unitary maps, evolution of the

[58] See Paunkovic & Vojinovic (2023) for an overview of possible challenges that need to be addressed in order to extend QCMs to the infinite-dimensional case.

[59] Barrett et al. (2020).

[60] A quantum channel is a linear map ε that is a completely positive trace preserving (CPTP) map. A map is a CPTP map if: a) it is trace-preserving, i.e., $\mathrm{Tr}(\rho) = \mathrm{Tr}(\varepsilon(\rho))$ for all density operators ρ, b) positive, i.e., $\varepsilon(\rho) \geq 0$ whenever the density operator $\rho \geq 0$, and c) completely positive. When only b) and c) are fulfilled, we have a completely positive (CP) map rather than a CPTP map. A CP-map can be associated with a positive operator-valued measure (POVM). See Nielsen & Chuang (2011).

[61] See the previous footnote.

system with noise, etc.[62] Both CP and CPTP maps are written as positive semi-definite operators via the Choi-Jamiolkowski (CJ)-isomorphism.[63]

The QMC representing a causal structure held fixed is written via the process operator σ, which is a CPTP map and factorizes analogously to the CMC. More precisely, a process operator $\sigma_{A_1,\ldots,A_n}$ is compatible with a DAG G with nodes $A_1, \ldots, A_n$, if and only if it obeys the quantum Markov condition (QMC, Barrett et al., 2019) where this condition says for all i, l in the DAG G there are quantum channels such that $\left[\rho_{A_i|Pa(A_i)}, \rho_{A_l|Pa(A_l)}\right] = 0$, and

$$\sigma_{A_1,\ldots,A_n} = \prod_i \rho_{A_i|Pa(A_i)}. \tag{9}$$

We need to have $\left[\rho_{A_i|Pa(A_i)}, \rho_{A_l|Pa(A_l)}\right] = 0$ because the product of two positive operators is positive if and only if they commute. $\sigma_{A_1,\ldots,A_n}$ factorize analogously to conditional probabilities in the CMC.

A version of the Born rule allows us to represent the overall causal structure, which also involves certain measurements on the nodes $A_1, \ldots, A_n$ with outcomes $k_{A_1}, \ldots, k_{A_n}$, given interventions $x_{A_1}, \ldots, x_{A_n}$,

$$\begin{aligned} &P\left(k_{A_1}, \ldots, k_{A_n} \mid x_{A_1}, \ldots, x_{A_n}\right) \\ &= \mathrm{Tr}_{A_1,\ldots,A_n}\left[\sigma_{A_1,\ldots,A_n} \tau_{A_1}^{k_{A_1}|x_{A_1} SDC} \otimes \ldots \otimes \tau_{A_n}^{k_{A_n}|x_{A_n} SDC}\right]. \end{aligned} \tag{10}$$

An obstacle that one must face to provide a local causal explanation of Bell correlations via QCMs is to deal with their operationalism. Causal influences are typically understood by the possibility of "signaling" from one node to another.[64] The causal structure represented by QCMs represents the constraints on these signaling relations. So, node X cannot signal to node Y if and only if node X doesn't precede node Y in the DAG (e.g., see Figure 4, more on this below). Signaling between node X and Y can be understood as occurring when a variation in the choice of certain instruments/interventions performed at node X can vary the probabilities of an outcome k concerning measurements performed at node Y.

One may worry that, like in other QTs such as Bohmian mechanics,[65] although there isn't signaling, we still have non-local influences, and QCMs are hiding such influences. If we adopt EnDQT, which doesn't consider that there are

[62] Each (quantum) node A_i is associated with an input Hilbert space $\mathcal{H}_{A_i^{\text{input}}}$, which I will write as A_i^{input}, and an output Hilbert space $\mathcal{H}_{A_i^{\text{output}}}$, corresponding to the incoming and outgoing system, which I will write as A_i^{output}, and each edge is associated with an output Hilbert space of one node and the input Hilbert space of another node. When it is written $\rho_{B|DA}\rho_{C|AE}$, what is meant is that $\rho_{B|DA}\rho_{C|AE} = \rho_{B|DA} \otimes \rho_{C|AE} = \left(\rho_{B|DA} \otimes I_{E^{\text{output}}} \otimes I_{C^{\text{input}}}\right)\left(\rho_{C|AE} \otimes I_{B^{\text{input}}} \otimes I_{D^{\text{output}}}\right)$, where X^{input} and X^{output} is the inputs and outputs of node X. Moreover, $\mathrm{Tr}_A\, \rho_{AB|C} = \rho_{B|C}$ and $\mathrm{Tr}_B\, \rho_{AB|C} = \rho_{A|C}$.

[63] See, e.g., Barrett et al. (2019).

[64] When all the relevant systems participating in causal relations are included (Barrett et al., 2019).

[65] See, e.g., Goldstein (2021).

hidden non-local influences that cannot be used for signaling, we don't need to have this worry. This is because, according to EnDQT, SDCs are necessarily involved in the influences that give rise to determinate values, and they represent local interactions between systems (see previous section). Furthermore, using the concept of signaling and an operationalist language is unnecessary, and we don't need to adopt an account where signaling or causation is irreducible. We can rather consider that systems in a region influence the determinate value of certain systems in another region, where such influences are modally described/governed by QT, and QCMs allow us to represent and infer those influences.

