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The physics and metaphysics of Tychistic Bohmian Mechanics

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ABSTRACT

The paper takes up Bell's (1987) "Everett (?) theory" and develops it further. The resulting theory is about the system of all particles in the universe, each located in ordinary, 3-dimensional space. This many-particle system as a whole performs random jumps through 3*N*-dimensional configuration space – hence "*Tychistic* Bohmian Mechanics" (TBM). The distribution of its spontaneous localisations in configuration space is given by the Born Rule probability measure for the universal wavefunction. Contra Bell, the theory is argued to satisfy the minimal desiderata for a Bohmian theory within the Primitive Ontology framework (for which we offer a metaphysically more perspicuous formulation than is customary). TBM's formalism is that of ordinary Bohmian Mechanics (BM), without the postulate of continuous particle trajectories and their deterministic dynamics. This "rump formalism" receives, however, a different interpretation. We defend TBM as an empirically adequate and coherent quantum theory. Objections voiced by Bell and Maudlin are rebutted. The "for all practical purposes"-classical, Everettian worlds (i.e. quasi-classical histories) exist sequentially in TBM (rather than simultaneously, as in the Everett interpretation). In a temporally coarse-grained sense, they quasi-persist. By contrast, the individual particles themselves cease to persist.

1. Introduction

The present paper advances a "minimally" Bohmian theory – Tychistic[1] Bohmian Mechanics (TBM) – as both empirically and metaphysically adequate. It is minimally Bohmian in two senses. First, it satisfies a plausible minimum of desiderata for a theory to qualify as Bohmian; secondly, it uses only a minimum of assumptions on which the predictive success of ordinary Bohmian Mechanics (BM) rests – BM's "working posits".[2] Metaphysically, its key novelty consists in a distinctive *combination* of fundamental stochasticity, its many-worlds ontology, and Bohmicity (i.e. it belongs to the class of Bohmian quantum theories).[3]

In a nutshell, TBM retains BM's overarching ontological framework. Its referents are particles, located in ordinary 3-dimensional space. Their positions are always determinate. In contrast to standard BM, however, TBM drops the supposition that those particles follow continuous trajectories: according to TBM, the universe – understood as an *N*-particle system *as a whole* – performs fundamentally stochastic jumps through configuration space. Rather than co-existing simultaneously as in the Everett interpretation, different worlds pop into existence *sequentially*: by hopping through configuration space, the universe instantiates (actualises) those structures in the wavefunction of the universe which correspond to Everettian worlds (i.e. quasi-classical histories, warranted by decoherence), see Fig. 1. The probability for those spontaneous materialisations is given by the Born Rule for the wavefunction of the universe.

An inchoate articulation of the theory harkens back to Bell's (1987) interpretation of Everett's many-worlds interpretation.[4] Demurring that it leads to a temporal form of solipsism, he dismissed it. The subsequent

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[1] To avoid confusion with Nelson Stochastics or versions of Bohmian Mechanics with a non-standard stochastic dynamics, we stick to Tychistic Bohmian Mechanics; "tychistic" here is meant to denote objective, irreducible randomness. An association with C.S. Peirce's tychism is unintended.

[2] TBM can be understood as an attempt to turn a principle-theory stance towards the Born Rule into a constructive sub-quantum theory (see Brown, 2005, esp. Ch. 5 and Flores, 1999 on Einstein's constructive/principle theory distinction). We thank Harvey Brown (Oxford) for pointing this out.

[3] We thank an anonymous referee for pressing us on this!

[4] For details see below in §3. The theory is mentioned in e.g. Brown (1996b, p. 196); Daumer et al. (1997, p.393); Barrett (1999, p. 122, pp. 183); Butterfield (2001, p. 3.1.2); Allori et al. (2008, sect.6); Drezet (2016); Gao (2016, Ch.7.4.4); Maudlin (2016, p. 324).Yet, it's given little serious attention. A partial exception is Barbour (1994 a,b, 1999), who draws inspiration from it for his own time-less interpretation of quantum gravity.

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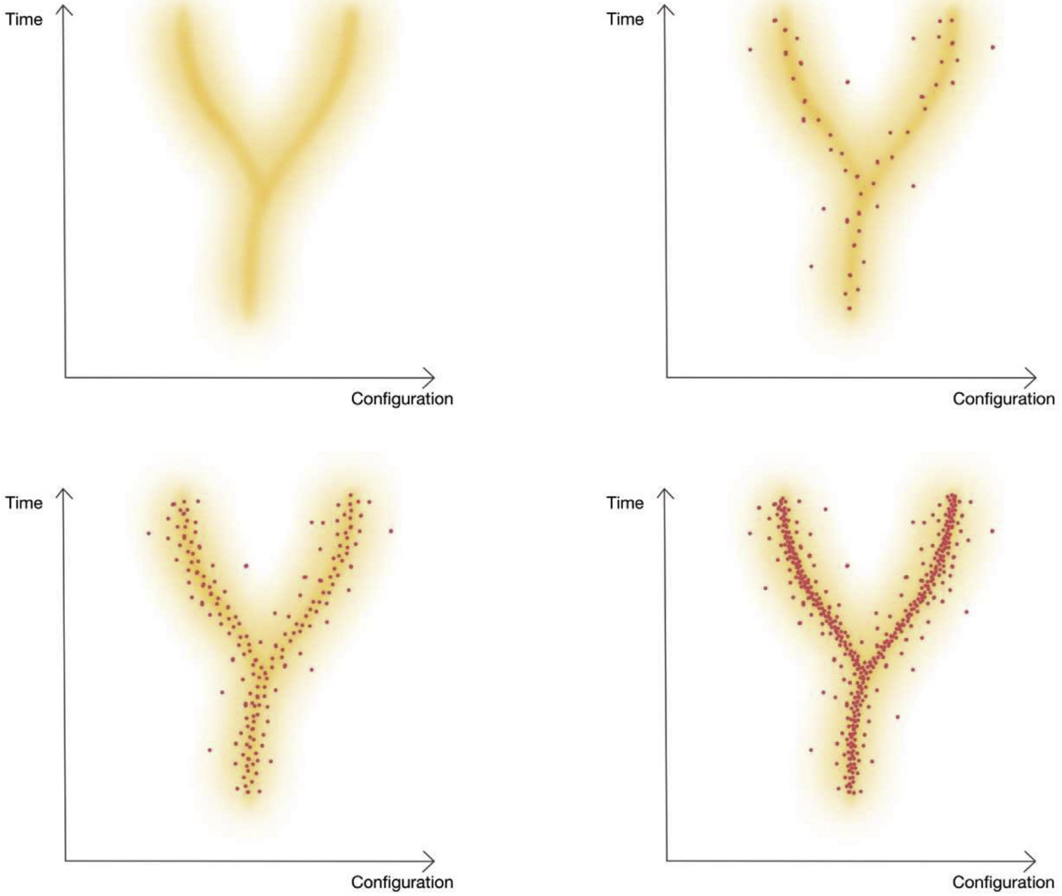

Fig. 1. The figure illustrates three points: 1. The N-corpuscle system (or the "totality of corpuscles", TOC) carves out (almost surely) the universal wavefunction. 2. Space is densely filled with many-worlds sequentially popping into existence. The corpuscles form a quasi-plenum. 3. On a temporally coarse-grained level, the FAPP-worlds quasi-persist.

literature has largely concurred with the arguments Bell gestures at. In consequence, the theory received only marginal attention. We are unhappy with several of the received arguments in that discussion. Accordingly, our present paper pursues four goals:

(1) To provide a more perspicuous formulation of the theory – TBM.
(2) To re-appraise the extant criticism of its central idea, in particular by Bell and Maudlin.
(3) To argue that TBM is a close cognate of BM – what is left of BM, once one shears the latter of all dispensable elements (and re-adjusts the interpretation of one of its remaining postulates) – rather than a reading of the Everett interpretation.
(4) To outline TBM's salient metaphysical features.

Our present aim *isn't* to advocate TBM as necessarily superior to BM (nor to the Everett interpretation). That would require a circumspect evaluation of *all* of their respective shortcomings and advantages. In particular, we don't argue that TBM scores necessarily better in terms of parsimony. Such claims call for a separate analysis – one that must pay attention to different forms of parsimony/simplicity exemplified in the theories in question (and how they are supposed to trade off against each other – *if* one wants to regard them as truth-indicative criteria for theory selection at all). Here, we rest content with demonstrating that TBM is an empirically adequate and coherent theory. As such, it deserves a place at the table of the current discussions. Like standard BM, it falls within the framework of so-called Primitive Ontology (see §3.4 for details). Thus, TBM circumvents criticism of those who insist on compliance with that framework as a metaphysical sine qua non for any theory. Insofar as in what follows we compare TBM and other theories, it solely serves the purposes of clarification, in particular by demarcating TBM from those other theories.

The paper proceeds as follows. In **§2** we review BM, recapitulating its motivation, formulation and standard interpretation. In **§3** we introduce and develop TBM. **§3.1.** argues that an investigation of TBM is rewarding, even if one rejects it in favour of BM. **§3.2** elucidates TBM's principles and interpretation. We demonstrate its empirical adequacy. **§3.3.** sketches the role of probabilities in TBM, and their possible interpretations. In **§3.4.**, we argue that TBM counts as a Bohmian theory, distinct from the Everett interpretation. We next turn to TBM's salient metaphysical features. **§3.5.** critically re-evaluates Bell and Maudlin's reasons for rejecting TBM. In elaborating further its many-worlds character, we show TBM to be coherent. We summarise our findings in **§4.**

2. Review of Bohmian Mechanics

This section outlines the motivation, basic postulates and received interpretation of standard BM. It's a theory about particles with determinate, deterministic trajectories, whose dynamics is constructed from the wavefunction.

Vis-à-vis the strife over the foundations of QM, especially the measurement problem, the interpretation of the Heisenberg relations and their joint culmination in the EPR "paradox", the question arises whether QM in its orthodox form (e.g. Von Neumann, 1932) is incomplete: might there exist an element of physical reality that has no counterpart in the description of the QM formalism (cf. Einstein et al. (1935), cited in Redhead (1987), p.71, who also discusses the EPR argument in detail)? Einstein (1949, p. 666), for instance, was "[…] firmly convinced that the essentially statistical character of contemporary quantum theory is solely to be ascribed to the fact that this [theory] operates with an incomplete description of physical systems."

BM is an attempt to complete QM (if only in the sense of supplying the latter with a clear ontology). It offers a deterministic account of a corpuscular sub-quantum reality. From it, QM emerges in some sense, in a manner "approximately analogous […] to the statistical mechanics within the framework of classical mechanics" (ibid.).

From a non-historical perspective, BM is primarily motivated by the desire for a thoroughly ontic interpretation of QM – a "quantum theory without observer" (see e.g. Bell, 1990, p. 215; Allori et al., 2008, sect. 4): it's about objective matters of fact, rather than subjective or epistemic states of experimenters. Such a form of realism had come under attack with influential anti-realist presentations of QM (for historical accounts, see e.g. Howard, 2004; Scheibe, 2007, Ch. VIII; Oldofredi & Esfeld, 2018).

BM is a non-relativistic theory about N (massive, charged, etc.) particles and their continuous spatiotemporal evolution in 3-dimensional space. Their dynamics is such that the empirical content of QM, as enshrined in the Born Rule, remains unaltered.

Within a realist setting, BM thereby achieves its goal to provide a solution to the measurement problem (cf. Dürr &Teufel, 2009, p. 177; Esfeld, 2019; Lazarovici, 2019; Maudlin, 1995a). The latter consists in the incompatibility of the following three propositions (see e.g. Maudlin, 1995b):

(A) The wavefunction of a quantum-mechanical system is complete: It specifies (directly or indirectly) all of the physical properties of a system.
(B) The wavefunction evolves unitarily (in accord with e.g. the Schrödinger Equation).
(C) Measurements, such as of an electron's spin, always have determinate outcomes (represented by the corresponding eigenstates): After a measurement, the measurement device is in a(n eigen)state either indicating spin-up or spin down. Superpositions aren't recorded.

While any two of these propositions are consistent with each other, their conjunction isn't. Schrödinger's famous cat paradox illustrates this. Assume that a cat's state is completely described by the wavefunction. Then, the QM formalism implies that at some point it's no longer in a determinate state of *either* dead *or* alive: the cat will be smeared out in a superposition of life and death. This seems to flout experience.

BM eschews the dilemma by contesting (A): for a *complete* description of a system's state, its wavefunction must be supplemented by the positions the system's constituent particles occupy. (To distinguish the Bohmian particles from classical ones, we'll hereafter refer to them as "corpuscles".[5]).

