Does the Primitive Ontology of GRW rest on Shaky Ground?

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> It's all about gelatin. An electron can be here and there and that's it.
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> Angelo Bassi, 2020, *Interview for the NY Times*

Abstract

The notion of Primitive Ontology (PO) has recently received a great deal of attention in the quantum foundations literature. The PO is the fundamental ontology posited by a certain theory, what is *out there in the world* which makes the predictions of theory true. Can we make sense of the idea that the PO is indeterminate? And if we do, would this idea be explanatory useful in some way, or would it simply lead us too far from the very reasons we had to posit a PO in the first place? As I will show in this paper, these issues become of crucial importance when it comes to understanding what the ontology of the Mass Density approach to GRW (GRW_M) ultimately looks like. Proponents of the PO are never explicit in claiming that the determinacy is a requirement for the notion, yet arguably this is entailed by one of the criteria for a suitable PO, namely its being always well defined in every point in 3D space. I will argue that this requirement is however not satisfied in GRW_M. The conclusion I will draw is that the notion of indeterminate PO should be taken seriously, for it is suggested by one the major interpretations of quantum mechanics.

Keywords

GRW. Mass Density. Primitive Ontology. Quantum Mechanics. Quantum Indeterminacy.

1 Introduction

Some of the major issues in both contemporary philosophy of science and naturalistic metaphysics come from the conceptual puzzles arising from quantum mechanics (QM). And in particular, they come from the fact that this theory

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seems to challenge many of our classical intuitions, thus making it hard to be reconciled with the everyday picture of the world. Experiments have revealed that microscopic particles sometimes behave as if they can be located in two places at the same time, that the precise values of certain pairs of quantities cannot jointly be assigned, that certain properties are not possessed independently of observation, or that instantaneous interactions at a distance are allowed. A long standing, still lively tradition has taken all of this to suggest, if not entail, that the standard reductionist program should be abandoned, and even that novel forms of realism have to be developed if we wish to understand the quantum world.

It is against this background that we can understand the reasons why the notion of Primitive Ontology (PO) has been advocated [4], and why it is recently gaining more and more attention. The inspiration for this approach comes from Bell's [9] reflection on the idea of *be*-ables, a term coined to be clearly distinguished from the notion of *observ*-ables (p. 52).

> 'Observables' must be *made*, somehow, out of beables. The theory of local beables should contain, and give precise physical meaning to, the algebra of local observables. (p. 52)

As the term itself indicates, the *be*-ables of a theory should represent what exists in the world, the ontology:

> The beables of the theory are those entities in it which are, at least tentatively, to be taken seriously, as corresponding to something real. (p. 234)

While introducing this notion, Bell expresses full agreement with Bohr's idea that every experience and physical evidence must be accounted for in *classical* terms, and claims that "it is the ambition of the theory of local beables to bring these 'classical terms' into the equations" (p. 52). So it is quite natural to suppose that according to Bell whatever beables a certain theory has, these must be described in classical terms. The PO program aims at developing Bell's insights into a full-fledged approach to the ontology of physical theories, be them quantum or not. Here is Allori [3], summing up nicely the guiding ideas behind the view:

> According to this approach, any satisfactory fundamental physical theory, if taken from a realist point of view, contains a metaphysical hypothesis about what constitutes physical objects, the PO, which lives in three-dimensional space or space-time and constitutes the building blocks of everything else. In the formalism of the theory, the variables representing the PO are called the primitive variables. In addition, there are other variables necessary to implement the dynamics for the primitive variables: these non-primitive variables could be interpreted as law-like in character. Once the primitive and the non-primitive variables are specified, one can construct an

> explanatory scheme based on the one that is already in use in the classical framework. (p. 177)

According to Allori, a suitable PO has to be (i) microscopic, (ii) well localized in 3D space, and (iii) appropriately distinguished from the dynamical variables of the theory. The criterion (ii) plays a crucial role, for it is meant to avoid problematic states of superposition at the level of the fundamental ontology. Once again, this idea traces back to Bell's claim [9] that the "beables are those which are *definitely* associated with particular space-time regions" (p. 234, emphasis mine). If met, the requirements (i)-(iii) would ground a classical reductive explanation of the behaviour of the macroscopic ontology as determined by the behaviour of the PO. The overall goal of this approach is then to show that such a classical explanatory scheme, which is not dissimilar from the one we can find in classical physics, can be obtained in most of the live interpretations of QM [4], [5]. And if this is true, as proponents of this approach claim, then arguably we would have little reasons to completely revise the way we think about physics and its place in our understanding of nature.