Let's see how adopting the point of view of EnDQT, QCMs provide a local causal (non-relationalist, non-retrocausal, and non-superdeterministic)[66] common cause explanation of quantum correlations. Now, A, B, and Λ, represent spacetime regions, instead of classical variables. Consider below how, via the QMC and a version of the Born rule, we can represent the local common cause structure that explains Bell correlations (Figure 4),

$$P(x, y \mid s, t) = \mathrm{Tr}_{\Lambda \mathrm{AB}} \left(\rho_\Lambda \rho_{A|\Lambda} \rho_{B|\Lambda} \tau_A^{x|s\ SDC} \otimes \tau_B^{y|t\ SDC} \right). \tag{11}$$

Note that eq.(11) is analogous to eq.(8). The systems prepared at the source act as common causes for Bell correlations, having indeterminate values until each system interacts with Alice and Bob's measurement devices, giving rise to the correlated outcomes. ρ_Λ via its subsystems represents the systems prepared at the source, which, for example, could be systems that have indeterminate values of spin-p (where p ranges over all possible directions of spin). We use ρ_Λ to represent each system in the different regions separately by keeping track of the labels A and B and the channels $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$. Each system evolves locally to region A/B, where Alice/Bob influences the outcomes that arise in A/B. This influence is represented via the quantum channel $\rho_{A|\Lambda}$ in the case of A, and $\rho_{B|\Lambda}$ in the case of B. $\rho_{A|\Lambda}$ and $\rho_{B|\Lambda}$ are identity channels that acting on the density operator ρ_Λ representing the systems in region Λ, evolve them to regions A and B, respectively. The influence that gives rise to the outcomes is also represented via the POVMs $\tau_A^{x|s\ SDC}$ in the case of Alice, where s is her random measurement choice, and x is her outcome/the determinate value of S, and analogously via $\tau_B^{y|t\ SDC}$ in the case of Bob. The superscript SDC means that these are interventions that give rise to a determinate value, connecting systems with an SDC, and correspond to other kinds of edges in the DAG in Fig. 4. Alice and Bob, due to their measurements, will lead the systems to become part of an SDC because they also belong to SDCs.

So, with the above account, EnDQT allows QCMs to be explicitly local and nonoperational. The local interactions at each wing are mediated by the SDCs, and these interactions, plus the prepared systems at the source, provide a local non-relational common cause explanation of quantum correlations.

Note that by adopting EnDQT's view of quantum states, it isn't considered that the (local) measurement of Alice on the system affects the system of Bob

[66]See Wood & Spekkens (2015) for examples of non-local, superdeterministic, and retrocausal causal structures.

and Bob, and vice-versa. We aren't reifying quantum states. We can represent this situation via the following (what I will call) EnDQT-causal-DAG (Fig. 4), where the nodes in grey represent the systems that *don't* belong to an SDC, and the arrows in grey represent their evolution and influences on the values of the systems these arrows point to. The nodes in black represent the systems that belong to an SDC (Alice/Bob). The arrows in black represent their interactions with other systems that give rise to the latter having determinate values, pointing to these systems. These arrows and interactions in grey are mathematically represented by POVMs. EnDQT-causal-DAGs aim to highlight the fact that measurement-like interventions in QCMs involve systems that are locally connected with SDCs.[67]

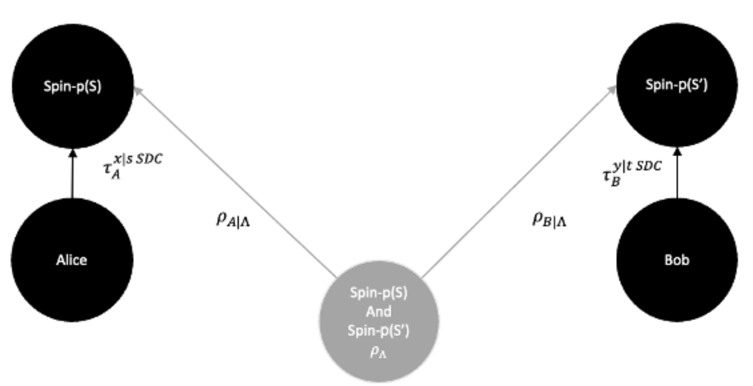

Figure 4: EnDQT-causal-DAG of the common cause structure of Bell correlations, which respects relativity being local, non-retrocausal, and non-superdeterministic, and is adopted by quantum causal models as interpreted by EnDQT. Furthermore, the outcomes are absolute/non-relative.

EnDQT approach to quantum causation is not restricted to Bell scenarios but also has the benefit of being applicable to scenarios where it's difficult to see how to apply QCMs coherently, such as in the popular extended Wigner's friend-like scenarios.[68] Suppose we have two friends/agents in isolated space-like separated labs in each wing,[69] and one Wigner/agent next to each lab, where the friends share an entangled pair prepared at the source like in the Bell scenario. It's also assumed that the lab is isolated in such a way that Wigner can perform arbitrary unitary operations on the contents of the lab. Here we have the case explained in section 2 of a process represented by pragmatic reversible decoherence models involving the target system and the friend or their measurement device. The friend is a macroscopic system that (supposedly) makes a measurement/decoheres her target system; however, Wigner can reverse this process.

[67]Note that this DAG is different from the ones above involving the propagation of the DC.

[68]See, e.g., Bong et al. (2020); Brukner (2018), Frauchiger & Renner (2018), Ormrod et al. (2023), Myrvold (2002), and Schmid et al. (2023) for a review.

[69]I will focus on the scenario from Bong et al. (2020) and Brukner (2018).