More precisely, for a universe with N corpuscles of mass m_i each,[6] standard BM comprises three postulates (cf. Bohm & Hiley, 1993; Holland, 1993; Dürr & Teufel, 2009; Passon, 2010; Tumulka, 2017; Goldstein, 2017 for detailed reviews):

(1) The standard, non-relativistic N-particle Schrödinger Equation (SE):

$$i\hbar\frac{\partial}{\partial t}\Psi_t(\boldsymbol{Q}) = \widehat{H}\Psi_t(\boldsymbol{Q}),$$

with the universal wavefunction (i.e. the wavefunction of the universe) $\Psi_t:\ \mathbb{R}^{3N}\times\mathbb{R}\rightarrow\mathbb{C}$, the (ordered) configuration $\boldsymbol{Q} := (\boldsymbol{Q}_1,\ldots,\boldsymbol{Q}_N)\in\mathbb{R}^{3N}$ of the N particles, and the N-particle Hamiltonian $\widehat{H} = -\sum_{i=1}^{N}\frac{\hbar^2}{2m_i}\nabla_{\mathrm{i}}{}^2 + V(\boldsymbol{Q},\ t)$ with $\nabla_{\mathrm{i}} = \frac{\partial}{\partial \mathbf{Q}_{\mathrm{i}}}$, $i = 1, \ldots,\ N$ acting on the i-th particle. (For convenience, we'll subsequently suppress the wavefunction's time-index.)

(2) The Guidance Equation (GE):

$$m_i\frac{d\boldsymbol{Q}_i}{dt} = \hbar\,\Im\mathfrak{m}\{\Psi^{-1}\nabla_i\Psi\}\big|_{(\boldsymbol{Q}_1,\ldots,\boldsymbol{Q}_N)}.$$

It supplies the dynamics for each ($i = 1,\ \ldots,\ N$) corpuscle. Note that the expression on the r.h.s. depends on the configuration of all particles. (This renders BM's non-locality manifest.)

Given initial positions of the corpuscles, the GE determines their positions at any other time. Existence and uniqueness of the trajectories are guaranteed under prima facie reasonable assumptions. Note that the corpuscles' velocity fields generated by the GE depend on the wavefunction: $\boldsymbol{V}_i := \frac{d\boldsymbol{Q}_i}{dt} = \boldsymbol{V}_i^{\Psi}$.

(3) The Quantum Equilibrium Hypothesis (QEH):

Let Ψ denote the wavefunction of the universe. Via its associated (Born) measure $|\Psi|^2$, it (uniquely[7]) induces a measure of typicality: It quantifies which (measurable) sets of corpuscle configurations $\mathcal{Q}\subseteq\mathbb{R}^{3N}$ count as large ("typical"), i.e. $\int_{\mathcal{Q}} d^{3N}\boldsymbol{Q}|\Psi(\boldsymbol{Q})|^2 = 1-\varepsilon$, for some small ε.[8] (This definition of typicality is time-independent in a suitably generalised sense ("equivariant"), see Dürr et al. (1992), sect. 7.)

Given this typicality measure, one can then show that for ensembles of identically prepared subsystems of the universe, each with the wavefunction ψ, the corpuscles' configurations are typically distributed according to the Born Rule, $\rho = |\psi|^2$ (ibid.; Goldstein, 2011, p. 4.4). That is: for typical, large ensembles, the Born Rule approximates the corpuscles' empirical distribution, $\rho_{emp}(\boldsymbol{Q}) := \frac{1}{N}\sum_{i=1}^{N}\delta(\boldsymbol{Q} - \widehat{\boldsymbol{q}}_i)$, with $\widehat{\boldsymbol{q}} := (\mathbf{0},\ldots,\mathbf{0},\boldsymbol{q}_i,\mathbf{0},\ldots,\mathbf{0})\in\mathbb{R}^{3N}$, where $\boldsymbol{q}_i\in\mathbb{R}^3$ denotes the i-th corpuscle's actual position: $\rho_{emp}(\boldsymbol{Q})\approx|\psi_t(\boldsymbol{Q})|^2$. (This forges the link between BM's

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[5] We borrow this terminology from Dewdney and Brown (e.g. Dewdney & Brown, 1995 or Brown, Elby, & Weingard, 1996). Thereby, we hope to alert to – albeit perhaps not necessarily compelling – subtleties for identifying the Bohmian "primitive stuff" with classical particles. Two salient features of the latter have been discerned (cf. Mittelstaedt, 1995; Falkenburg, 2007, Ch. 6.1): (INDEP): (a) They may be in non-interacting, uncoupled states. (b) Their initial conditions are statistically uncorrelated.(COMP): A "law of thorough-going determination" (Mittelstaedt) holds: For every property, we can predicate either it or its negation of the particle. Bohmian particles flat-out flout (INDEP). Qua BM's non-locality, they don't seem to conform to (a). Nor do they respect (b): the quantum equilibrium hypothesis (viewed as a kind of law-like statement as part of the orthodox Bohmian-package deal) imposes a statistical constraint on initial conditions; they must be distributed approximately in accordance with the (QEH). Due to the Bohmian particles' contextuality, (COMP) is also plausibly violated: according to DGZ's interpretation of the contextual variables, these don't represent properties of the system/the corpuscles; in particular, one can't meaningfully ascribe, say, angular momentum to particles – in contradiction to what "thorough-going determination" would demand.Sincere thanks to an anonymous referee for pressing us on this!

[6] Ascribing the masses to the corpuscles alone isn't uncontroversial, cf. Dewdney & Brown (1995); Brown (1996a). Esfeld (2018, p. 170) denies that corpuscles possess any intrinsic mass or charge (or *any* intrinsic properties). However, the interference phenomena Esfeld cites *don't* unequivocally support that (cf. Brown et al., 1996, sect. 4).

[7] More precisely: $|\Psi|^2$ is the unique, natural measure that is equivariant under the dynamics defined by the GE, see Goldstein & Struyve (2007).

[8] For more on the typicality interpretation of the QEH, see Maudlin (2011); Goldstein (2011); Lazarovici & Reichert (2015); cf. Frigg (2009, 2011) or Valentini (2020) for a critical voice.

formalism and its empirical content. Consider the large, but (arguably) finite number of position measurements, performed in the universe's life-time on identically prepared systems with wavefunction ψ. The *specific* positions of those systems' corpuscles vary. But at a *statistical* level, their distribution is well approximated by the density $|\psi_t|^2$: in almost all measurements, the corpuscles are roughly distributed by $|\psi_t|^2$. In the absence of any further, i.e. more fine-grained information (information that given contemporary QM isn't available to us *in principle*), we may – according to advocates of the typicality interpretation – treat our observational-empirical data as typical, see e.g. Dürr & Struyve, 2019.)

For extensions of BM to incorporate spin or external electromagnetic fields, we refer the reader to the literature (e.g. Holland, 1993, Ch. 9, 10; Norsen, 2014).

A comment on BM's ideology (in the sense of Quine) is in order: what, according to BM, are the corpuscles' properties and relations (besides their mass, charge and magnetic momentum)? All dynamical variables – momentum, energy, spin, etc. – other than position, are contextual: their values depend on which other variables are assigned definite values. Position is the only non-contextual variable: only the corpuscles' positions (and their time-derivatives, i.e. velocities) always possess a sharp value. (Thus, BM evades the Kochen-Specker no-go theorem for hidden variable theories, see e.g. Redhead, 1989, Ch. 5, 6; Held, 2018 for details.) Ontologically, therefore momentum, energy, spin, etc. are subsidiary, non-fundamental quantities: in BM, they are non-classical degrees of freedom[9] that merely codify (supervene on) the corpuscles' motion (for details, see Daumer et al., 1997; Esfeld et al., 2014; Lazarovici et al.. 2018, sect.5).

For the present purposes, we set aside the thorny issue of the status of the wavefunction in BM (cf., for instance, Esfeld et al., 2014). Suffice it to state the dilemma one faces. On the one hand, the quantum state – the putative entity to which the wavefunction refers (Maudlin, 2013) – appears real at least in two regards. First, the wavefunction enters the QEH – and in this (at least, purely mathematical) sense constrains the corpuscles' distribution; secondly, it also enters the GE – and in this (at least, purely mathematical) sense determines their dynamics. Vis-à-vis these observations, Bell (1987, p. 128) judged: “Nobody can understand this theory, until he is willing to think of ψ as a real, objective field – rather than just a probability amplitude.” On the other hand, as Bell likewise stresses, the wavefunction is defined on 3*N*-dimensional configuration space. At first blush, it's unclear how to understand such an entity inhabiting this space. It's even more mysterious how it relates to and is supposed to affect the particles, inhabiting our familiar 3-dimensional space (for a survey of possible responses, see the contributions in Ney & Albert, 2013). We'll return to this dilemma in §3.2.

In summary: BM provides an objective account of the world, made up of point-like corpuscles. Their only dynamical variables are positions. At all times, their positions are determinate. Via the wavefunction, a dynamics is defined that guides the corpuscles' deterministic spatiotemporal evolution. A universal constraint on the corpuscles' initial distribution secures empirical equivalence with QM.

This provides the background against which we'll now elaborate a cousin of BM.

3. Tychistic Bohmian Mechanics

This section introduces and unpacks TBM – the theory that naturally emerges upon removing the GE from BM (with suitable interpretational re-adjustments).

TBM can be considered the “rump Bohmian theory” of randomly materializing corpuscles which one obtains after jettisoning BM's GE (and the concomitant determinism) – together with a re-interpretation of the QEH as a *stochastic* guidance law (rather than a typicality statement, as in BM). The corpuscles are no longer assigned continuous trajectories. But their positions remain determinate at all times. With the probability equal to the Born Rule, the *N*-corpuscle system as a whole localizes itself in a fundamentally stochastic process: it performs random jumps through configuration space. Can TBM deliver a coherent picture of the world? We'll answer this in the affirmative.

We'll first (3.1.) say why it's worthwhile inspecting this theory. In 3.2, we'll clarify TBM's conceptual basis and defend TBM's empirical adequacy. 3.3. discusses possible interpretations of its probabilities. In 3.4., we categorise TBM as a minimally Bohmian theory. Subsequently, we elaborate on TBM's metaphysical and epistemological adequacy: 3.5. re-evaluates Bell's criticism of TBM as “solipsistic” by illuminating its many-worlds character.

3.1. *Motivation*

Let's first spell out the motivation of (and the intention behind) our discussion of TBM: why consider removing the GE – *even if* one considers BM perfectly acceptable?

In light of BM's three postulates, two questions arise: are they logically independent? Are all of them strictly necessary?[10] Here, we wish to remain conservative with respect to the established physics. That is, we want to retain as few of BM's postulates as possible, whilst keeping its spirit intact. We'll probe a different question: can the GE be excised from BM, whilst forfeiting neither empirical and metaphysical viability nor, to a reasonable extent, BM's spirit?

Such an inquiry will not only deepen our understanding of BM along two lines. It's also one prima facie plausible reaction to the empirical underdetermination of BM's dynamics.

First, imagine a reader who endorses BM in its current form. She should welcome the envisaged study. To fully appreciate BM's merits, one needs to understand the import of each of its postulates – in particular that of the GE. A crucial question then is: what (metaphysical) consequences ensue if one abandons it? Our understanding of scientific theories is considerably deepened by systematically exploring such modifications (including omissions of some) of their axioms/postulates (cf. Lehmkuhl, 2017).

But the project is also of interest to those disconcerted by one of BM's features: the GE is vastly underdetermined by any *possible* observational data. An infinitude of equally viable, empirically equivalent alternative dynamics – different forms of the GE – exist. Each generates *distinct* trajectories (Deotto & Ghirardi, 2002; Holland & Philippidis, 2003). In principle – and by construction – it's impossible to experimentally discriminate between those options.

Such empirical under-determination obstructs a naïve realism about BM (Kukla, 1994, p. 157; cf.; Stanford, 2017): why assume one *particular* particle dynamics – say, the standard GE – rather than another, equally suitable alternative? Advocates of BM have responded that the standard GE is distinguished as the simplest choice for a dynamics (Dürr, Goldstein, & Zanghì, 1992, p. 852) that respect certain desiderata.[11]

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[9] “Degree of freedom” here shouldn't be understood traditionally, as representing a system's *properties*. Mindful of Dürr et al.'s warnings of “naïve realism about operators”, we use the term in a purely formal-mathematical sense, denoting the parameters that need to be specified for a full description of the system and its behaviour. Thanks to an anonymous referee for pressing us on this.

[10] One particularly intriguing issue is: Is it possible to *derive* the Born Rule in a manner analogous to Boltzmann's H-Theorem? That is: Do the configurations of most subsystems relax – via the corpuscle dynamics – into a “quantum equilibrium”, i.e. the distribution$|\psi_t|^2$? We'll not pursue further such questions (see, however, Valentini & Westman, 2005; cf. Callender & Weingard, 1997; Callender, 2007).

[11] Dürr et al. demand that the guidance law to be constructed be a first order differential equation, homogeneous (of degree zero) as a function of the wavefunction, Galilei-invariant and invariant under time-reversal.