How far this program can go, and especially how *classical*, in Bell's sense, can the PO be, is highly debated. The two major lines of criticisms seem to point in opposite directions. On the one hand, it has been argued that the notion of PO is too general and empty to be useful when applied to concrete cases, especially if we consider that every theory that has been proposed as an example of the PO scheme is not a fundamental theory (e.g. [33], p. 20). On the other hand, it has been stressed that some of the criteria for a suitable PO are too strict, and may not be satisfied in QM (e.g. [28], p. 115).[1] In this paper I will be focusing on this latter line of criticism, and especially on whether the criteria according to which the PO is "definitely associated with particular space-time regions", to use Bell words, is indeed satisfied within the context of the Mass Density approach to GRW ([17], GRW$_M$). Proponents of the PO approach have argued that GRW$_M$ provides a good exemplification of their view, and yet, as I will show, the PO in this theory cannot always be ascribed a definite localisation in 3D space.

Once the desiderata of definiteness for the PO is put into question, it becomes legitimate to ask whether the notion we are left with does indeed serve the purposes for which it was developed. The very idea of an *indeterminate* PO, as I will be calling it, may seem to contradict our intuitions. The reason is probably that the PO is the fundamental ontology according to a given theory, and while we may be tempted to accept indeterminacy at some derivative level of reality [25], it is hard to entertain the thought that the world is indeterminate at its fundamental level. However, I will suggest that if this idea is supported by one of the major interpretations of QM, and if it proves to be both consistent and explanatory useful, then a good naturalistic attitude should prevent us from ruling it out just based on our intuitions.

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[1] I note that in this context quantum non-locality also poses a very serious threat since, as Bell himself claimed, "it may well be that there just *are* no local beables in the most serious theories" ([9], p. 235). Here I will not be concerned with this issue.

Roadmap. In §2 I analyse how the Mass Density ontology of GRW_M has been interpreted within the PO framework. In §3 I argue that a crucial feature of the Mass Density is that the PO is not always well localised in 3D space. In §4 I suggest the notion of *indeterminate PO* as a way to understand the ontology of GRW_M.

2 The PO Approach to GRW

The guiding idea behind the spontaneous collapse models such as GRW [18], is to modify the Schrödinger's dynamical equation of standard QM by adding a stochastic and non-linear element to it. This allows for an explanation of the wave function collapse within the dynamics itself, and provides what Ghirardi Rimini and Weber called a "unified dynamics for microscopic and macroscopic phenomena" [18]. In theories like GRW, the collapse is an objective, physical mechanics, and contrary to standard QM, we need no obscure reference to observers, measurements, or experimental apparata in order to explain it. Given the dynamics of the theory, collapses happen spontaneously and randomly with a certain probability rate per unit time.[2] The rate is such that for microscopic systems (like nucleons) the collapse of the wave function is incredibly rare, whereas for macroscopic objects made of a large number of mutually entangled particles, the collapse is practically certain to occur in a very short time. In this way, the theory allows to explain why microscopic objects can show quantum behaviour (such as interference pattern in a double slit experiment), and at the same time why at the macroscopic scale this behaviour has no effect.