So, if we manage to achieve this isolation from the SDCs (see section 2), the Wigners can unitarily manipulate the friend plus her system, possibly reversing their state. We would then treat each friend and their target systems as being in an entangled superposition of states at each wing. Thus, the evolution of each system of the entangled pair to each wing and the "measurements" of each friend would be treated via a unitary channel that entangles each friend and their target system, where these channels would also represent the causal structure of this situation.[70] Then, as I have mentioned, the Wigners in each wing can unitarily manipulate or measure these entangled states. We could then calculate the probabilities for these measurement outcomes for the different measurement settings of the Wigners using a version of the Born rule like in eq.(10), providing a local common cause explanation for this situation.[71]

Notice that, in (the unlikely or perhaps even impossible case) case that the above isolation from the SDCs is successful, contrary to what is assumed by the theorem underlying the scenario mentioned above, there is no joint probability distribution for the outcomes of the friends and Wigner. This is because the friends inside their labs don't obtain any outcomes since they don't interact with SDCs, which allows the Wigners to manipulate them unitarily. So, it rejects the so-called *absoluteness of observed events* assumption of this theorem, not because events aren't absolute like relationalist views claim, but rather because the events concerning the outcomes of the friends don't occur.

One may wonder what the friend experiences when it is in a superposition. In other words, in the unlikely possibility that we manage to isolate such a macroscopic system from SDCs, what's going on with their mental content (e.g., their thoughts, desires, etc.)? More concretely, in the "local friendliness theorem" mentioned above[72], Wigner sometimes opens the door and asks the friend which outcome they obtained; what's happening with the mental content of the friend? There are different possibilities that I don't have space to go in-depth here: one could consider that the friend lacks mental content. However, this position might seem unsatisfactory since it's hard to conceive what it is for a friend-like system to lack mental content. So, this possibility can be deemed as incoherent. Instead of adopting this position, I think that a more satisfactory possibility is to consider that friend-like systems when isolated from SDCs, have indeterminate mental content, where this content depends on the indeterminate physical properties of their brain. When the lab is open, their indeterminate mental content becomes determinate. This possibility has the advantage of not being foreign to the philosophy of mind. Externalism about mental content roughly consists of the thesis that mental content depends on the external environment of the subject that has that mental content.[73] The friend *having* determinate mental content is dependent on the SDCs that render that content determinate.[74]

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[70]In a toy scenario, we could represent the quantum channels that entangle each friend in each wing by a CNOT gate in the CJ-form, and each friend as a being initially in the state $|0\rangle$.

[71]More on this in Pipa (forthcoming).

[72]Bong et al. (2020)

[73]Putnam (1975).

[74]In the case of the local friendliness theorem where the friend is an AI system (Wiseman et

It doesn't seem that any current quantum theories, which don't modify the fundamental equations of QT, can use QCMs in this local, non-relationalist, and non-operational way to give a local common cause explanation of quantum correlations like the ones in the Bell and extended Wigner's friend scenarios. So, EnDQT seems to be currently the only one to be able to do so in this way. Note that relationalist theories are, along with EnDQT, the only non-operational, non-hidden variable theories that don't modify the fundamental equations of QT and consider it a universal theory. So, they are the only ones who could also consider that QCMs, which use standard QT, provide the whole causal story. Furthermore, spontaneous and gravity collapse theories will necessarily impose fundamental limitations on these macroscopic superpositions. As I have said, in the case of EnDQT, it all depends on the details of the histories of the SDCs (which includes not being subject to human ingenuity). However, typically, in relationalist theories, the shared correlations of the friends or Wigners only arise when they meet (if they ever meet). So, there isn't a common cause explanation in the above sense. Moreover, QCMs in the single-world cases (at least) should be modified or adapted to account for these multiple varying perspectives since they don't consider that variation. So, contrary to the suggestions of others, EnDQT considers that QCMs don't need to be modified or adapted to a relationalist approach for them to explain the correlations that arise in the extended Wigner's friend scenarios.[75] Adopting EnDQT, we don't need to adopt this more complex approach to QCMs, which can be regarded as another benefit of this view.

Finally, how to support P-2) and P-3)? QCMs consider that common causes can have indeterminate values represented via QT, i.e., via subsystems of an entangled state, and probabilities explicitly don't arise from the ignorance of underlying determinate values. Contrary to CCMs and in agreement with EnDQT, for QCMs, common causes, represented by the subsystems of the entangled state, don't have determinate values and a Born probabilistic model independently of the interactions with Alice or Bob. Also, contrary to CCMs, the relations of influence are explicitly represented via QT, i.e., via CPTP maps when systems don't interact with members of an SDC and by CP-maps/POVMs when systems interact with members of SDCs. Only in a limit where we can consider the systems as having determinate values, the QMC reduces to the CMC.[76]

So, according to EnDQT, CCMs with their CMC are inappropriate in pro-

al., 2023), granting that such system has mental content, one can similarly also consider that before the friend delivers their output to the exterior, their mental content is indeterminate. So, in this version, one would deny the "Friendliness" assumption. In Appendix A, I briefly argue that some influential interpretations of QT would also deny this assumption.

[75] Cavalcanti & Wiseman (2021), Schmid et al. (2023), and Yīng et al (2023). See Ormrod & Barrett (2024) for a recently proposed relationalist adaptation.

[76] The details about how to obtain this limit precisely are too evolved to be presented here. Basically, the classical limit should involve a process operator $\sigma_{A_1 \ldots A_n}$, where there is an orthonormal basis at each node (that is, an orthonormal basis for $\mathcal{H}_{A_i^{\text{in}}}$, along with the basis for $\mathcal{H}_{A_i^{\text{out}}}$), such that $\sigma_{A_1 \ldots A_n}$ is diagonal with respect to the product of these bases. This corresponds, for example, to the situation where the systems at the source are prepared in a product state.

viding an account of quantum causal relations, contrary to QCMs. The latter provides an appropriate causal explanation of Bell correlations, which is local. In this way, EnDQT deals with Bell's theorem.