One may well question the force of this response: all supposedly natural desiderata turn out to be tenuous (Belot, 2010; Fankhauser & Dürr, 2021 §2.2). Moreover, suppose, for the sake of the argument, that they *were* compelling. Yet, the argument still isn't entirely convincing: it pivotally turns on *mathematical* simplicity – that is, simplicity of the mathematical form of the dynamics. The infinitely many variants of BM with alternative guidance equations that differ from standard BM's only by a divergence-free term (cf. Fankhauser & Dürr, 2021) don't differ in their ontology. Hence, mathematical simplicity here doesn't even imply differences with respect to ontological parsimony. But why deem *mathematical* simplicity[12] – rather than a pragmatic criterion or even a subjective, rather elusive aesthetic preference – a reliable guide to truth? To do so is controversial (see e.g. van Fraassen, 1980, esp. Ch. 4.4; Ivanova, 2014) – already on inductive grounds (cf. Hossenfelder, 2018; Norton, 2018). Dürr et al.‘s reliance on simplicity thus considerably detracts from their argument's force. More generally, vis-à-vis the coexistence of empirically equivalent theories one may, of course, always invoke *super*-empirical criteria for theory selection. The challenge for an advocate of such a strategy then is: how to justify this choice of super-empirical criteria – and, in particular, why believe that they track truth?

Empirically equivalent, *genuinely* distinct theories are in fact rare (Norton, 2008). This raises a double worry: are they merely notational variants of the same theory, or does (at least) one of them posit superfluous structure? The former case is exemplified by the duality between Heisenberg's matrix mechanics and Schrödinger's wave mechanics (for caveats, see Muller, 1997a; 1997b). Germane for us is the latter case: could it be that all variants of BM share a common core – and that we should only be realists about this common core (cf. Le Bihan & Read, 2018)? Different variants of BM[13] differ primarily over the (in principle undetectable) corpuscle trajectories. It's therefore natural to contemplate whether one can dispense with them altogether. This would in some sense attenuate the challenge of underdetermination: it would efface the postulated key differences between different versions of BM as illusory.

Our study of TBM explores the viability of such a "'common core'-strategy" (Le Bihan & Read) in the case of BM: it would require, of course, that the "common core"-theory be both empirically adequate, and that it admit of a coherent interpretation. This we affirm. Thereby, TBM is shown to be a prima facie serious rival to BM vis-à-vis the latter's empirical underdetermination.[14]

In fact, selective realism – a cautious form of realism that has emerged from detailed analyses of historical challenges (see e.g. Kitcher, 1995; Psillos, 1999, esp. Ch. 5&6; Vickers, 2017, 2018, 2019) – suggests that our realist commitment is only warranted towards the "working posits" of successful theories, i.e. those parts indispensable for their predictive and explanatory success. The remaining "idle posits" don't merit realist commitment. If – as we maintain – TBM is empirically adequate and metaphysically coherent, it's conceivable that the GE counts as an "idle posit". In that case, following the selective realist's suggestion, realism about the GE – and by implication, BM in its entirety – wouldn't be justified.

We refrain, however, from any verdict as to whether TBM is indeed *superior* to BM. Only a detailed comparison of all of its explanatory successes (and, arguably, super-empirical virtues) can decide this. Here, we merely provide a proof of principle: to discard TBM in favour of BM calls for non-trivial arguments.

In sum: Irrespective of parsimony considerations that might commend the resulting theory, exploring whether one can still make sense of the formalism of BM without the GE promises to shed light on the latter's function, both physical and metaphysical.

With this prospective pay-off in mind, let's now plunge into the theory. To maintain TBM's adequacy, we'll rectify two misapprehensions about it that have impeded a wider consideration of Bell's proposal: one concerns Bell's metaphysically opaque presentation; the other concerns his worry that TBM exhibits a temporal form of solipsism, which he and others deem problematic. We'll address both points by firstly delineating a more perspicuous formulation, and secondly by demonstrating that TBM *doesn't* entail temporal solipsism. Bell's concern turns out to be unfounded. To these issues we turn now.

3.2. *Basics and empirical adequacy*

In this section, we'll unravel some of TBM's central conceptual structure by clarifying the status of its corpuscles' persistence. Notwithstanding their lack of persistence in TBM, we'll argue for TBM's empirical adequacy.

First, let's briefly dwell on persistence of corpuscles within BM. Here, the GE fulfils a metaphysical function: it ensures the corpuscles' persistence. With no GE, TBM's corpuscles are no longer guaranteed to persist. Should this faze us? The worry splits into two components.

(1) The first revolves around empirical coherence (or "epistemic stability"): without the corpuscles' persistence, does TBM undermine the reliability of its own empirical evidence (cf. Barrett, 1996)? To address this worry, we need some conceptual preparations.
(2) The lack of persistence prompts a second worry: is the GE necessary for empirical adequacy within BM? We contend that it isn't.

Persistence is closely tied up with the measurement problem. The latter encompasses in fact two distinct problems. The first concerns how to account for the determinacy (value-definiteness) of measurement outcomes. BM achieves this solely in virtue of determinate corpuscle positions (determined, of course, by the wavefunction). Persistence per se is irrelevant for this measurement problem. But it plays a role in a related, other measurement problem – the "Problem of Effect" (Maudlin): "The result of a measurement […] has predictive power for the future: after the first measurement is completed, we are in a position to know more about the outcome of the second than we could before the first measurement was made" (Maudlin, 1995a,b, p. 13).

In BM, the GE accounts for the Problem of Effect: it allows information of the measurement to propagate into the future. As measurements effectively (albeit not actually) induce a collapse of the wavefunction (e.g. Dürr & Teufel, 2009, p. 175; Lazarovici, 2019), repeated (sufficiently non-invasive) measurements yield the same outcomes. In our interactions with reality, the stability and temporal continuity appear to be robust empirical phenomena.

Removing the GE from standard BM disconnects the past from the present. This threatens TBM's empirical adequacy: TBM appears to flat-out contradict the aforesaid stability and temporal continuity. If thus the past and the present are no longer connected, why are measurements recorded at different times and places mutually consistent? Shouldn't we rather expect, say, the datings of organisms in our phylogenetic past via

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[12] It deserves to be pointed out that there are other forms of simplicity, not necessarily compatible with mathematical simplicity (Bunge, 1963). Even if one believes in simplicity as a guide to truth, it's far from clear that *mathematical* simplicity – however that term may be made precise or objective (in particular: objective in the sense of formalism/representation-independent!) – is the relevant form of simplicity (cf. also Barrett 1999, p. 156 on different types of simplicity).

[13] We'll not be concerned with Bohm's original quantum potential theory (championed also by Holland, 1993). Due to the latter's ontological differences, we deem it a theory distinct from the first-order theories under consideration. To these we'll refer as "variants of BM".

[14] This isn't to deny, of course, the existence of *other* serious rival theories: they likewise constitute prima facie plausible reactions to BM's underdetermination. Goldstein's Identity-Based Bohmian Mechanics is a particularly interesting such alternative, due to its *qualitative* parsimony in the sense of Lewis (1973, pp. 87). In the present paper, we refrain from any further evaluation of – let alone arbitration between – those empirically equivalent theories along their super-empirical virtues.

fossils and molecular clocks, respectively, to diverge?

For TBM, the question is thrown into sharp relief. The actualisation of configurations is stochastically independent. That is, for measurable regions $\mathcal{Q}, \mathcal{Q}^{'} \subseteq \mathbb{R}^{3N}$, one stipulates that the joint probability factorises:

$$\mathbb{P}^{\Psi}(\mathcal{Q}_t \in \mathcal{Q} \,\&f\, \mathcal{Q}_{t'} \in \mathcal{Q}^{'}) = \mathbb{P}^{\Psi}(\mathcal{Q}_t \in \mathcal{Q})\mathbb{P}^{\Psi}(\mathcal{Q}_{t'} \in \mathcal{Q}^{'})$$

.That is: the actualisation of one configuration at some instant in time doesn't affect the probability for another configuration at some other instant in time. Accordingly, any link between generic actual configurations is cut. All memory of an antecedent configuration is erased in a jump. It seems absurdly *improbable* that both you and your spouse hold consistent memories of, say, your childrens' names. Prima facie, TBM appears to predict that our memories should tell of disparate pasts, more bizarre than surrealists' paintings or Borges' City of the Immortals. Doesn't this seal TBM's fate as hopelessly inadequate?

To glean how that danger is warded off, we'll avail ourselves of three ingredients: first, to represent (for convenience) the *N*-corpuscle universe's total configuration in 3*N*-dimensional configuration space[15]; secondly, to hone our understanding of empirical adequacy, borrowing Barbour's notion of ‘time-capsules’; and thirdly, to hone our understanding of an empirically adequate theory's acceptability in terms of empirical coherence.

In order to defend TBM's acceptability, it will be advantageous to adopt the perspective of the *N*-particle system's total configuration. For readability, we'll henceforth refer to the N-particle system as a whole, comprised of all corpuscles in the universe as the totality of corpuscles (TOC). On TBM's interpretation of the QEH, we stipulate, it's the TOC that performs random jumps through configuration space. At any instant, it always occupies a definite configuration. By implication, the corpuscles' positions, too, are always definite.

Talk of such simultaneous jumps may sound a little mysterious: how do the corpuscles “coordinate” or “synchronise” their behaviour? Two responses are possible – depending on one's penchants for a metaphysically thin or thick interpretation of the wavefunction. (We'll revert to this topic in greater detail in §3.4.)

Consider first a metaphysically thin reading, for instance, a Humean (e.g. Bhogal & Perry, 2017) or nomological stance towards the wavefunction, according to which a system's statistical behaviour is thought-economically encoded or summarised in the wavefunction. On a metaphysically thin interpretation of the wavefunction, that's all there is to say about it; all further metaphysical commitments are refrained from. Hence, the simultaneous jumps of the corpuscles *aren't* coordinated or synchronised in that they aren't explained or caused by anything deeper; the universe's *N* corpuscles positions at any time just are what they are – and we can effectively describe them as a random walk tracing out the amplitude square of the *N* corpuscle universe's wavefunction (see Fig. 1).

A metaphysically thick perspective on the wavefunction yields a different response. From this perspective, a presupposition of the question becomes important: that the corpuscles are ontologically independent, and that therefore the behaviour of the system must ultimately be explained on the level of their individual properties, interactions and spatial distribution. Due to its peculiar nature as an essentially non-classical system, the TOC and its constituent corpuscles exhibit an unfamiliar *mutual* dependence. On the one hand, the corpuscles are mereological parts of the former. This compositional dependence is familiar. Yet, there also exists a distinctively quantum, converse dependence: the TOC can't be ontologically reduced to the corpuscles. Rather, it's holistic in the following sense (cf. Esfeld, 1998, 2003): the corpuscles stand in a salient relation – entanglement of the quantum states – that *doesn't* supervene on their individual properties and spatial arrangements. It characterises the system as a quantum (rather than classical) system. Empirically, entanglement manifests itself in the correlations in virtue of which the Bell Inequalities are violated (see Bell, 2004, esp. Ch. 2,4, and 8; Howard, 1989, 1992; Brown, 2005, Appendix B1–B3 for details).

In consequence, from the vantage point of a metaphysically thick stance towards the wavefunction, one shouldn't say that the corpuscles (instantaneously) influence each other, when jumping simultaneously. Such a causal account requires that the causal relata be distinct. That is, they mustn't stand in *any* ontological dependence relation, such as supervenience, grounding, etc. This isn't the case here: the TOC possesses a property that doesn't supervene on the properties of its constituents[16] – the quantum state, represented by their *N*-particle wavefunction; in virtue of it its constituent corpuscles lose one form of ontological independence (but not *all*, see e.g. Tahko & Lowe, 2015). Therefore, the corpuscles' simultaneous jumping is better understood as a fact of the *holistic* system they form (rather than a mysteriously synchronised action of *independent* corpuscles).[17]

Irrespective of whether one adopts a metaphysically thin or thick interpretation of the wavefunction: the fundamentally random localisation process of TBM's TOC replaces the deterministic trajectories of BM's corpuscles. The TOC's jumps are stochastically independent. The QEH – interpreted now as a stochastic law – furnishes the probability measure for this localisation process: the probability density for the universe – i.e. the TOC formed by all corpuscles – to localise itself spontaneously at $\boldsymbol{Q} := (\boldsymbol{Q}_1, \ldots, \boldsymbol{Q}_N) \in \mathbb{R}^{3N}$ is $\mathbb{P}^{\Psi_t}(\boldsymbol{Q}) = |\Psi_t(\boldsymbol{Q})|^2$, with the universal wavefunction Ψ_t. In other words: while we keep BM's QEH as a formal postulate, we no longer interpret it in terms of typicality. Instead, in TBM, it takes over the role of an irreducibly stochastic guidance law for the corpuscles.

> **$(\mathbf{QEH})_{\mathbf{TBM}}$** The *N*-corpuscle universe (TOC) locates itself spontaneously in a measurable set of configurations $\mathcal{Q} \subseteq \mathbb{R}^{3N}$, with a probability given by $\int_{\mathcal{Q}} d^{3N}\boldsymbol{Q} |\Psi(\mathbf{Q})|^2$.