A major problem with any spontaneous collapse model is that the dynamical evolution never evolves into eigenstates of the relevant operators, but only very close to them. When a GRW collapse occurs, the wave function gets multiplied by a Gaussian that localizes the system with a certain accuracy. And although a large part of the post-collapse state is localized in a small portion of space, the system is also spread infinitely in both sides of the *tails* of the Gaussian. This is known as *tails problem*, and it is among the most discussed issues in the literature on GRW (for an overview, see [22], and [26]). The main strategy to solve this problem is to change the standard way of ascribing properties to physical systems starting from the quantum state, namely the Eigenstate-Eigenvalue Link (EEL). Several revisions to the EEL have been proposed in order to explain the definiteness of experimental outcome in GRW ([2], [27], [23], *inter alia*), and despite the differences between them, the general idea is to allow for property ascription even when the relevant observable is not in an eigenstate, but appropriately close to it. The major drawback of this strategy is that it seems to introduce a certain degree of vagueness and arbitrariness at

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[2] This is achieved by introducing two constants for the spontaneous localization, one for its accuracy in space ($\alpha = 10^{-5}$cm), and one for its frequency in time ($\lambda = 10^{-16}\mathrm{s}^{-1}$). These values for α and λ were proposed in [18], but I report that during the years different values have been proposed (e.g. [1]), some of which have been empirically falsified. For a recent discussion, see [29].

the level of the ontology ([23], [32]). An alternative option to solve the *tails problem*, proposed in the context of the PO approach, consists in postulating additional ontology over and above the wave function.[3] Moreover, this strategy looks especially motivated when we consider in more details one of the most developed versions of the theory, namely the one proposed in [17] and [8], and later called Mass Density GRW (GRW_M for short).[4]

In every GRW-type of theory, the collapse is defined by picking a preferred basis on the Hilbert space on which it occurs. The crucial conceptual amendment of GRW_M with respect to previous versions of the theory concerns the introduction of a new operator $M(\mathbf{r})$ for the Mass Density, which serves as the preferred basis of collapse, and which is defined in [17] as follows:

$$M(\mathbf{r}) = \sum_k m_k N_k(\mathbf{r}) \tag{1}$$

Where k are the particles of a given type, $\mathbf{r}$ stands for a given spacetime point, and N is the operator describing the number of particles, which is in turn defined as:

$$N(\mathbf{r}) = a^{\dagger}(\mathbf{r})a(\mathbf{r}) \tag{2}$$

In [18], the eigenbasis of $N(\mathbf{r})$ was the preferred basis in the Hilbert space on which collapses occur, whereas in GRW_M the selected basis is $M(\mathbf{r})$. An important consequence of this amendment is that it provides a way to indicate unambiguously what the theory is about, its be-ables, by defining a Mass Density Function $\mathcal{M}(\mathbf{r}, t)$ in 3D space.[5] Consider a physical system S of N particles with corresponding Hilbert space $\mathcal{H}(S)$ of $3N$ dimensions. We then define $\mathcal{M}(\mathbf{r}, t)$ as follows:

$$\mathcal{M}(\mathbf{r}, t) = \langle \psi(t) | M(\mathbf{r}) | \psi(t) \rangle \tag{3}$$

$|\psi(t)\rangle$ is the normalized vector[6] describing S at time t, and $M(\mathbf{r})$ is the mass density operator defined in Eq. (1) above. The mass density function defined in (3) provides a way to map $\mathcal{H}(S)$ onto the space of 3D functions $\mathbf{r}$, at a given

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[3] See [32] for an extensive review of the reasons why a PO helps solving the conceptual problems of GRW, *tails problem* included.

[4] Proponents of the PO have also individuated another version of GRW as a good exemplification of their view, namely the theory developed by Tumulka [31] and known as GRW Flash. Since my focus in this paper is on GRW_M only, I will not discuss this other option any further.

[5] I note *en passant* that the reasons behind the choice made in [17] of a Mass Density operator also have to do with certain technical issues (see [16] for a review) which are largely independent from the philosophical problem I am discussing here. This is important insofar as it reminds us that whatever inclination one has towards the PO approach, it is still a fact that in the most developed version of GRW mass is going to play a crucial role.

[6] Notice that the Stratonovich equation of any GRW-type of theory does not actually generate normalized vectors. I am going to set this complication aside here.

time t. If we now suppose that the physical system S is the whole universe (and therefore that $\mathcal{H}(S)$ is its corresponding Hilbert space), it follows that (3) gives the average, continuous distribution of mass throughout the 3D space.