Sometimes, it is argued that QT is non-local and that the EPR argument (Einstein et al., 1935) ruled out the existence of local indeterministic theories (e.g., Maudlin, 2014), and so one might worry that there is something wrong with my argument above. However, this argument concerning the non-locality of QT shouldn't be right because EnDQT, as an indeterministic local theory, is a counterexample to that claim. I don't have space to enter into details, but note that the so-called EPR criterion of reality assumed in this argument can precisely be seen as a consequence of the classical Reichenbach common cause principle (Gömöri & Hofer-Szabó, 2021), which, as I have mentioned, is a special case of the more general CMC (Hitchcock & Rédei, 2021). However, EnDQT doesn't consider that the CMC can, in general, represent causal relations between quantum systems. Thus, it rejects the EPR criterion as representing such causal relations and one of the basic premises of that argument for non-locality.

4 Conclusion and future directions

I have proposed EnDQT and argued that, contrary to the other well-known quantum theories, it has the great benefit of being a local, non-relational, and non-superdeterministic/non-retrocausal QT. Systems have determinate values only while interacting with other systems of SDCs. On top of that, EnDQT has the benefit of being conservative, not modifying the fundamental equations of QT, and, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time. Also, EnDQT is able to give a local causal explanation of quantum correlations. There are many future directions. For instance, one should develop more realistic models involving initiators, explore their explanatory potential, seek to develop techniques to map SDCs, and test and extract further predictions from EnDQT, which might distinguish it empirically from other quantum theories.[77]

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[77]See appendix C for further discussion on future directions.

Appendix A: The Wigner's friend experiences

One might object that in some extended Wigner's friend theorems,[78] it's plausible to consider that the friend Alice inside her isolated lab sees a determinate outcome. In a sense, this theorem assumes that Wigner, without performing any operations on Alice and her lab and after her measurement, simply opens her lab door and asks her about what outcome she obtained. In the simple case where the friends share a spin 1/2 entangled particles, she will answer that she obtained spin-up or spin-down with 50% of probability each (i.e., if Wigner makes a projective measurement on the state of Alice after her measurement, without performing any other operation on the lab, he will obtain these outcomes). So, it seems that Alice sees a determinate outcome contrary to what EnDQT claims in (the highly idealized) situations where we manage to isolate the friend from interacting with SDCs. To put the objection more dramatically, the measurement problem can be regarded as the problem of accounting for the experiences of determinate outcomes of experimentalists upon measurements, despite QT predicting that measurement-like interactions can yield indeterminate outcomes. The friend inside the isolated lab seems to experience a determinate outcome, but EnDQT seems to give no account of what this agent is experiencing. Hence, EnDQT doesn't solve the measurement problem.

First, note that in the case where we manage to isolate the lab's contents from the SDCs, according to EnDQT, Wigner opening the lab triggers a physical process that leads to Alice obtaining determinate outcomes and reporting them to Wigner. It's not necessarily the case that Alice sees a determinate outcome inside her lab before opening the door. Seeing a determinate outcome can arise due to the interactions with the SDCs when the door is opened.

Second, as I have mentioned in the main text, there are different positions one may adopt regarding the friend's experiences, and which one is the correct one depends on deep philosophical and empirical issues, which I don't have space to settle here. The main point that I want to make now is that the above objection is not worrying, and there are different ways of answering it. On top of that, I will argue that the above objection could also be applied to other more accepted interpretations of QT in certain circumstances (such as the MWI), and in so far, it is a legitimate worry, it could also be a worry applicable to these interpretations. Given how accepted these interpretations are, it shouldn't be a reason to reject EnDQT.

Regarding the different positions, as I have mentioned in the main text, a possible one is that a) the agent lacks mental content underlying its perception of the outcome: this is the *absent experience hypothesis*. The claim would be that we shouldn't worry that EnDQT (and other interpretations, as we will see below) can lead us to friend-like agents without experiences. We shouldn't follow our intuitions in the extreme (and quite possibly unrealistic) environments of a completely isolated agent and think that that agent will be exactly like us. The problem with this possibility is that it's hard to make sense of an agent without

[78] See Bong et al. (2020).

mental content.

However, as I have also mentioned, EnDQT can even consider that the friend experiences something in the isolated lab via particular hypotheses, dissolving the above worry. We might consider that b) friend-like systems in isolated regions have indeterminate mental content, where this content depends on the indeterminate physical properties of their brain. When the lab is open, their indeterminate mental content becomes determinate. I will call this possibility the *quantum experience hypothesis.* This hypothesis has the benefit of not being foreign to the philosophy of mind. Externalism about mental content is roughly the thesis that mental content depends on the external environment of the subject that has that mental content.[79] The friend *having* determinate mental content is dependent on an environment that renders that content determinate.

One might object that it is conceivable that we have a situation where the friend is in a coherent superposition (we don't open the lab's door) and could send messages via a sheet of paper in a sealed box so that the paper maintains its superposition. The box is only opened much later and/or in a faraway location from where the friend is. Furthermore, if we open the box, the message seems to make perfect sense. So, it seems plausible that the friend has determinate mental content already inside their lab in the spatiotemporal location where the message was produced.