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[15] Albeit perhaps reminiscent of the move in Albert (1996) (anticipated by Bell, 1987, sect. D) we'd like to stress that we *don't* subscribe to any of Albert's further interpretative/metaphysical commitments, especially concerning his “marvellous point” or “super-particle”. Our use of 3*N*-dimensional configuration space solely serves as a formal representation of the N-particle universe's total state.

[16] A few advocates of BM may baulk at this, due to their allegiance to the so-called nomological interpretation of the wavefunction (see e.g. Dürr et al., 2013, Ch. 11–13). It takes an ontologically deflationist stance towards the status of the wavefunction: rather than representing a physical entity (what, following Maudlin, we called the “quantum state”), it merely codifies the corpuscles' dynamics. The wavefunction's status resembles more that of a Hamiltonian or Lagrangian in classical mechanics than that of, say, an electron. In that vein, the wavefunction should be primarily understood through its dynamical role for the corpuscles' motion. (An extreme form of this nomological interpretation is Esfeld's quantum Humeanism, to which we'll come further below.) If one thus construes the wavefunction nomologically, one will be inclined to reject the ontological holism and (partial) dependence of the corpuscles: our above reasoning for them crucially involved taking the corpuscles' quantum state ontologically serious. That consequence worries us little. First, we regard the nomological interpretation as (at best) an *option* for BM (or any other quantum theory) – not a universally compelling stance towards the wavefunction (not even for BM). Furthermore, the nomological interpretation has incurred scathing criticism from various authors (e.g. Wallace & Brown, 2004; Ney, & Philipps, 2013; Solé & Hoefer, 2019). We largely concur with their assessments. Accordingly, we remain skeptical of the nomological interpretation. But, of course, readers are free to adopt it: they can safely skip our elaborations of our proposed ontologically meaty interpretation of the wavefunction as a holistic disposition.

[17] That is, with this holistic construal, the TOC view eschews the interaction (or “communication”) problem of the “two-space reading” of BM (Ney, 2012, p. 535) – the difficulty to conceptualise how the wavefunction (as an inhabitant of 3*N*-dimensional configuration space) can influence the corpuscles (as inhabitants of 3-dimensional “physical” space). Note that any “two space” dualism is straightforwardly avoided: there are no two distinct substances whose interaction needs to be accounted for: the TOC and the corpuscles aren't ontologically independent entities.

To complete our defence of TBM's empirical adequacy, we need a second ingredient – a more precise notion of what we are after: what does empirical adequacy amount to? According to van Fraassen's standard definition, a theory is empirically adequate, if the observable phenomena can be embedded into it: "(T)he structures which can be described in experimental and measurement reports we can call appearances: The theory is empirically adequate, if it has some model such that all appearances are isomorphic to empirical substructures of that model" (van Fraassen, 1980, p. 64).

How does this translate in the case of TBM and its empirical adequacy? For the moment, we postpone the question of how van Fraassen's definition applies to TBM's *probabilistic* nature (and whether the given definition of empirical adequacy *suffices* to make TBM acceptable). We'll return to that particular problem shortly.

To gauge TBM's empirical adequacy (or rather: its *non*-probabilistic component), we must heed what according to Bell was the (in his eyes largely overlooked) "really novel element in the Everett theory" – "a repudiation of the concept of the 'past' which could be considered in the same liberating tradition as Einstein's repudiation of absolute simultaneity" (Bell, 1987, p. 118): "We have no access to the past. We have only our 'memories' and 'records'. But these memories and records are in fact *present* phenomena" (op.cit., p. 136). Elsewhere, Bell states even more clearly: "For we have no access to the past, but only to memories, and these memories are just part of the instantaneous *configuration* of the world" (Bell, 1976, p. 16, our emphasis). In other words: to save the appearances – i.e. to achieve empirical adequacy – it suffices to be able to explain why corpuscle configurations are actualised that contain structures corresponding to the records (in particular of measurements, but more mundane "traces of the past", such as a diary, a scar or a glacier) and brain states involved in memory, abundant in our world.

Characteristic of such records and (non-pathological) memories is that they allow for consistent causal stories. In TBM, a causal link between two *arbitrary* configurations of the universe evidently can't be had. (In this regard, i.e. the absence of a causal link between configurations, it resembles the GRW flash theory; we'll revert to the differences between the two theories with respect to their ontology, what kind of primitive stuff they posit, in §3.4.). With the aforementioned "novel element in the Everett theory" – the "repudiation of the concept of the 'past'" – this needn't make us despond over TBM's empirical adequacy: it's preserved, if configurations of the universe permit of consistent quasi[18]-causal stories. For TBM to be empirically adequate, it must give rise to worlds like ours, i.e. with the following two features (cf. Barrett, 1996):

(DEF) Measurement outcomes – and properties of macro-objects – must possess sharp (definite) values.

(REC) Records, including memories, must be mutually consistent.

(DEF) is equivalent to a solution to the first measurement problem mentioned in §3.2. With positions as its local beables, we already saw how TBM accomplishes this. What about (REC)? Is it satisfied?

Barbour (1999, p. 31, Ch. 2, 3, 17–19; 2009) evocatively dubbed configurations achieving this – i.e. configurations "that (appear) to contain mutually consistent records of processes that took place in a past in accordance with certain laws" – 'time-capsules'. An example are configurations that instantiate our planet. Its multifarious strata, fossil records and rock formations, tell a mutually compatible, robustly regular story with uniform structural layers: "The story of antiquity of the Earth and of its creation from supernova debris – the stardust from which we believe we ourselves are made – is a story of patient inference built upon patient inference based upon marks and structures of rocks. On this rock – the Earth in all its glory – the geologists have built the history of the world, the universe even" (op.cit., p. 33).

In short: the standard definition of empirical adequacy requires that in TBM amongst the actualised configurations there be time-capsules. But the cited standard definition of empirical adequacy can't be the whole story. It brackets TBM's probabilistic (statistical) nature. For probabilistic theories, we must supplement van Fraassen's definition (as van Fraassen (1980, Ch. 4) does himself): for a probabilistic theory to be acceptable, it must be also empirically coherent (or: "epistemically stable", cf. Myrvold, 2016; Carroll, 2017). That is, it must guarantee that we may trust our epistemically accessible empirical data. Else, it would undermine its own evidential basis – the empirical data on which belief in the theory's truth rests.

TBM is *acceptable* (i.e. empirically adequate and coherent), if high-probability time-capsules are TBM's empirical substructures into which the observable phenomena can be embedded. Is this requirement satisfied? Prima facie, prospects appear forlorn: time capsules form only a miniscule fraction of all configurations which the TOC could visit during its erratic wanderings. (Recall: with every random jump, the TOC always lands on exactly one, unique point in configuration space.)

This answer, however, overlooks that one mustn't naively count configurations: they aren't equidistributed. The distribution afforded by the QEH – construed in TBM as a probability measure – involves the structurally rich wavefunction of the universe. In particular, it contains a mechanism for the universe to ferret out time-capsules (op.cit., Ch. 20) – decoherence (see e.g. Bacciagaluppi, 2012; Schlosshauer, 2014; Wallace, 2011).

Entrenched in the wavefunction is the decoherence-induced branching structure. The details are familiar from the literature on the Everett interpretation; we needn't rehearse them here (e.g. Zeh, 2003, 2000; Wallace, 2002, 2003, 2010, 2011, 2012a, 2012b). Note, however, that nothing *extraneous* is borrowed: Everettian branching is no prerogative of the Everett interpretation. A direct consequence of decoherence, it's a *generic* feature of any theory respecting the standard quantum formalism – as Everettians are keen to stress.

Wavefunctions of subsystems of the universe, large enough to accommodate observers, have the functional structure of classical worlds – "for all practical purposes (FAPP)" (Bell). Corpuscles that occupy them realise FAPP-classical worlds. In particular, macro-scale interference effects are suppressed in them.

With its jumps, the TOC traces out the universal wavefunction. It thereby traces out the Everettian branching structure, too: with overwhelming probability the TOC lands on a point in configuration space, perched on a FAPP-classical world-branch. The latter is thereby actualised: a FAPP-world materialises. Each such world is FAPP-uniformly structured, admitting of FAPP-causally consistent histories. In other words: the TOC has a preponderant probability to actualise time-capsules.

This completes the vindication of TBM's empirical adequacy and coherence (*contra* Barrett, 1996, sect. 4): due to decoherence, the TOC has an overwhelmingly high probability to actualise FAPP-classical worlds. They allow for consistent histories governed by FAPP-causal laws. Historical evidence, including memories, contained in them is mutually FAPP-consistent.

Probabilities feature pivotally in this defence of TBM's acceptability. Its empirical coherence – our trust in the reliability of empirical data – was vouchsafed probabilistically: according to TBM, empirically adequate configurations with mutually consistent records are actualised with overwhelming probability. But how to understand this reference to probability? What is the status of probabilities in TBM? How to interpret them? We'll sketch this in the next section.

3.3. Probabilities in TBM

In §2, we reported that in BM identical copies of a system reproduce the same statistics – those of the Born Rule. To better understand this result, we'll now state more carefully the QEH and its relation to the

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[18] "Pseudo-causal" would be equally apt, since the appearance of such causal stories isn't warranted at a fundamental level (see §3.5). Thanks to an anonymous referee for stressing this.

statistics of subsystems (following Dürr, Goldstein, & Zanghì, 1992.) We'll then sketch possible interpretations of TBM's probabilities.

Let's first refine our terminology. A subsystem of the universe (i.e. a proper subset of the corpuscles constituting the TOC) is said to have an "effective" wavefunction ψ, if the universal wavefunction $\Psi : X \times Y \to \mathbb{C}$, with X and Y denoting the configuration space of the subsystem and its environment, respectively, can be decomposed as

$$\forall (\mathrm{x},\mathrm{y}) \in X \times Y : \Psi(\mathrm{x},\mathrm{y}) = \psi(\mathrm{x})\varphi(\mathrm{y}) + \Psi_{\perp}(x,y).$$

Here φ and $\Psi_{\perp}$ have macroscopically disjoint y-support and $Y \subseteq \mathrm{supp}(\varphi)$. Subsystems with an effective wavefunction and negligible interaction with their environment can be shown to satisfy the SE for ψ.

Recall that the QEH supplies a probability measure $\mathbb{P}^{\Psi}(\boldsymbol{d}^{3N}\boldsymbol{Q}) = |\Psi(\boldsymbol{Q})|^2 \boldsymbol{d}^{3N}\boldsymbol{Q}$ on the configuration space $\mathbb{R}^{3N}$. In contrast to BM, this *isn't* interpreted as a typicality measure in TBM, as we'll see presently.

First, though, let's see how this probability measure for the *universe* induces a probability measure for *subsystems.* Consider subsystems with the same wavefunction ψ. Let their number of corpuscles be M. The $\mathbb{P}^{\Psi}$-measure, conditional on all environmental configurations Y that yield the same effective wavefunction ψ, is then determined (independently of Y) as:

$$\mathbb{P}^{\Psi}\left(\left\{\boldsymbol{Q} = (X,Y) \in \mathbb{R}^{3N} : X \in d^{3M}x \;\&\; \Psi(.,\mathrm{Y}) = \psi\right\}\right) = |\psi|^2 d^{3M}x.$$

From this, a Law of Large Numbers follows: For any measurable set $\boldsymbol{A} \subseteq \mathbb{R}^{3M}$ and an ensemble of n identically prepared subsystems with the effective wavefunction ψ and the position (at time t) random variables $X_i(t)$, it holds that

$$\forall \varepsilon > 0 : \mathbb{P}^{\Psi_t}\left(\boldsymbol{Q} \in \mathbb{R}^{3N} : \left| \frac{1}{n}\sum_{i=1}^{n} \chi_{X_i(t)\in \boldsymbol{A}}(\boldsymbol{Q}) - \int_{\boldsymbol{A}} d^{3M}Q' \left|\psi(\boldsymbol{Q}')\right|^2 \right| < \varepsilon \right) \overset{n\to\infty}{\longrightarrow} 0,$$

with the indicator function $\chi_{X_i(t)\in \boldsymbol{A}} := \begin{cases} X_i(t) \in \boldsymbol{A} : 1 \\ X_i(t) \notin \boldsymbol{A} : 0 \end{cases}$. The distribution of corpuscles in sufficiently large ensembles of subsystems, each prepared with the same *effective* wavefunction ψ, probabilistically approximates the statistics of the Born Rule – that is, $\left|\psi\right|^2$. Via this Law of Large Numbers, one can therefore explain why the Born Rule (for effective wavefunctions) probabilistically holds in subsystems (Oldrofredi et al., 2016, sect. 3).