The conceptual move made by proponents of the PO approach is to posit an ontology, the Mass Density, that always has definite values in every point in 3D space, and which is fully represented by the Mass Density function $\mathcal{M}(\mathbf{r}, t)$.[7] This view was first suggested in [20], and then discussed in more details in [4], [14], and [32]. Ghirardi himself has expressed sympathy towards this approach in many of his writings (e.g. [15], [16]).

It is important to note that, on this view, although the ontology is determinate in every point in 3D space, the location of microscopic objects is not definite ([14] p. 2), since their mass is literally smeared out in physical space (again due the tails of the Gaussian). This is however not problematic as far as the large portion of the mass of a certain object is located within a small region [14]. Microscopic objects are derivative entities which are grounded on the mass density distribution. And if there is any indeterminacy to them, this does not affect the PO itself. What really matters is that the fundamental ontology, which is given by the distribution of mass throughout space, is not itself indeterminate. And indeed, the idea that the mass density distribution is, to use Glick's words, "perfectly determinate" ([19], p. 205) has been advocated many times in the literature ([14], [5], [19], [12], [32]).

In the next section I argue that this supposition is however unmotivated, and that we have good reasons to believe that the mass density (so the PO) may not be always well localised in 3D space, and may therefore be indeterminate.

3 Accessible and Non-Accessible Mass

The Mass Density function $\mathcal{M}(\mathbf{r}, t)$ is a many to one mapping, as Ghirardi *et al* [17] immediately notice. To see this, consider a large number of particles N and two regions A and B both of spherical shape and of the same size, and then compare the following two states $|\psi^{\oplus}\rangle$ and $|\psi^{\otimes}\rangle$:

$$|\psi^{\oplus}\rangle = \frac{1}{\sqrt{2}}\left[|\psi_N^A\rangle + |\psi_N^B\rangle\right] \tag{4}$$

$$|\psi^{\otimes}\rangle = |\phi_{N/2}^A\rangle \otimes |\phi_{N/2}^B\rangle \tag{5}$$

Eq. (4) expresses a linear superposition of equal amplitudes of the states $|\psi_N^A\rangle$ and $|\psi_N^B\rangle$. Eq. (5), on the other hand, expresses the tensor product of the states $|\phi_{N/2}^A\rangle$ and $|\phi_{N/2}^B\rangle$ describing the physical situation of $N/2$ particles in region A and $N/2$ particles in region B.

Now notice that the states $|\psi^{\oplus}\rangle$ and $|\psi^{\otimes}\rangle$ give rise to the same mass density function $\mathcal{M}(\mathbf{r}, t)$ for each region A and B. Consider for example region A:

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[7] This also means that there *no* hidden variables here.

$$\mathcal{M}^{\oplus}_{(\mathbf{r},t)} = \langle \psi^{\oplus}_t | M(\mathbf{r}) | \psi^{\oplus}_t \rangle \approx \frac{1}{2} \langle \psi^A_N | M(\mathbf{r}) | \psi^A_N \rangle \approx \frac{Nm}{2} \tag{6}$$

$$\mathcal{M}^{\otimes}_{(\mathbf{r},t)} = \langle \phi^{\otimes}_t | M(\mathbf{r}) | \phi^{\otimes}_t \rangle \approx \langle \phi^A_{N/2} | M(\mathbf{r}) | \phi^A_{N/2} \rangle \approx \frac{Nm}{2} \tag{7}$$

The same goes for region B. Although the functions generated by (6) and (7) are the same, it is important to discriminate between the states that originate them. For instance, Monton ([27], pp. 14-15) imagines a particle traveling between regions A and B, and ask what we should expect to happen in both cases. In the case of $|\psi^{\oplus}\rangle$, the particle would become entangled with the mass in both regions, and would therefore be deflected upwards or downwards with equal probability. In the case of $|\psi^{\otimes}\rangle$ instead, since both regions have the same mass density, the particle would proceed its trajectory undeflected.