To deal with these cases, together with b), we can adopt a version of the extended mind hypothesis of Clark & Chalmers (1998), which I will call the *quantum extended mind hypothesis.* The idea is that the bearers of the friend's mental content would be the outputs of the friend to the exterior (i,e, the sheet of paper). At first, their mental content is indeterminate; then it becomes determinate when the box is opened. Like the most sophisticated technology is perhaps an extension of our mind, for an incredible agent like the friend, its outputs that interact with the external environment are an extension of their mind. Note that there isn't any action at a distance here according to EnDQT. So, Wigner measuring the output doesn't influence the friend's body.[80]

So, we have here familiar situations in the philosophy of mind. Alice could, in fact, have experiences in these situations, and EnDQT can account for them. There is much more to say about this. Future work will go into more detail on a), b), and c). Note that a), b), and c) are options that may be adopted if we reject the absoluteness of observed events assumption in the way EnDQT did (section 3).

It's important to notice that if we consider realist Wigner's friend scenarios, the position adopted by EnDQT regarding the friend's experiences and the adoption of the above hypotheses shouldn't be seen as something restricted

[79] Putnam (1975).

[80] Note also that the extended quantum mind thesis differs from the traditional extended mind thesis by considering that even phenomenal content can have extended bearers. I don't see any problem with considering that. More concretely, some might justify the extended mind thesis via individuating mental content through its functional roles (Clark & Chalmers, 1998). However, some may reject the claim that phenomenal content can be individuated by its functional roles (e.g., Chalmers, 1996). It's unclear that my thesis requires a functionalist account of phenomenal content. I will leave the investigation of this topic for future work.

to EnDQT. More concretely, if extended Wigner's friend scenarios become realizable one day, it will very likely be via quantum computers and quantum agents running on those quantum computers as friends instead of human friends (see Wiseman et al., 2023 for a proposal). Assuming the controversial position that such quantum agents have mental content, which is a requirement if we want this version to mimic the original extended Wigner's friend version, many realist interpretations of QT will be pressed to assume that quantum agents don't have internally determinate mental content. This is because, plausibly,[81] their experiences will depend on superpositions of qubits. As it is recognized by many MWI proponents,[82] we can have robust branching into worlds when there is decoherence, but inside some quantum computers, we shouldn't often have such branching because there isn't a lot of decoherence (at least ideally and in many architectures of quantum computers). Many proponents of interpretations such as the MWI *won't consider* that, in many situations, there is enough robust branching inside the quantum computer so that we could have something like an agent with determinate mental content running on those circuits. Spontaneous collapse theories won't also consider that there is such an agent because they don't consider that collapses happen (at least frequently) in situations like those within a quantum computer.

Wiseman et al. (2023) basically acknowledge the above in the case of spontaneous-collapse theories, saying that the "thoughts [of the artificial agent] are thus not real in the way that my thoughts as a human are real." This amounts to the rejection of the "Friendliness" assumption of the theorem of Wiseman et al. (2023). My claim is that EnDQT also rejects this assumption, as well as the (at least some influential versions of the) MWI.[83]

So, if we ever come up with a scenario where that replicates the original extended Wigner's friend scenario, EnDQT leads to the same account of the agent's experiences as (at least) these realist and consistent quantum theories, and so the above objection could also apply to them. Thus, these views are on an equal footing when it comes to realistic scenarios in terms of accounting for the agent's experiences, and they could also adopt one or more (i.e., b) and also c)) of the above hypotheses concerning the friend's experiences along with EnDQT.

Furthermore, although single-world relationalists can account for the relative friend's experiences and prima facie this is an advantage relative to EnDQT, there is a good case to be made that these experiences aren't absolute. A more careful inspection of single-world relationalist views, such as Relational Quantum Mechanics,[84] shows that relative to some systems, other systems' mental content can be indeterminate since relative to one system, the other system might be

[81] I am setting aside strong emergentist and dualist perspectives about such content here.

[82] See most prominently, Wallace (2012, section 10.3).

[83] Of course, accepting b) and c), one shouldn't talk in terms of the reality of the thoughts/mental content. Instead, we should talk in terms of how different they are from our thoughts because the quantum agents have thoughts, they are just different from what we typically conceive our thoughts to be.

[84] See, e.g., Rovelli (1996) and Di Biagio & Rovelli (2021).

in a superposition of quantum states that the mental content depends on. So, views such as Relational Quantum Mechanics, in these circumstances, would be in a similar position as EnDQT and be subject to a version of the above worry.

Appendix B: The basics of an ontology of quantum properties

One might object that EnDQT doesn't offer a clear ontology since an ontology that views the world in terms of systems, observables, and determinate or indeterminate values is unclear and not so satisfactory when we compare it with the richer ontologies where the wavefunction is reified. As I have said, EnDQT offers the possibility of different ontologies that reject the view that quantum states are entities in the world. I have also mentioned the alternative ontology of determinable and determinates in Section 1. So, the above objection has no force.

However, there is another alternative ontology where the world is filled with matters of fact even when systems are not interacting, and not just observables and flashes, for example. Also, contrary to the previously mentioned ontologies friendly to EnDQT, the changes modeled and inferred via the irreversible process of decoherence that give rise to determinate values become manifest via specific interactions. This is an ontology of quantum properties, where systems are collections of quantum properties. Quantum properties have a certain structure or features that impact the determinacy of the values that systems having them give rise to, which I will call the differentiation D^* of quantum properties.

So, for example, we have spin in a given direction, which comes in terms of different degrees of differentiation. These features of quantum properties are represented through observables concerning P (e.g., where P could be energy, momentum, etc.) and quantum states that are eigenstates of those observables. Systems have, by default, quantum properties with the lowest degree of differentiation, i.e., undifferentiated. Certain interactions change the degree of differentiation of such properties.