This brings us back to the notion of probabilities in TBM.[19] They constitute the core of TBM's counterpart of standard BM's QEH: in essence, it frees the latter from its interpretation in terms of typicality. But we still owe the reader a positive interpretation of those probabilities. With TBM aspiring to an objective account of reality, a fundamentally objective interpretation seems most natural.[20]

Both[21] standard objective interpretations of probability are applicable, we submit – propensity and Humean Best System approaches.[22] On a propensity interpretation (e.g. Bunge, 2011, Ch. 4; Suárez 2007, 2009, 2013, 2014, 2016), probabilities in TBM quantify an inherent, physical tendency (propensity/disposition) of the universe to randomly materialise a certain configuration: The universe is *irreducibly* chancy. Such a propensity interpretation lends itself to TBM. As a fundamental theory of the whole universe, its probabilities don't depend on other factors. Absent extraneous triggering conditions, the TOC *spontaneously* jumps through configuration space. The universe's propensity manifests itself in the series of actual configurations. On TBM's propensity interpretation, the universal wavefunction represents this propensity.

On the other hand, a Humean Best System interpretation takes probabilities to be theoretical terms that meet the following criteria (e.g. Hoefer, 2011):

(1) They satisfy the axioms of the probability calculus.
(2) They are suitably related to credences (i.e. rational agents' degrees of belief) such that the Principal Principle holds.
(3) They are invoked in the best systematisation of the empirical categorical facts of the universe.

The "best systematisation" here is understood as the one that strikes the best balance between simplicity, "fit" (empirical accuracy) and "strength" (empirical scope).

TBM's amplitude square of the universal wavefunction satisfies those criteria (1)–(3): the first one by construction; the second one due to its empirical adequacy (via its explanation of the Born Rule, as discussed above); and the third one due to its extraordinary simplicity. Hence, a Humean Best Systems approach to TBM's probabilities is both natural and attractive.

In conclusion: befitting a "quantum theory without observers", objective probabilities are possible in TBM. We'll not arbitrate amongst the options (including non-objective ones).

Now the conceptual tolls are in place to launch into a distinctive metaphysical feature of TBM – its many-worldliness. Before discussing it, it will prove useful to present TBM as a minimally Bohmian theory in the following section.

3.4. TBM as a minimally Bohmian theory

We christened the theory introduced so far "Tychistic Bohmian Mechanics". What justifies its classification as *Bohmian*? We'll now legitimise this claim. To that end, we'll offer a metaphysically precise formulation of the Primitive Ontology (PO) paradigm.

Our concern here isn't merely terminological. The section serves four main purposes. First, it provides a metaphysically perspicuous characterisation of the theory's ontology and ideology – in particular with respect to notions of fundamentality and ontological dependence. Secondly, our results poignantly pinpoint the regards in which TBM differs from the Everett interpretation and the GRW flash theory. Thirdly, by showing that TBM can be classified as a PO theory, we seek to by-pass a

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[19] At first glance, the status of probabilities resembles that of the Everett interpretation (e.g. Greaves, 2006; Saunders, 2021; Wallace, 2012b, Part II): according to both TBM and the Everett interpretation, it seems, all physically possible branches are realised. In the latter this indeed is strictly true: *all* branches are actualised *simultaneously* in a perfectly *deterministic* manner – giving rise to the so-called "Incoherence Problem" of Everettian probabilities. In TBM, the situation is slightly different in three regards – a difference that (depending on how deleterious one regards the Incoherence Problem) one may deem an advantage over the Everett interpretation. First, TBM is a fundamentally *stochastic/indeterministic* theory (to be elaborated in the main text). Secondly, fundamentally, in TBM only *one* branch is actualised at any given instance. (TBM's many-worldliness emerges at a temporally coarse-grained, non-fundamental level. We'll expand on this issue in greater detail in §3.5.) Thirdly, only at an *effective* level – for all intents and purposes – are all branches actualised in TBM within any finite time interval (TBM's "indefinite world-rate", as we'll call this phenomenon in §3.5): this doesn't occur with nomological necessity – as it does (ex hypothesi) in the Everett interpretation; the actualisation of all branches within any finite time interval in TBM is merely overwhelmingly probable.We thank an anonymous referee for pressing us on this.

[20] There exists a weaker notion of objective probabilities — "epistemic" probabilities (e.g. Uffink, 2011). Arguably, they are compatible with the agenda of a quantum theory without observer. For our purposes, it suffices to show that TBM allows of objective probabilities sensu stricto.

[21] We pass over frequentism for two reasons. First, its defects are legion, rendering it not a particularly auspicious interpretation of probability to begin with (see e.g. Hájek, 1997, 2009 for extensive surveys). Secondly, due to TBM's many-worldliness, we expect a frequentist approach to TBM's probabilities to face similar challenges as in the case of the Everett interpretation (cf. Wallace, 2012, Ch. 4.5–4.7).

[22] The arguments we'll sketch below carry over almost verbatim from the analogue case of GRW (see Dorato & Esfeld, 2009; Frigg & Hoefer, 2007).

divide in the foundations of quantum community – that between wave-function realists and PO (more below), with the latter insisting on a theory's Primitive Ontology status as a metaphysical conditio sine qua non. Fourthly, as a spin-off, the prerequisite terminological clarifications will in turn, we hope, help sharpen the core doctrine of that framework – and thereby advance the debate.

Let's ponder: is TBM sailing under false colours? Is it perhaps *not* a Bohmian theory? Prima facie, a glaring difference might suggest so. First, the spatiotemporal evolution of *BM's* corpuscles is deterministic. *TBM's* corpuscles, by contrast, make random jumps. Closely related is a second issue, related to persistence: whereas BM's corpuscles exist continuously (cf. Esfeld, 2017), TBM's corpuscles spontaneously (dis-)locate themselves.

Both differences we deem benign. Echoing Bohm, Dürr and Teufel declare determinism inessential for Bohmian theories (cf. also Oldofredi, 2020 for a recent, explicit case for the compatibility between stochasticity and "Bohmicity"): "It is often said that the aim of Bohmian Mechanics is to restore determinism in the quantum world. That is false. […] What is 'out there' could just as well be governed by stochastic laws […]. [BM] happens to be deterministic, which is fine, but not an ontological necessity" (Dürr & Teufel, 2009, p. 9; cf. Bohm & Hiley, 1993, Ch. 9; Goldstein, Tumulka, & Zanghì, 2009, p. 11). In the same vein, persistence seems inessential: qua their deterministic trajectories, the corpuscles just happen to persist.

Following Dürr et al. (1995), sect. 5; see also Allori et al., 2006, sect. 6), a theory qualifies as Bohmian iff it's a theory about entities in 3-dimensional space that satisfies the following criteria:

(1) The theory's objects are corpuscles (particles) – rather than, say, flashes, strings or matter fields. To them, all ordinary matter – cats and molecules – is reducible.
(2) At all times, the corpuscles have definite position – rather than, say, a definite fermion number density or bosonic field configurations.[23]

Both intellectual fathers of BM, deBroglie and Bohm, expressly intended it as an interpretation of *standard* QM, not an alternative theory (cf., for instance, Bohm & Hiley, 1993, Ch. 1). This physical conservatism is reflected in Dürr et al.'s third requirement for a Bohmian theory:

(3) It's fully empirically equivalent with QM. By contrast, objective collapse theories modify the Schrödinger dynamics. In principle, this yields empirical deviations from QM.

Only with respect to (1) might one have non-trivial queries. Compliance with (1) is ordinarily phrased in terms of the Primitive Ontology (PO) framework (see e.g. Allori et al., 2008; Allori, 2013b, 2015). Does TBM fall under it? Besides being a purely objectively interpreted "quantum theory without observer", this would amount to requiring that TBM be a theory fundamentally about entities *located in 3-dimensional space* that form the constituents of all macroscopic objects of our everyday experience. (PO theories more generally aren't limited to *particle*-theories: whatever fundamental entities – flashes, matter fields, etc. – they posit, the only requirement is that they be located in 3-dimensional space.) It's a little obscure what exactly this (standard) formulation of a PO theory actually demands. The reference to fundamentality admits of multiple readings (cf. Oldofredi, 2021, for an illuminating perspective). Fundamentality is an ambiguous notion that may denote a number of distinct concepts (see Tahko, 2018). Most germane here are two – fundamentality as a complete minimal basis, and as ontological independence, respectively.

A complete minimal basis captures the idea of a foundation of our physical reality: what the demiurge had to create in order to determine everything else that exists. That is, a complete minimal basis is the smallest possible set of entities – not necessarily restricted to objects – that determines the rest of reality. An entity is then fundamental in this sense ("fundamental$_{\mathrm{CMB}}$"), iff it belongs to a complete minimal basis.

Fundamentality in the second sense ("fundamental$_{\mathrm{ODEP}}$") encapsulates a sense of priority amongst entities. An entity counts as fundamental$_{\mathrm{ODEP}}$, iff it doesn't ontologically depend on anything else. Ontological dependence relations include grounding, part-whole relations, existential, essential or causal dependence (for details, see e.g. Correia, 2008; Koslicki, 2013; Tahko & Lowe, 2015).

This terminology allows us to formulate the criteria for PO theories more precisely:

(PO1) The theory's stuff and its properties (e.g. mass, position, etc., represented by the so-called "primitive variables") are fundamental$_{\mathrm{CMB}}$ for a complete minimal basis *for material reality*. In particular, they constitute all macro-objects, such as ouds and axolotls.

(PO2) The various elements comprising the theory's stuff are also fundamental$_{\mathrm{ODEP}}$.

A comment on (PO1) is in order. It doesn't assert that what is represented by the primitive variables – stuff and its properties – exhausts necessarily all of reality. Other entities might exist, such as numbers, universals or laws; but they'd be *immaterial* (see e.g. Allori, 2018, sect. 4; cf. also Allori, 2013a, 2013b, 2015). This doesn't mean that only material entities are important. A complete theoretical description of the world must also account for the behaviour of immaterial entities. This is implemented via the so-called non-primitive variables, such as momenta in Classical Mechanics. Their role is to determine how matter interacts and moves. Advocates of the PO paradigm standardly take an ontologically deflationary stance towards such variables (cf. Chen, 2019, sect. 3, and esp. 4). (A routine option is a so-called "nomological interpretation".) They needn't deny their reality (only their *material* reality). But the role of non-primitive variables, those authors suggest, is primarily to be understood as incorporating the dynamics of primitive variables.[24] For a theory to qualify as a PO theory, no "thicker" realism towards them is mandatory (cf. Allori et al., 2008, sect. 4: "In [BM or the GRW theories], the only reason the wave function is of any interest at all is that it is relevant to the behaviour of the [Primitive Ontology]. Roughly speaking, the wave function [as a paradigmatic example of a non-primitive variable, our addition] tells the matter how to move".). We'll therefore take a theory to be a PO theory, iff the theory, when equipped with an ontologically thin (e.g. nomological) attitude towards the non-primitive

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[23] Other choices for (1) and (2) lead to merely Bohm-like *generalisations/extensions* of BM, which – notwithstanding non-trivial differences – continue to exhibit close similarities, such as family resemblance, certain senses of reduction in certain limits, etc. (cf. Passon, 2006, sect. 4). It lies outside of the present paper's scope to tackle the fascinating (and largely open) question regarding inter-theory relations that underlies such a distinction: what are criteria for classifying a theory that is sufficiently different from another (think of quantum field theories and (non-)relativistic quantum mechanics) as the latter's generalisation? BM and its Bohm-like generalisations would provide an ideal case study.

[24] The context of theory individuation/identity drives home this ontologically thin attitude towards non-primitive variables. Two theories, according to advocates of the PO framework, are supposed to be identified as physically equivalent, iff they agree over all matters of fact *encoded* via *primitive variables* (see e.g. Allori et al., 2008, sect. 4.1) – even, if they disagree over claims *expressed* via *nomological variables*.We confess that we'd be hard pressed to elaborate how this doesn't segue into anti-realism about the nomological variables, given a standard construal of physical equivalence (viz. as asserting the same matters of fact simpliciter, cf., for instance, Ben-Menahem, 1990; Coffey, 2014; Read & Møller-Nielsen, 2020).

variables, satisfies the two above criteria (or their modifications, see below).[25]

(PO2) also deserves elucidation. As we mentioned above, fundamentality$_{\text{ODEP}}$ makes reference to ontological dependence. Which form is relevant here? At first blush, one might be inclined to forbid *all* forms of dependence. But such absolute/unrestricted fundamentality$_{\text{ODEP}}$ strikes us as too austere for two reasons. First, it includes mereological independence (mereological simplicity). A PO theory's stuff then wouldn't be allowed to have any parts. This choice would throw out the baby with the bathwater: it rules out the GRWm theory with its “gunky” (i.e. infinitely divisible into smaller parts, cf. Arntzenius & Hawthorne, 2005; Esfeld, 2018) matter density. In the literature, however, the GRWm theory is unanimously classified as a PO theory. To relax the demanded sense of fundamentality$_{\text{ODEP}}$ – by restricting it to only *some* forms of ontological dependence – seems apposite already on purely metaphysical grounds (Tahko, 2018, sect. 1.1).