To explain the difference between the two states, Ghirardi *et al* [17] define a criterion for individuating what are the states that give rise to *accessible* mass distributions (like $|\psi^{\otimes}\rangle$), and what are the states that do not ($|\psi^{\oplus}\rangle$). Their method is simply to define the ratio between the mean expectation value for a given outcome and the variance. We first define the variance $\mathcal{V}(\mathbf{r},t)$ for the mass density operator $M(\mathbf{r})$ as follows:

$$\mathcal{V}(\mathbf{r},t) = \langle \psi(t) | \left[M(\mathbf{r}) - \langle \psi(t) | M(\mathbf{r}) | \psi(t) \rangle \right]^2 | \psi(t) \rangle \tag{8}$$

Given $\mathcal{V}(\mathbf{r},t)$, we can define the ratio:

$$\mathcal{R}^2(\mathbf{r},t) = \mathcal{V}(\mathbf{r},t) / \mathcal{M}^2(\mathbf{r},t) \tag{9}$$

Now, if $\mathcal{R}$ turns out to be much smaller than 1, this suggests that the corresponding mass density can be considered *accessible.* If instead $\mathcal{R}$ is close to 1, the corresponding mass is defined as *non-accessible.* Thus, we can now state the following *Criterion of Accessibility* (CAM) for any Mass Density state:

CAM — $\mathcal{M}(\mathbf{r},t)$ is accessible *iff* $\mathcal{R}(\mathbf{r},t) \ll 1$.

Given CAM, it can be shown that in the above example the mass corresponding to the state $|\psi^{\otimes}\rangle$ is *accessible* because the value of $\mathcal{R}$ is much smaller than 1:

$$\mathcal{R}^{\otimes}(\mathbf{r},t) \ll 1 \tag{10}$$

Contrariwise, for $|\psi^{\oplus}\rangle$ the value of $\mathcal{R}$ is close to 1, and therefore the corresponding mass is *non-accessible.*

$$\mathcal{R}^{\oplus}(\mathbf{r},t) \approx 1 \tag{11}$$

According to Ghirardi and Bassi [8], the *Criterion of Accessibility*, along with the distinction between *accessible* and *non-accessible* mass, is what explains why, as we should have expected all along, macroscopic superposition states like $|\psi^{\oplus}\rangle$ are not empirically accessible.

Now let us ask: what is the ontological status of the *non-accessible* portion of mass? Recall that, on the PO approach, the ontology of GRW$_M$ is fully represented by the Mass Density function $\mathcal{M}(\mathbf{r}, t)$. However, as I have just shown, there can be different states corresponding to the same $\mathcal{M}(\mathbf{r}, t)$, not all of which describe well localised mass density configurations. We seem to have two options here: either we reject states like $|\psi^{\oplus}\rangle$ as representing something real, or we provide an explanation of the difference between the states $|\psi^{\oplus}\rangle$ and $|\psi^{\otimes}\rangle$ in terms of the PO.[8]

The first option is to simply stipulate that there is *no* ontology corresponding to *non-accessible Mass*. As a matter of fact, this option is suggested by Ghirardi and collaborators in the very same paper where the argument I gave above is presented [17], where instead of "not accessible" it is used the adjective "not objective" to refer to the mass corresponding to states like $|\psi^{\oplus}\rangle$. This option looks however highly problematic. Given that the *Criterion of Accessibility* is purely operational (recall that it is given by the variance), by claiming that states like $|\psi^{\oplus}\rangle$ are not objective or real it would follow that what exists according to the theory, its ontology, depends on what observers can and cannot do.[9] And in effect Tumulka—one of the major defenders of the PO approach for GRW$_M$—is explicit in rejecting this option:

> [...] the PO does provide a picture of reality that conforms with our everyday intuition. All this is independent of whether the PO is observable (accessible) or not. Bassi and Ghirardi sometimes sound as if they did not take the matter density seriously when it is not accessible; I submit that *the PO should always be taken seriously.* ([32]: p. 142, italics mine)