At least in the simple cases of decoherence that I have been assuming, the degree of differentiation is measured via the non-diagonal terms of the reduced density operator of the system subject to decoherence by systems that have the DC, when we trace out the degrees of freedom of the environmental system that are interacting with the system of interest. The quantum state of some system S with $\alpha, \beta \neq 0$,

$$\alpha \left|\uparrow_z\right\rangle_S + \beta \left|\downarrow_z\right\rangle_S , \tag{12}$$

and the observable S_z that acts on the Hilbert space of S, represents the quantum property spin-z of S. The spin-z of S has a degree of differentiation $D^* = 0$ and we consider that the system has an undifferentiated spin-z. This is because this system is not interacting with any other systems (note that it would still have an undifferentiated spin if it interacted with systems that don't have the DC).

Let's consider a system E, constituted by many subsystems that are interacting with S. For instance, S with quantum properties spin in different directions that interacts strongly with the many systems, also with spin in multiple directions, that constitute E. I will again put a subscript SDC in the systems that belong to an SDC. A system belonging to an SDC will have a stably differentiated quantum property represented via its quantum states when it interacts, in agreement with the CDCs (Section 2), with another system S, decohering it and thus giving rise to interactions belonging to an SDC. So, if S is interacting with a system E belonging to an SDC and having the DC-S (Section 2), we have that

$$\alpha \left|\uparrow_z\right\rangle_S \left|E_\uparrow(t)\right\rangle_{\text{E SDC}} + \beta \left|\downarrow_z\right\rangle_S \left|E_\downarrow(t)\right\rangle_{\text{E SDC}} . \tag{13}$$

The degree of differentiation of a quantum property that systems end up with after their interaction can be inferred and calculated via the overlap terms that concern the distinguishability of the states of E concerning S, such as $\langle E_\uparrow(t) \mid E_\downarrow(t)\rangle_{\text{E SDC}}$ and $\langle E_\downarrow(t) \mid E_\uparrow(t)\rangle_{\text{E SDC}}$. Generally, given

$$\hat{\rho}(t) = \sum_{i=1}^{N} \left|\alpha_i\right|^2 \left|s_i\right\rangle_S \left\langle s_i\right| + \sum_{i,j=1, i\neq j}^{N} \alpha_i \alpha_j^* |s_i\rangle_S \left\langle s_i\right| \left\langle E_j(t) \mid E_i(t)\right\rangle_{\text{E SDC}} \tag{14}$$

a measure of the degree of differentiation of the different D-P of S in spacetime region over time t for the simple scenarios that we are considering will be given by the von Neumann entropy[85] $S\left(\hat{\rho}_S(t)\right)$ of $\hat{\rho}_S(t)$ over $\ln N$, where N is the number of eigenvalues of $\hat{\rho}_S(t)$,

$$D^*(P, S, t) = \frac{S\left(\hat{\rho}_S(t)\right)}{\ln N} \tag{15}$$

Thus, we can measure and represent the degree of differentiation D* of the quantum property D*-P that S will end up with at the end of the interaction with E at t with $0 \leq D^*(P, S, t) \leq 1$, and the differentiation timescale (which is inferred via the decoherence timescale).

S ends up having a stably (qua irreversibly) differentiated quantum property if $D^*(P, S, t)$ goes quasi-irreversibly to one over time (in the sense that the recurrence of this term back to significantly different from zero is astronomically large). We also consider that system E decohered system S, and that both systems have undergone a so-called process of stable differentiation, which leads them to each have a determinate value. Upon knowing the actual result, we update the state of S to one of the $\left|s_i\right\rangle_S$, and consider that the system has a determinate value, which is an eigenvalue of the observable that $\left|s_i\right\rangle_S$ is an eigenstate of. Similarly in the case of E for $\left|E_i\right\rangle_E$.

A quantum property of S might not be fully stably differentiated and just be stably differentiated to some *degree* D^* by E, and thus, it has a value with a

[85] Given a density operator ρ_S for quantum system S, the von Neumann entropy is $S\left(\rho_S\right) = -\operatorname{tr}\left(\rho_S \ln \rho_S\right)$. $S\left(\hat{\rho}_S\right)$ is zero for pure states and equal to $\ln N$ for maximally mixed states in this finite-dimensional case.

degree of determinacy $D = D^*$. This can be inferred if the quantum states of an environment, which has the DC, have a non-zero overlap that is stable over time.

I will come back below to the intuition for why we can consider that there are values with degrees of determinacy. For now, note that not all interactions with a system give rise to systems having a determinate value, although there is something that changes in the quantum properties of the systems under these interactions. As a toy example, consider the spin of a particle in different directions in a series of Stern-Gerlach devices without letting the particles hit a screen between each device. The inhomogeneous magnetic field leads the subsystem of the particle with a spin in a certain direction to interact with the subsystem with the quantum property position, leading to their entanglement. There is something that changes in the spin direction of the quantum systems when the particle goes from one magnet to the other, but there is no determinate value arising. If there was, we would have an irreversible process, and thus, we wouldn't be able to reverse the result of the operations of the magnet via a Stern-Gerlach interferometer. So, the spin of the system that interacts with the other subsystem of the particle has an indeterminate value, although there is something that changes in the quantum property that corresponds to this indeterminate value.