The ontological independence we are after should be especially tight: a PO theory's stuff is supposed not to be “reducible to more elementary notions” (Oldofredi & Esfeld, 2018, p. 11). Elsewhere, we argue that the pertinent sense of reducibility is best understood in terms of identity (in the sense in which the physicalist envisages mental states to be identical to physical/brain states), grounding or functional role (in the sense in which, according to functionalism, to be in a mental state is conceptualised as possessing a brain state that plays the functional role of that mental state). We hence reformulate (PO2) as follows:

> (PO2*) The theory's stuff mustn't be ontologically reducible to entities that are immaterial or not located in 3-dimensional space, in the sense of *functional reduction, grounding or (type or token) identity*.

Two advantages commend this refined characterisation – i.e. the conjunction of (PO1) and (PO2*) – of the Primitive Ontologist's core tenet. First, it recovers the classification of the paradigm examples of Primitive Ontological theories in the literature (viz. classical mechanics, classical electromagnetism, standard BM, GRWf, and GRWm), as well as of the paradigm counterexamples (in particular, the Everett interpretation, as we'll see in detail presently). Secondly, it captures what we take to be the intuition underlying the pertinent authors' insistence on irreducibility: in theories not satisfying (PO2*), what appears to be spatiotemporally located stuff, *really* is something else, e.g. patterns in the wavefunction. This mimics the physicalist's hunch that mental states *really* are brain states.[26]

How now does TBM fare vis-à-vis those two criteria for PO theories? That TBM satisfies (PO1) is straightforward. On TBM, the 3-dimensional corpuscles clearly belong to the complete minimal basis. If now we adopt an ontologically thin – say, either a Humeanistic (recall §3.3) or nomological – stance towards the wavefunction (in complete analogy to BM), the complete minimal basis for material reality solely consists of the corpuscles and their respective positions.[27] They are fundamental$_{\text{CMB}}$. Compliance with (PO2*), too, is immediate to see: just as in standard BM, TBM's corpuscles aren't really anything else, not residing in spacetime. TBM thus satisfies both criteria for a PO theory.

As a particle-based PO theory, fully equivalent with standard QM, TBM consequently is a card-carrying member of the family of Bohmian theories (cf. Barrett, 1996; 1999, Ch. 5.1 for a similar classification of “Bell's Everett (?) theory”). Fine (1996, p. 249) encourages a bolder conclusion: “At the heart of Bohmian mechanics is the wave function and determinate particle positions, and perhaps we need be realists about nothing else.” Indeed, TBM only needs two postulates – the Schrödinger Equation (SE) and the (re-interpreted) Quantum Equilibrium Hypothesis (QEH$_{\text{TBM}}$) – whereas standard BM needs three.[28] (This claim is, of course, predicated on the premise that Valentini's agenda to dispense with the QEH as an independent assumption in standard BM isn't successful, see fn. 10.) We therefore don't quite agree with Goldstein (2017, sect. 4) who touts *standard* BM as “[…] the minimal completion of Schrödinger's equation, for a nonrelativistic system of particles, to a theory describing a genuine motion of particles”.

Our classification of TBM as a (minimally) Bohmian theory contradicts Bell's own classification.[29] Originally, he had proposed something like TBM as a (the most?) plausible version of Everett's Many Worlds Interpretation of QM (see Bell 1987, 1976).[30]

Before turning to the differences between TBM and the contemporary Everett interpretation, let's dwell on the differences between Bell's theory and TBM. Indeed, at first blush the two look indiscernibly similar. A crucial detail is easy to overlook: the way worlds are defined in each. We simply imported the notion from the Everettian literature. Worlds or quasi-classical branches, then, are coarse-grained notions. Bell explicitly rejects such notions (see Bell 1987, (B) and (D)), since they are “meaningful […] only on some ill-defined macroscopic level” – a level of description recourse to which, Bell prescribes, should be banned, when defining a (fundamental) theory's fundamental concepts. Therefore, he diagnoses temporal solipsism: having discarded the Everettian branching-structure, Bell is left with isolated, individual configurations, actualised at one given point in time – with no link to prior configurations. (Such a link would come about by either an extremely improbable random coincidence or by the Everettian branching structure. But since Bell rejects the latter in the context of interpreting the theory's fundamental postulates, effectively all ties to prior configurations are cut.) In consequence, he doesn't distinguish between worlds and configurations. (Although he isn't explicit about this, it becomes clear in statements such as “Thus instantaneous classical configurations x are supposed to exist, and to be distributed in the comparison class of possible worlds with probability $|\psi|^2$” (p. 133).

While it's true that at the level of the theories' fundamental postulates, TBM and Bell's Everett (?) theory are the same, they differ in their stance towards worlds: we (following the Everettians) embrace them as real (albeit emergent/non-fundamental) structures; Bell jettisons them wholesale. Doesn't this sameness with respect to

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[25] With this slightly cumbersome qualification we wish to make our characterisation of PO theories interpretatively flexible: it shouldn't be wedded ab initio to one particular interpretation of, say, the wavefunction (as a paradigmatic candidate for a non-primitive variable). Other – in particular non-nomological or even ontologically thick – interpretations of the wavefunction (such as a multi-field view, see Hubert & Romano, 2018) should be compatible with a theory's status as a PO theory.

[26] It's grist to our mills that Esfeld (2019b) explicitly seems to have this sense of fundamentality in mind (albeit in a slightly different context), cf. Lam & Wüthrich, 2018.

[27] To preempt misunderstandings, we hasten to add that nothing *compels* us to adopt such an interpretation; it's merely an *option*. That's all we need to establish TBM's status as a PO theory. As we argued in §3.2 and §3.3, an ontologically thick interpretation of the wavefunction in terms of a disposition is equally viable (and attractive on independent grounds – viz. as a solution to the two-space reading, cf. fn. 17.).

[28] Nelson Stochastics might come to mind as another candidate for a minimally Bohmian theory (see e.g. Bacciagaluppi, 2005). It dispenses with the SE by assuming that the particles' position is described by a (stochastic) diffusion process. (A special choice for the diffusion coefficient yields BM.) However, Nelson Stochastics *doesn't* fully recover the equivalence with QM. To restore that, *additional* constraints need to be imposed, casting into doubt the claim of its being minimally Bohmian.Two other candidate minimally Bohmian theories are Sebens' “Newtonian QM” (2015) and Goldstein et al.‘s (2005 a,b) “Identity-Based Bohmian Mechanics”. A comparison with TBM would be particularly interesting especially with respect to explicating the – prima facie different – senses in which they can lay claim to being simple or parsimonious. Unfortunately, this lies outside of the present paper's ambit.

[29] To be fair, though, Bell (1987, p. 133) introduces his theory as “simply […] the pilot wave theory [i.e. BM] without trajectories”.

[30] By contrast, Daumer et al. (1996), p. 393; fn 13 distinguish between the Everett interpretation and Bell's Everett (?) Theory; ditto Allori et al. (2008), sect.6.

fundamental postulates imply that TBM and the "Everett (?) theory" are identical? Not necessarily: it's not clear that theory individuation/inequivalence – whether we should regard two theories as distinct, rather than merely notational variants of each other – should be based solely upon the theory's *fundamental* postulates. Regrettably, there is no consensus in the literature on sufficient criteria for theory individuation.

Observational/empirical equivalence is a little controversial necessary criterion for two theories to count as equivalent. But – what counts as the empirical substructure of a theory is a delicate business. It's here that non-fundamental/coarse-grained concepts might become important: they, after all, delimit the observationally distinguishable from the observationally indistinguishable. (This is particularly clear in van Fraassen's account of empirical adequacy, and his overarching semantic view of theories.) To us, caution seems prudent; we therefore opt for the (tentative) distinctness of TBM and Everett's theory.

Return now to what, following Bell, may look like a natural identification – TBM and the (contemporary) Everett interpretation. This identification can be opposed for resting on a spurious identification of what constitutes the supposed essence of the Everett interpretation. As we saw in §3.2 (and will examine more closely in §3.5), TBM's ontology is many-worldly: it contains many worlds. It's therefore tempting to consider TBM a variant of the Everett interpretation. But – albeit absent in prime specimens of Primitive Ontology theories, such as BM or the GRW flash theory – also some Primitive Ontology theories display many-worldliness, e.g. the GRW matter theory (e.g. Allori et al., 2008) or Schrödinger's many-world theory (see e.g. Allori et al., 2011).[31] The absence of many-worldliness thus can only be a contingent feature of a PO theory. (NB: One should strictly distinguish between many-worldliness and Everettianity, i.e. the classification of a theory as Everettian. Many-worldliness denotes an *ontological* feature of a given, interpreted theory: the presence/absence of multiple, synchronous existing worlds amongst the theory's (not necessarily fundamental) ontology. Everettianity, by contradistinction, denotes a particular *interpretative* scheme for quantum theories, based on the interpretative principles paradigmatically invoked in the Everett interpretation of QM, as canonised by Wallace (2012b; 2013).[32][33]).

For Bell (1987, p. 133), "keeping the instantaneous configurations, but discarding the trajectory, is the essential […] of the theory of Everett". Most contemporary Everettians, however, will gainsay this as a faithful reconstruction of their views (cf., for instance, Wallace, 2012b; Vaidman, 2014).

For one, they refuse to postulate any corpuscles (or any other stuff) over and above the wavefunction.[34] In this spirit, Wallace (2012b), p. 38, for instance, writes with respect to the *standard* quantum formalism: "The 'Everett interpretation of quantum mechanics' is just quantum mechanics itself, 'interpreted' the same way we have always interpreted scientific theories in the past: as modelling the world."

In other words, the Everett interpretation violates (PO1): only the wavefunction is fundamental$_{\text{CMB}}$ for our material reality; 3-dimensional particles aren't. Corpuscles – or three-dimensional objects more generally – only exist as structural patterns in the wavefunction. In this sense, the Everett interpretation also violates (PO2*): all three-dimensional objects are identical with structural patterns in the wavefunction. That is, they merely have *counterparts,* playing roughly the same functional role at some non-fundamental, coarse-grained, effective description (see Wallace's explicit invocation of structuralism and Dennettian functionalism in Wallace, 2012b, Ch. 2).

Contemporary Everettians will disown what Bell takes to be the essence of the Everett interpretation – the commitment to instantaneous configurations: Everettians explicitly forgo a preferred decomposition into orthogonal states. Its detractors perceive this as a flaw – the so-called "problem of a preferred basis". Conversely, Pauli and Heisenberg, for instance, rebuke BM for foisting an "artificial asymmetry" on position and momentum (see e.g. Myrvold, 2003, sect. 3). In QM simpliciter – with the Everett interpretation as a conceivable interpretation – both are on a par. In other words: even *critics* of the Everett interpretation controvert Bell's identification!

Let's also push back against another misidentification of TBM's ontology: according to Esfeld (private communication), it's identical to the GRW flash ontology. The latter's "flashes" (or "hits") are elementary events, the centres of the spontaneous collapse of the wavefunction. Thus defined – absent a collapse of the wavefunction in TBM – the "flashes" or "hits" have no direct counterpart in TBM. Nonetheless, Esfeld (2018), p. 173) descries a salient ontological analogy between GRWf and TBM in the following: "The GRWf ontology of single, discrete events can be considered as a particle ontology without the trajectories so that what remains of the particles are isolated events in space-time."

Underlying Esfeld's verdict is his "Quantum Humeanism" or "Humeanism without intrinsic properties" (see e.g. Esfeld, 2014a; Esfeld et al., 2017). According to this proposal, fundamentally only primitive stuff exists without any further specified qualities – a kind of otherwise featureless *prima materia*/ὕλη πρωτη, the different chunks of which are individuated only via spatial (or spatiotemporal) relations. These chunks or matter points lack any intrinsic properties. Mass, charge, etc. are merely formal parameters introduced in order to account for the occupants' spatiotemporal evolution. On this view, then, non-permanent corpuscles and flashes coincide. But Esfeld's Quantum Humeanism will strike many as inordinately radical (for a critique, see Wilson, 2018).[35] To say the least, it's not the only option for an interpretative framework.

For those who don't subscribe to Esfeld's Quantum Humeanism, discriminating between TBM's and the GRW flash ontology is straightforward. Events aren't things: our weddings and our wives fall (for better or worse) into different metaphysical *categories* or *kinds* (cf. Casati & Varzi, 2014, esp. sect.1.1). Furthermore, we *don't* take it to be essential for Bohmian corpuscles to possess continuous trajectories: it's possible for

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[31] In fact, TBM is the Bohmian – that is, *corpuscle*-based – cousin of Schrödinger's many-world theory: the latter's referent is a primitive matter density field.

[32] Cf. also Wallace, 2020, p. 85: "what should we expect from an 'interpretation' of quantum mechanics? Here is one natural answer: we should expect an *interpretative recipe*, a set of instructions which tells us, for any given quantum theory, how to understand *that* theory."

[33] Although much work remains to be done in order to flesh out those principles (cf. Conroy, 2016), salient features (exemplified at least to some extent) arguably include: (1) the absence of additional postulates that go beyond the theory's working posits (e.g. a preferred basis or the introduction of an ad-hoc collapse mechanism); (2) a "literal" realist interpretation of the formalism; (3) quantum probabilities as primitive branch weights, rather than dispositions/propensities; (4) a "wavefunction pattern ontology": the wavefunction's fundamentality$_{\text{CMB}}$ and, concomitantly, a structuralist/functionalist approach to higher-level/emergent entities.