Tumulka suggests that the second option is preferable, and so we have to accept the existence of *non-accessible mass* and give an ontological explanation of the difference between $|\psi^{\oplus}\rangle$ and $|\psi^{\otimes}\rangle$ in terms of the PO. The most immediate way to do so would be to simply assume that, even if not accessible, in the state $|\psi^{\oplus}\rangle$ the mass is spread evenly over the two regions, half in A and half in B (precisely as it happens for the state $|\psi^{\otimes}\rangle$). But then the natural worry is that we are left with no explanation whatsoever as to why, in the case of $|\psi^{\oplus}\rangle$, the test particle we send through regions A and B is deflected, whereas in the case of $|\psi^{\otimes}\rangle$ it is not. As Myrvold [28] nicely puts it: "[s]omething that you might

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[8] There is actually a third option, which is to accept that there is more to the quantum state than just the PO. The reason why I do not consider this view is because it would entail that the PO is redundant, since we would still need the quantum state to play an *ontological* role (beyond just determining the dynamics). But since the whole point of positing the PO is to avoid that, this option should not be adopted.

[9] A similar argument can be found in [26], [32], [27], *inter alia*. See [24] for a more extensive critique of this approach to non-accessible mass, and for a review of the various options.

be inclined to call a "mass", if it doesn't act like a mass, is not a mass" (p. 114). And even if we were to call it "mass", the problem is still that if there is PO corresponding to states like $|\psi^{\oplus}\rangle$, and if we want to explain the physical difference with respect to the state $|\psi^{\otimes}\rangle$, we simply have to accept that in the former case the "mass" is not associated to a definite region of 3D space.[10] We cannot simply stipulate that it is, for if the configuration of the PO is the same, we would have no explanation whatsoever for the difference between the two states. The explanation has to be based in the PO itself.[11]

Thus, the question before us is this: is there a plausible way to take *non-accessible mass* states seriously, and give an ontological explanation to them, while still endorsing the PO approach?

4 The Indeterminate Primitive Ontology

I suspect that at this point the reader may be inclined to wonder why not simply take the arguments in the previous section as a straightforward objection to the PO approach. The thought would go something like this: if the ontology of GRW_M allows for states of non-accessible mass, and if these states are not well localised in 3D space (as the view requires them to be), then the PO approach fails to apply to GRW_M. This is a fair point, and yet I believe it generates from a confusion on the very role that the PO is supposed to play as something we need to postulate over and above the wave function.

In a somewhat general way, the need to posit a PO comes from the simple thought that any physical theory should describe something in the world, the *stuff* in 3D space, and that everything else should be reduced to, and explained by the behaviour of the PO. Moreover, this approach is motivated by the idea that the quantum state or the wave function are *not* the right candidates for a satisfactory ontology. If both these goals are achieved in GRW_M, then why bother if the PO turns out to be indeterminate in the sense of lacking definite properties? Perhaps, once we realise that the general reductive explanatory scheme proposed by the PO approach is indeed satisfied, and that an ontology beyond the wave function is provided, a more interesting question to address is what motivated in the first place the claim that the PO must be definite and well localised in every point in 3D space.

As I anticipated in the introduction to this paper, I think that the justi-

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[10] Also note that, for this reason, the ontology of GRW_M is crucially different from the case of a classical field in which, despite not being well localised, the ontology is definitely associated to any spacetime point. I thank two anonymous reviewers of this journals for inviting me to elaborate on this point.

[11] As Tumulka claims in the very same context:

> [The problem] concerns whether GRW theories provide a picture of reality that conforms with our everyday intuition. Such a worry cannot be answered by pointing out what an observer can or cannot measure. Instead, I think, the answer can only lie in what the ontology *is like*, not in what observers see of it. ([32]: 142)

fication for this claim goes something like this: (i) the PO of a theory is, by definition, its fundamental ontology; (ii) the fundamental ontology cannot be indeterminate; therefore, the PO cannot be indeterminate. This very simple two-premise argument not only explains why proponents of the PO assume that the determinacy is a requirement, but also suggests why, for instance, Myrvold [28] takes the the existence of non-accessible mass as a good reason to reject the PO and endorse realism towards the quantum state in the context of GRW_M. As it should be clear enough by now, the point I am trying to make is that premise (ii) of the above argument is unwarranted, for we have no reasons to believe that fundamental indeterminacy is incoherent. I will shortly come to this. First though, since I think it is very instructive to realise that the truth of this premise is assumed by both defenders and detractors of the PO approach, let me spend a few words on Myrvold's view.