As I have mentioned in Section 2, pragmatic reversible decoherence models allow us to infer and represent E and S interacting but having indeterminate values. This occurs when E doesn't belong to an SDC, not having the DC. The Stern-Gerlach case above is a case appropriately modeled via a pragmatic irreversible decoherence model.[86] I will call the interactions represented and inferred via the pragmatic reversible decoherence models, unstable differentiation interactions. During these interactions, both systems continue with their quantum properties undifferentiated.

As I have been assuming above, it is plausible to consider that some quantum properties can be stably differentiated to a certain degree, and this impacts the subsequent degree of determinacy of the value that arises from a quantum property. Let's look at the intuition for this. In the double-slit experiment, if the detectors at the slits interact with a quantum system weakly in such a way that we can't fully distinguish in which slit it passed we get some disappearance of interference. These interactions will give rise to a low entanglement between the position and the degrees of freedom of the detector. Furthermore, the more these interactions distinguish the path of the system, the more entanglement we have between the position of the target system and the degrees of freedom of the detector, and the more the interference disappears until it disappears completely under maximal entanglement. So, I have considered that stable differentiation of a quantum property comes in degrees and the determinacy of the resultant values.

To explain the dependence between the degree of determinacy of values of systems and the degree of differentiation of their quantum properties, I will adopt a functionalist account of indeterminacy. Very roughly, functionalism about

[86] See, e.g., de Oliveira & Caldeira (2006) for one such model.

property P^* is the position that P^* is the property of having some other property P in a certain situation or having specific features. The functionalist position provides an account of the dependence relation between the values properties (henceforward, values) v that I have been talking about, which come in terms of different degrees of determinacy and quantum properties. We have that

For a system to have a value v of P (where P could be energy, position, etc.) with a nonminimal degree of determinacy D is to have stably differentiated quantum property $D^* - P$ with a non-minimal degree of differentiation D^* where $D = D^*$. A system with a quantum property (fully) stably differentiated will have a determinate value of P.

On the other hand, indeterminacy and differentiation are related when the systems have a quantum property undifferentiated (which is the lowest degree of differentiation).

For a system to have an indeterminate value of P is to have an undifferentiated quantum property.

Pipa (2024) will enter into further details about this ontology. It may initially seem pedantic compared with the simpler ontology of flashes and observables. However, it captures more structure represented by quantum states (and decoherence) than the flashes. Systems don't only have determinate values under interactions (which would be analogous to the flashes), they have quantum properties with different degrees of differentiation that change over time.

Appendix C: Future directions

Future work should seek to test and further develop EnDQT. As one can see, EnDQT has a series of distinct features when compared with other quantum theories. At first, it seems that it will be very hard to distinguish EnDQT empirically from the other unitary interpretations of QT because, in practice like EnDQT, all of them appeal to (irreversible) decoherence connected with some environments in one way or another.

However, I have mentioned in section 2 several distinct predictions of EnDQT. Furthermore, since EnDQT doesn't violate relativistic causality, we can regard that as indirect evidence for this view since such violations have yet to be seen. Also, EnDQT offers a finer account of how determinacy propagates than other views since certain interactions between systems become important. If this finer account is further developed and empirically confirmed, it provides good support for EnDQT since the other interpretations of QT don't require it. So, first, we should find ways to test the CDCs with their distinct predictions discussed in section 2 and possibly propose and test new ones.

Another way to find confirmatory evidence for EnDQT is by searching for other phenomena that it can further explain. Future work should seek to investigate SDCs associated with spacetime and gravity in order to see if EnDQT could help achieve the integration of QT with gravity. Indeed, SDCs and gravity/spacetime have some aspects in common. It was shown via the Hawking-King-McCarthy-Malament theorem (Hawking et al., 1976; Malament, 1977) that (roughly) the causal order of relativistic spacetimes *determines* its geometry up to a conformal factor. A *causal* order of events also arises between the non-spacelike separated events that constitute SDCs. If we consider the SDC, $X \to Y \to Z$, we obtain the following "causal" order of events, $E_{X\to Y} \to E_{Y\to Z}$.$E_{X\to Y}$ are the events occurring when X gives rise to Y having a determinate value and transmits the DC to Y, and $E_{Y\to Z}$ are the events occurring when Y gives rise to Z having a determinate value and transmits the DC to Z. More generally, we can have a DAG representing the events where a system transmits the DC to another one or potentially does so, and it also gives rise to each other having determinate values. Given the SDCs-starting hypothesis, the beginning of SDCs like the origin of gravity and spacetime may date back to the beginning of the universe, both SDCs and spacetime expand and they are widespread. Perhaps, the events that arise from EnDQT could even give rise to its own version of the causal set-like structures[87] because SDCs seem to naturally give to the DAGs that characterize such structures, but where such sets naturally arise from the quantum level contrary to the causal sets program.

Appendix D: Interference phenomena according to EnDQT

In this appendix, I put into practice some of the above features of EnDQT to see how it can account for interference phenomena via a simple example.[88]

The electromagnetic field can be quantized, where such quantization proceeds by associating to each radiation mode a quantum harmonic oscillator and the corresponding so-called creation and annihilation operators, allowing us to express the particle number operator $\widehat{N}_{Ch}$. Each channel of the interferometer's beam splitters is associated with a number Ch. Let's consider that the eigenvalues Ch of the operator $\widehat{N}_{Ch}$ obtained from

$$\widehat{N}_{Ch}|n\rangle = n_{Ch}|n\rangle \tag{16}$$

represents the number of photons (the particle number) in the channel Ch, where each channel is associated with a radiation mode.