[34] One of the essential points of contention between "wavefunction ontologists" – such as Everettians – and Primitive Ontologists lies in their respective attitudes towards functionalism (cf. Wallace, 2008, §2.6.7).The former rest content with the existence of an entity – viz. the quantum state – that possesses, at some effective, higher level of description, the approximate dynamical structure (functional description) of semi-classical objects. (cf. Brown, 2009; Brown & Wallace, 2004). By contrast, Primitive Ontologists demand that one must posit independent *realisers* of this dynamical structure – stuff, over and above the wavefunction: This stuff *instantiates* the functional roles of FAPP-classical objects. Furthermore, Primitive Ontologists insist that those realisers live in ordinary 3-dimensional space (cf. Maudlin, 2010, 2012, 2013).Underlying these conflicting ontological doctrines seems to be a *semantic* thesis concerning how abstract, formal terms are imbued with a physical interpretation (see Dewar, 2017, p. 7).

[35] One may even go a step farther and reprimand the GRW flashes – and Esfeld's proposal with them – as metaphysical monstrosities (cf. Myrvold, 2017, esp. 6.3): denuded of any intrinsic properties, don't they suspiciously resemble Lockean bare substrata?

Bohmian corpuscles to randomly relocate. To our minds, this merely reflects the corpuscles' non-classical nature (cf. Falkenburg, 2007, Ch. 6).[36]

To sum up: we argued that TBM is a bona fide minimally Bohmian theory. That is, it's a position-based corpuscle theory with a Primitive Ontology (in the most plausible construal of that framework) and empirically equivalent to standard QM. We rejected both Bell's classification of (his variant of) TBM as Everettian, as well as Esfeld's identification of TBM's ontology with the GRW flash ontology.

Bell had already contemplated something like TBM. Why did he reject it? For an answer, we must scrutinise TBM's many-worlds character.

3.5. *Temporal solipsism? – Quasi-persistent many-worlds!*

This section will rebut Bell's criticism that TBM is *temporally solipsistic*: according to Bell, it's overwhelmingly probable that our world only exists for one single infinitesimal moment.[37] This diagnosis is specious, however: in any interval of time, our world pops into existence infinitely many times – as does every other quasi-classical world.

As mentioned above, Bell adumbrated TBM (or something very similar, with the key difference consisting in the definition of worlds, see our preceding comment – for ease of readability, we'll here use TBM and Bell's "Everett (?) theory" interchangeably). He correctly realizes that in TBM configurations of the universe at two arbitrary instants are no longer causally connected: "Thus in our interpretation of the Everett theory [read: TBM], there is no association of the particular present with any particular past" (Bell, 1987, p. 135). Despite conceding TBM's empirical adequacy, Bell (op.cit., p. 136) deems this consequence fatal: "Everett's [read: TBM's] replacement of the past by memories is a radical solipsism – extending to the temporal dimension the replacement of everything outside my head by my impressions, of ordinary solipsism or positivism. Solipsism cannot be refuted. But if such a theory were taken seriously, it would hardly be possible to take anything else seriously."

If the universe randomly hops through the unfathomable vastness of configuration space, at first blush it appears astronomically unlikely that within our lifetime our world will ever pop into existence again. One might hence believe that, according to TBM, we only endure for *this one* single moment. Our hopes for any moment beyond the present would then degenerate into illusions. Maudlin (2016, p. 324) poignantly writes: "The Everett (?) theory [read: TBM] is a sort of physical blueprint for a Cartesian demon, but one where the subject is deceived about the past (and even her own past)."

What makes this (alleged) feature pernicious? Two reasons are hinted at: first, it's supposed to undermine the rationality of our belief in TBM; secondly and more generally, *temporal solipsism* is supposed to be incoherent.

Vis-à-vis the puny probability that our world existed a minute ago and will continue to do so for the next one, Bell demurs: how still to trust our memories or anticipations of the future? Bell denies that we could. Our quotidian practices, his argument goes, presuppose the reliability of memories and future anticipations. Therefore solipsism, temporal and metaphysical, despite being irrefutable in principle, is *pragmatically* unviable (in Kantian terminology: it violates a regulative principle): "It is always interesting to find that solipsists, when they have children, have life insurance" (Bell, 1987, p. 136).

More generally, Bell intimates that TBM's temporal solipsism, on the one hand, and metaphysical solipsism on the other share the same problems. Arguably foremost amongst them is that of incoherence (see e.g. Thornton, 2004, sect. 4). In the case of metaphysical solipsism, in so far as its articulated as a rational thesis, its advocate must resort to language and logic. But the solipsist's arguments forfeit their *intersubjective* force (and plausibly even their comprehensibility): after all, she disputes that anything exists outside of her own mind. This vitiates all her arguments ab initio.

The analogue of the incoherence argument in the case of *temporal* solipsism generalises the concern about practical reliability of memories and future anticipations: if a theory entails that all the relevant evidence in its favour is deceptive, on what grounds can we still rationally believe it? Bell (1987, p. 136) likens the situation to a Young Earth Creationists' response to contradictory empirical evidence: "The theory was that of the creation of the world in 4004 BC. […] The trees would be created with annular rings, although the corresponding number of years had not elapsed. […] The rocks would be typical rocks, some occurring in strata and bearing fossils – of creatures that had never lived." In other words: According to Bell, TBM resembles Young Earth Creationism in that it invalidates its own empirical evidence. Both are therefore incoherent.

Fortunately, TBM can be salvaged. Bell's concerns about temporal solipsism don't carry over: TBM *isn't* temporally solipsistic. What Bell and other commentators have overlooked – arguably, due to neglecting that worlds are a coarse-grained concept, see the above difference between Bell's Everett (?) theory and TBM – is a peculiarity of TBM's many-worlds character. It exhibits a "stochastically successive many-worldliness": within any finite time span, our world is actualised for (uncountably) infinitely many instants. This ensues from the following considerations.

Let $(\mathscr{W}, t_0)$ denote the event that the FAPP-classical macro-world $\mathscr{W}$ (recall 3.2) is actualised at $t = t_0$.

The probability for $(\mathscr{W}, t_0)$ is:

$$\mathbb{P}^{\Psi}[(\mathscr{W}, t_0)] = \int_{\substack{micro- \\ realisations\ of\ W}} d^{3N}\boldsymbol{Q}|\Psi_{t_0}(\boldsymbol{Q})|^2.$$

Macro-worlds are only FAPP-defined. They are coarse-grained concepts. This translates into them occupying finite "volume" in configuration space. Albeit tiny, the probability for $\mathscr{W}$'s actualisation is therefore always non-zero:

$$\forall t \in \mathbb{R} : 0 < \mathbb{P}^{\Psi}[(\mathscr{W}, t)] \ll 1.$$

Recall that probability distributions needn't have a well-defined expectation value. (The canonical example is the Cauchy distribution: it has neither finite expectation value nor variance.) Thereby, the formulation of laws of large numbers is blocked. This is the case here, too, as follows from the following simple argument.

Consider the compact time interval $I \subset \mathbb{R}$. Defined as a function on it, $\mathbb{P}^{\Psi}[(\mathscr{W}, .)] : I \to]0; 1]$ is continuous. It follows that its minimum is non-zero:

$$\mathbb{P}_{min}(\mathscr{W}, I) : = \inf_{t \in I} \{\mathbb{P}^{\Psi}[(\mathscr{W}, t)]\} > 0.$$

Now choose from I randomly N points $t_1, \ldots, t_N \in I$. These are the (discrete) blinks of His eyes God is willing to devote to the universe "below".

TBM's TOC is memoryless (in the mathematical-technical sense): its positions during those moments are stochastically independent. Hence, the expectation value for $\mathscr{W}$ popping into existence at least one moment out of the $t_1, \ldots, t_N$ is:

$$\mathbb{E}^{\Psi}[\mathscr{W}; t_1, \ldots, t_N] : = \sum_i \mathbb{P}^{\Psi}[(\mathscr{W}, t_i)].$$

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[36] We thank Michael Esfeld (Lausanne) for an illuminating discussion.

[37] We don't take Bell's main objection to be the inaccuracy of our memories and records of the past: that they don't track the complete, real history as disclosed, as it were, from the God's eye view. (We'll address *that* criticism later on in the main text, too.) Our reading of Bell is, we believe, buttressed by his repeated emphasis (p.133, p. 135, p. 136) on the fact that our only access to other times is via present data, and that the inherent link to those times is cut – to the effect (we take him to conclude) that we are epistemically trapped in the moment.

It's bounded from below:

$$\mathbb{E}^{\Psi}[\mathscr{W};t_1,\ldots,t_N] \geq \sum_i \inf_{t\in I}\{\mathbb{P}^{\Psi}[(\mathscr{W},t)]\} = N\mathbb{P}_{min}(\mathscr{W},I) > 0.$$

How often should God expect then to behold the world $\mathscr{W}$ during I? It depends on how frequently He's willing to peep. If His attention is unlimited, so is the expectation value for the actualisation of $\mathscr{W}$:

$$\mathbb{E}^{\Psi}[\mathscr{W};t_1,\ldots,t_N] \overset{N\to\infty}{\to} \infty.$$

In short: on TBM, our world ceases to exist *continuously*. Nonetheless, in any finite interval, it pops into existence infinitely many infinitesimal instants. This holds for all macro-worlds (Everettian branches): they are actualised infinitely many times within each second – successively. In the Everett interpretation, all worlds coexist *simultaneously*. By contradistinction, in TBM each world is realised only one at a time, randomly "selected". The Everettian multiverse picture thus resembles an ill-attuned TV displaying several channels at once. TBM's many-worldliness resembles that of a TV randomly and rapidly switching between different channels.[38] That is, the temporal order in which TBM's worlds are actualised is random. (Recall from §3.2 that the TOC's jumps through configuration space are stochastically independent.)

TBM's stochastically successive many-worldliness extricates the theory from temporal solipsism: our existence *isn't* restricted to one single moment. We continue to exist – albeit not continuously. Our memories and future anticipations *are* reliable: they permit inferences to our macro-world's history; within each atto-second, infinitely many temporal fragments of it are realised. On TBM, historical records aren't illusory or deceptive: they correctly describe a branch of reality (quite literally: an Everettian branch – that is, a quasi-classical history). This isn't to say that the FAPP-classical reconstructions of our world's history from those records are *fundamentally* correct. They are merely higher-level/emergent descriptions.[39] And most importantly, of course: there isn't just one such quasi-classical world, but staggeringly many. The fundamental picture is that of a stochastically successive multi-verse.

Quantum phenomena – interference experiments in particular – evince structure beyond each FAPP-classical world. Being empirically adequate, TBM is capable of accommodating those quantum phenomena: On TBM, they grant us glimpses into TBM's stochastically successive many-worlds.

In sum: we defended TBM against Bell's accusation of a form of solipsism that renders it incoherent. TBM is a coherent many-worlds theory: Decohered macro-worlds successively pop into existence for an instant; within any arbitrary time interval each world exists infinitely many times, with the exact temporal sequence being random. No longer persisting continuously, we still exist "densely" in time.

The panels in Fig. 1 visualise this result. The first shows the concentration of the probability density induced by the universal wavefunction (yellow). For simplicity, it's assumed to branch only into two FAPP-worlds. The other three panels show the actualised configurations of the universe (red dots) from a God's eye view. The increasing number of configurations in each picture is supposed to convey a feeling for the limit process that leads to TBM's *indefinite* world rate. The frequency with which snapshots are taken (or: "God blinks") increases from left to right.

4. Summary

We started with a review of standard Bohmian Mechanics (BM). We didn't question its viability and merits. Still, we proposed, it's worthwhile inquiring into the consequences of removing its Guidance Equation: first, this deepens our understanding of the role of the Guidance Equation in BM, and secondly, probing its (formal) eliminability is a prima facie natural response to its empirical underdetermination – to be sure: not necessarily the only option.

We showed that, based on the Quantum Equilibrium Hypothesis and the Schrödinger Equation alone (with an appropriate re-interpretation of the former), one *can* articulate an empirically adequate and metaphysically coherent theory – Tychistic Bohmian Mechanics (TBM). Pace Bell, we classified it as a Bohmian theory: 1. Its referents are (massive, charged, etc.) corpuscles (particles) in ordinary, three-dimensional space. 2. At all times, they have determinate positions. All other dynamical variables are contextual. 3. It's fully equivalent with QM. 4. All macro-objects of everyday experience are composed of TBM's corpuscles.

While ontologically deflationary interpretations of the wavefunction (such as the nomological one) are certainly possible, we showed that in TBM an ontologically thicker interpretation is both viable and natural – one in terms of an irreducibly dispositional, holistic property of the whole *N*-corpuscle system.