Some of the attempts to provide an understanding of the ontology of GRW refer, sometimes explicitly, to the notions of *indefiniteness*, *vagueness*, or *fuzzyness*. In most of the cases, these notions are meant to indicate that the fundamental entities described by this theory may objectively lack definite values for their properties.[12] Myrvold's *Distributional Ontology* [28] is a clear example:

> In classical physics, dynamical quantities always possess precise values. In quantum theory, there is always some imprecision [...] But the full reality is that associated with each dynamical variable is a *distribution of values.* This distribution, though formally like a probability distribution, is to be thought of not as a probability distribution over a precise but unknown possessed value but as reflecting a physical, ontological, lack of determinacy about what the value is. (p. 118)

Myrvold argues for this view mainly based on Ghirardi's argument about *non-accessible mass* which I also gave in §3. However, he also explicitly takes this argument as an objection to the PO program, and then defends a view according to which ultimately the mass density (along with every other physical property) is grounded on the quantum state. So in this case too, any indeterminacy appears at some derivative level (the mass density, for instance), but does not affect the fundamental level (the quantum state). However, if one were convinced that the quantum state is not the right kind of entity to be a candidate for the PO, and that we need to posit additional ontology beyond it, then presumably Myrvold's conclusion would hardly be taken to follow from the premises.[13] Once again, for such conclusion to be justified, we also need the assumption that the PO *must* be determinate, if it exists at all. If instead, as I am suggesting in this paper, we give up on this idea, there is no need to

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[12] For reasons of space, I cannot discuss other views in this vicinity. A notable example is Monton's *Mass Density Simpliciter* view, which, as discussed in [26] and [24], also seems to allow for indeterminacy in the ontology.

[13] Myrvold himself recognizes this, and goes on to defend the viability of quantum state realism.

reject the PO approach and endorse the view that the quantum state is more fundamental than the mass density distribution.

I have shown that there are good naturalistic reasons for taking seriously the idea that the PO may be indeterminate in GRW. Moreover, I have individuated what seems to be the cause of the scepticism towards this idea, and which is also probably why it has not been developed so far, namely the thought according to which the fundamental ontology cannot be indeterminate. As a matter of fact though, some fairly recent developments in the metaphysics of physics seem to go in the very opposite direction, suggesting that we can indeed make sense of this very idea. In particular, many authors ([13], [10], [30]; for an overview see [11]) have suggested that QM, by violating the supposition that objects always have definite values for their properties, may provide an instance of what philosophers call *ontological indeterminacy.* For several decades this notion was not even considered to be consistent (notably, [21]). Quite recently however, it has been shown that we can indeed provide clear accounts of what it means for something to be objectively indeterminate ([7], [34], *inter alia*), along with well defined criteria for distinguishing determinate from indeterminate states of affairs. As it happens sometimes, a good conceptual analysis may be useful in providing a more refined picture of what physics tells us, even though this might entail a departure from our classical presuppositions about the world. For all these reasons, I take it that the main lesson we learn from GRW is that we should start to seriously entertain the possibility that the world is fundamentally indeterminate.[14]

5 Conclusions

The core motivation for adopting the Primitive Ontology approach is to provide a classical reductive explanation of the behaviour of macroscopic objects as determined by the behaviour of the microscopic, fundamental ontology. Contrary to what proponents of this approach seem to suggest, however, all of this is independent from whether the PO is indeterminate or not. To make this point, in this paper I have been focusing on GRW$_M$, which has been taken by proponents of the PO approach as one of the best exemplifications of their view. The main claim of this paper is that, since it is suggested by one of the major interpretations of QM, the notion of *indeterminate PO* should be taken seriously from a naturalistic point of view.

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[14] I cannot develop this idea further here. However, a good working hypothesis seems to me that the approach to indeterminacy developed in [10] may be used in the context of GRW$_M$, for it would allow to distinguish between indeterminate and determinate states of affairs, thus providing an explanation to the distinction between accessible and non-accessible mass that is based on the PO itself rather than on the quantum state.

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