Now, let's consider the following states of the channels whose numbers appear in Figure 5, $|1000\rangle = |1\rangle_1 \otimes |0\rangle_2 \otimes |0\rangle_3 \otimes |0\rangle_4$, the same in the case of $|0100\rangle$, $|0010\rangle$, and $|0001\rangle$. The context will make clear whether, for example, 1 refers to A1 or

[87] Bombelli et al. (1987). In this case, the first events that constitute a set (i.e., the so-called "post") could arise from initiators. These events might allow us to hypothesize initiators that don't involve the inflaton. Such events could be the ones behind the origin of spacetime and gravity.

[88] This model is based on von der Linde (2021). See Cohen-Tannoudji et al. (1997) for a more extensive discussion of this framework.

B1, and so on. $|0\rangle$ is the vacuum state. Channels will allow us to represent the subsystems of the system under analysis, occupying different spatial regions of the interferometer.

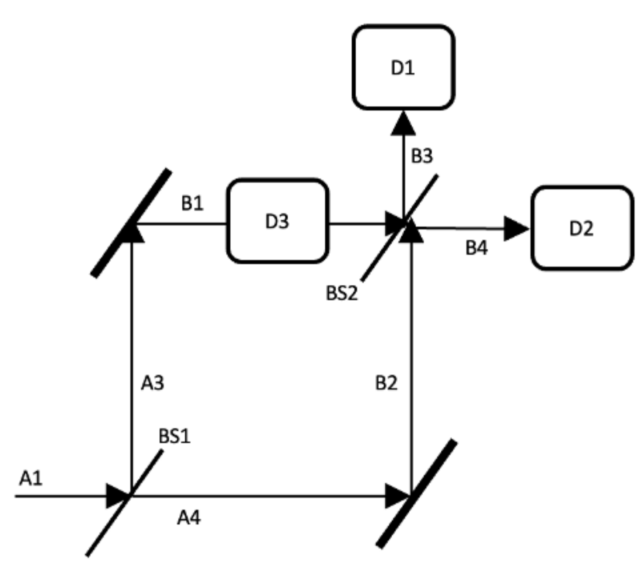

Figure 5: Mach-Zender interferometer

Let's start with the case where detector D3 is not present and consider that the initial state of the quantum system inserted into channel A1 together with the other systems is given by

$$|Input\rangle = |1000\rangle. \tag{17}$$

This system has an indeterminate particle number since it won't be interacting with systems that belong to an SDC at least after being prepared. After the interaction with the first beam-splitter, we obtain two subsystems with an indeterminate particle number whose state is given by the following entangled state,

$$\begin{aligned} |Final\rangle_{BS1} = 1/\sqrt{2}|0010\rangle \\ +i/\sqrt{2}|0001\rangle. \end{aligned} \tag{18}$$

Afterward, these systems will pass by the beamsplitter BS2, which gives rise to a system with the following state:

$$|Final\rangle_{BS2} = |0001\rangle. \tag{19}$$

After BS2, the system will interact with the detector D2, giving rise to a system having a 1 particle number determinate value during the interaction. Note that it's assumed that D2 is connected to an SDC.

Let's now clarify how interactions that lead to a determinate value work by examining what happens when detector D3 is placed at B1 (see Figure 5). This detector interacts with the quantum system, annihilating the above interference phenomenon. I am going to adopt the same SDC subscripts convention that I have adopted in the last sections. The interactions at time t' involving D3 (and omitting the interactions with D1 and D2) lead to the following state,

$$\begin{aligned}|\mathrm{Final}\,(t')\rangle = & \frac{1}{\sqrt{2}}|1000\rangle\,|E_1(t)\rangle_{SDC} - \frac{1}{2}|0010\rangle\,|E_0(t)\rangle_{SDC} \\ & + \frac{i}{2}|0001\rangle\,|E_0(t)\rangle_{SDC}\,,\end{aligned} \tag{20}$$

,

where these interactions can be represented via decoherence models.[89] How does EnDQT interpret the above phenomenon? First, note that contrary to $|E_1(t)\rangle\,, |E_0(t)\rangle$ concerns the inexistence of the measurement signal. It will also mean that the measurement device interacted with a subsystem, giving rise locally to a 0 particle number determinate value (i.e., the vacuum).

So, upon the placement of D3, there is also the probability of 1/2 of a photon arising at D3, and a 0 particle number arising at the other detectors. Furthermore, there is a 1/4 probability of one of the systems with an indeterminate particle number interacting with D1 or D2 and having a 1 particle number. Also, the other system giving rise to 0 particle number at D3. As I have argued in section 3 sections via the Bell scenario, note that all these interactions are local and there isn't any non-local influence. Here, we have a similar situation, but with quantum systems that can also give rise to interference.

Let's now consider instead the situation where the detectors are isolated from interacting with elements of an SDC, not belonging to an SDC as well. The quantum state $|\text{ Final }'(t')\rangle$ isn't anymore applicable to correctly represent the situation inside the lab. We would rather have

$$|Final(t)\rangle = \frac{1}{\sqrt{2}}|1000\rangle|E_1(t)\rangle - \frac{1}{2}|0010\rangle|E_0(t)\rangle + \frac{i}{2}|0001\rangle|E_0(t)\rangle, \tag{21}$$

and no systems would have determinate values.

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[89]For simplicity, I will not analyze in detail decoherence in the Fock basis and assume that the Schrödinger picture is applicable. See Walls and Milburn (1995), Mcclung et al. (2010), and Myatt et al. (2000) for a detailed account. I will also assume that a notion of spatiotemporal localization of particles arises during these interactions. See Fraser (2022) for a survey of different options that consider particles as non-fundamental, but emergent.

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