According to TBM, the *N*-corpuscle system that constitutes our universe – the TOC – performs irreducibly random jumps through configuration space. The TOC's (objective) localisation probability density is given by the modulo square of the wavefunction of the universe. Due to decoherence, it's concentrated over configurations in FAPP-classical Everettian branches (worlds). During any finite time interval, each world is actualised (almost certainly) uncountably infinitely many times – in random order. Their ratios (almost certainly) match their probability distribution. This guarantees TBM's empirical adequacy and coherence. Although the worlds – including macro-objects such as ourselves – cease to exist continuously at a *fundamental* level, in a *temporally coarse-grained* sense they persist. At this higher level of description, all FAPP-classical worlds co-exist. At TBM's fundamental level of description, each world pops into existence only one at a time.

If TBM is a *viable* minimally Bohmian theory – minimally Bohmian in the sense that it satisfies the minimal desiderata for a Bohmian theory – one would like to know: how does it fare vis-à-vis BM and other Primitive Ontology theories? This question must be taken up elsewhere, e.g. along Esfeld's (2014b) guidelines for evaluating Primitive Ontological quantum theories.

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References

Albert, D. (1996). Elementary quantum metaphysics. In J. T. Cushing, A. Fine, & Sh. Goldstein (Eds.), *Bohmian mechanics and quantum theory: An appraisal* (pp. 277–284). Amsterdam: Kluwer Academic Publishers.

Allori, V. (2013a). On the metaphysics of quantum mechanics. In S. Lebihan (Ed.), *Precis de la Philosophie de la Physique* (pp. 116–151). preprint http://philsci-archive.pitt.edu/9343/.

Allori, V. (2013b). Primitive ontology and the structure of fundamental theories. In A. Ney, & D. Albert (Eds.), *The wave function: Essays on the Metaphysics of quantum mechanics*. Oxford: Oxford University Press, 2013, preprint http://philsci-archive.pitt.edu/9342/.

Allori, V. (2015). Primitive ontology in a nutshell. *International Journal of Quantum Foundations, 1*(3), 107–122. http://www.ijqf.org/wps/wp-content/uploads/2015/06/IJQF2015v1n3p1.pdf.

Allori, V. (2018). Primitive ontology and scientific realism. Or: The pessimistic meta-induction and the nature of the wave function. *Lato Sensu: Revue de la Société de*

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[38] We borrow this simile from Allori, 2013a, sect. 4.4, who uses it to illustrate the many-worldliness of the GRW matter theory.

[39] Butterfield (2001, sect. 3.1.3) speaks of a "kind of coarse-grained surrogate of history".

Philosophie des Sciences, 5(1), 69–76 (2018), preprint https://valiaallori.com/wp-content/uploads/2017/10/PMI-and-the-nature-of-the-WF-lato-suensu-REVISED2.pdf (accessed: 1/2/2020).

Allori, Valia, Goldstein, Sheldon, Tumulka, Roderich, & Zanghì, Nino (2008). On the Common Structure of Bohmian Mechanics and the Ghirardi-Rimini-Weber Theory. *The British Journal for the Philosophy of Science, 59*(3), 353–389. https://doi.org/10.1093/bjps/axn012

Allori, Valia, Goldstein, Sheldon, Tumulka, Roderich, & Zanghì, Nino (2011). Many Worlds and Schrödinger's First Quantum Theory. *The British Journal for the Philosophy of Science, 62*(1), 1–27. https://doi.org/10.1093/bjps/axp053

Arntzenius, F., & Hawthorne, J. (2005). Gunk and continuous variation. *The Monist, 88*, 441–465. https://doi.org/10.5840/monist200588432

Bacciagaluppi, G. (2005). *A coneptual introduction to Nelson's mechanics*. http://philsci-archive.pitt.edu/8853/1/Nelson-revised.pdf.

Bacciagaluppi, G. (2012). The role of decoherence in quantum mechanics. In *Stanford encylopedia of philosophy*. https://plato.stanford.edu/entries/qm-decoherence/ (accessed: 3/12/2017).

Barbour, J. (1994a). The emergence of time and its arrow from timelessness. In J. Halliwell, et al. (Eds.), *Physical origins of time asymmetry*. Cambridge, online: Cambridge: Cambridge University Press. https://cqi.inf.usi.ch/qic/94_Barbour.pdf.

Barbour, J. (1994). The timelessness of quantum gravity: II. The appearance of dynamics in static configurations. *Classical and Quantum Gravity, 11*(12). https://doi.org/10.1088/0264-9381/11/12/006

Barbour, J. (1999). *The end of time*. Oxford: Oxford University Press.

Barbour, J. (2009). *The nature of time*. https://arxiv.org/abs/0903.3489 (accessed 24/12/2017).

Barrett, J. (1996). Empirical adequacy and the availability of reliable records in quantum mechanics. *Philosophy of Science, 63*, 49–64. March, 1996 https://www.jstor.org/stable/188225.

Barrett, J. (1999). *Quantum mechanics of minds and worlds*. Oxford: Oxford University Press.

Bell, J. S. (1976). *The measurement theory of everettt and de Broglie's pilot wave*. Bell (2004).

Bell, J. S. (1987). *Quantum mechanics for cosmologists*. Bell (2004).

Bell, J. S. (1990). Against measurement. In A. I. Miller (Ed.), *Sixty-two years of uncertainty* (pp. 17–31). Plenum Press.

Bell, J. S. (2004). *Speakable and unspeakable in quantum mechanics. Collected papers on quantum philosophy*. Cambridge: Cambridge University Press.

Belot, G. (2010). On a symmetry argument for the guidance equation in Bohmian mechanics. *International Studies in the Philosophy of Science, 24*. https://doi.org/10.1080/02698595.2010.543350 (2010).

Ben-Menahem, Y. (1990). Equivalent descriptions. *The British Journal for the Philosophy of Science, 41*(2), 261–279. https://doi.org/10.1093/bjps/41.2.261, 1990.

Bohm, D., & Hiley, B. (1993). *The undivided universe: An ontological interpretation of quantum theory*. London: Routledge.

Brown, Harvey, Elby, Andrew, & Weingard, Robert (1996). Cause and Effect in the Pilot-Wave Interpretation of Quantum Mechanics. In J. T. Cushing, A. Fine, & S. Goldstein (Eds.), *Bohmian Mechanics and Quantum Theory: An Appraisal* (pp. 309–319). Springer.

Brown, H. R. (1996a). Bovine Metaphysics: Remarks on the significance of the gravitational phase effect in quantum mechanics. In R. Clifton (Ed.)*, 1996. Perspectives on quantum reality: Non-relativistic, relativistic and field-theoretic* (pp. 183–193). Dordrecht: Kluwer Academic Press.

Brown, H. R. (1996b). Mindful of quantum possibilities. *The British Journal for the Philosophy of Science, 47*(Issue 2), 189–199. https://doi.org/10.1093/bjps/47.2.189

Brown, H. R. (2005). *Physical relativity: Space-time structure from a dynamical perspective*. Oxford: Oxford University Press.

Brown, H. R. (2009). *Comment on Valentini, 'de Broglie-Bohm-pilot-wave theory: Many worlds in denial?*. https://arxiv.org/abs/0901.1278.

Brown, H. R., & Wallace, D. (2004). *Solving the measurement problem: deBroglie-bohm loses out on Everett* (accessed: 5/7/2017) http://arxiv.org/pdf/quant-ph/0403094.pdf.

Bunge, M. (1963). *The myth of simplicity*. New Jersey: Prentice Hall Inc.

Bunge, M. (2011). Tratado de filosofía. In *, Vol. III. Ontología 1: El moblaje del mundo*. Barcelona: Gedisa.

Butterfield, J. (2001). *The end of time?*. https://arxiv.org/pdf/gr-qc/0103055.pdf (accessed 2/5/2018).

Callender, Craig (2007). The emergence and interpretation of probability in Bohmian mechanics. *Studies in History and Philosophy of Modern Physics, 38*(2), 351–370. https://doi.org/10.1016/j.shpsb.2006.08.004

Callender, C., & Weingard, R. (1997). Trouble in paradise: Problems for Bohm's theory. *The Monist, 80*(Issue 1), 24–43. https://doi.org/10.5840/monist19978011

Carroll, S. (2017). *Why Boltzmann Brains Are Bad*. arXiv. https://arxiv.org/pdf/1702.00850.pdf (accessed: 17/12/2017).

Casati, R., & Varzi, A. (2014). Events. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/entries/events/ (accessed: 31/5/2018).

Chen, E. (2019). *Realism about the wavefunction*. Philosophy Compass. https://doi.org/10.1111/phc3.12611 (2019).

Coffey, K. (2014). Theoretical equivalence as interpretative equivalence. *The British Journal for the Philosophy of Science, 54*(4), 821–844. https://doi.org/10.1093/bjps/axt034

Conroy, Chr. (2016). Everettian interpretations of quantum mechanics. In *Internet encyclopedia of philosophy*. https://www.iep.utm.edu/everett/ (accessed: 23/1/2020).

Correia, F. (2008). *Ontological dependence*. Philosophy Compass. https://doi.org/10.1111/j.1747-9991.2008.00170.x (2008).

Daumer, Martin, Dürr, Detlef, Goldstein, Sheldon, & Zanghì, Nino (1996). Naïve realism about operators. *Erkenntnis, 45*, 379–397. https://doi.org/10.1007/BF00276801

Deotto, E., & Ghirardi, G. C. (2002). Bohmian mechanics revisited. *Foundations of Physics, 28*(Issue 1), 1–30. preprint https://arxiv.org/abs/quant-ph/9704021 (accessed: 13/7/2018).

Dewar, N. (2017). Interpretation and equivalence; or, equivalence and interpretation. In S. Lutz, & E. Curiel (Eds.), *The semantics of theories*. Forth., preprint http://philsci-archive.pitt.edu/13234/ (accessed: 2/4/2019).

Dewdney, Chris, & Brown, Harvey (1995). Bohm particles and their detection in the light of neutron interferometry. *Foundations of Physics, 25*, 329–347. https://doi.org/10.1007/BF02055211

Dorato, M., & Esfeld, M. (2009). GRW as an ontology of dispositions. *Studies in History and Philosophy of Science B: Studies in History and Philosophy of Modern Physics, 41*(Issue 1), 41–49. https://doi.org/10.1016/j.shpsb.2009.09.004, 2010.

Drezet, A. (2016). Analysis of Everett's quantum interpretation from the point of view of a Bohmian. *International Journal of Quantum Foundations, 2*, 67–88. http://www.ijqf.org/wps/wp-content/uploads/2016/02/IJQF-3352.pdf.

Dürr, D., et al. (2013). *Quantum Physics without quantum philosophy*. Heidelberg: Springer.

Dürr, D., & Struyve, W. (2019). Typicality in the foundations of statistical physics and Born's Rule. In V. Allori, et al. (Eds.), *Do wavefunctions jumps? Perspective of the work of GianCarlo Ghirardi*. forth: Springer. preprint https://arxiv.org/abs/1910.08049.

Dürr, D., & Teufel, S. (2009). *Bohmian mechanics: The Physics and mathematics of quantum theory*. Heidelberg: Springer.

Dürr, Detlef, Goldstein, Sheldon, & Zanghì, Nino (1992). Quantum equilibrium and the origin of absolute uncertainty. *Journal of Statistical Physics, 67*, 843–907. https://doi.org/10.1007/BF01049004

Dürr, Detlef, Goldstein, Sheldon, & Zanghì, Nino (1995). Bohmian Mechanics and Quantum Equilibrium. *Stochastic Processes, Physics and Geometry II*. World Scientific. https://www.ge.infn.it/∼zanghi/BMQE.pdf.

Einstein, A. (1949). Reply to criticisms. In P. A. Schilpp (Ed.), *Albert Einstein, philosopher-scientist* (pp. 663–688). Evanston, IL: Library of Living Philosophers.

Esfeld, M. (1998). Holism and analytic philosophy. *Mind, 107*, 426. April, 1998 https://www.jstor.org/stable/2659881.

Esfeld, M. (2003). Philosophical holism. In G. Hirsch Hadorn (Ed.), *Encyclopedia of life support system, section Encyclopedia of social sciences and humanities*. https://www.unil.ch/files/live/sites/philo/files/shared/EOLSS-PhilHolism03.pdf.

Esfeld, M. (2014a). Quantum humeanism, or: Physicalism without properties. *The Philosophical Quarterly, 64*(256), 453–470. https://doi.org/10.1093/pq/pqu030

Esfeld, M. (2014b). The primitive ontology of quantum physics: Guidelines for an assessment of the proposals. *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics, 47*, 99–106. https://doi.org/10.1016/j.shpsb.2014.06.003

Esfeld, M. (2017). *Individuality and the account of non-locality: The case for the particle ontology in quantum physics*. https://arxiv.org/abs/1712.03372 (accessed 2/2/2018).

Esfeld, M. (2018). Collapse or No Collapse? What Is the Best Ontology of Quantum Mechanics in the Primitive Ontology Framework? In Shan Gao (Ed.), *Collapse of the Wave Function* (pp. 167–184). Cambridge: Cambridge University Press.

Esfeld, M. (2019). From the measurement problem to the primitive ontology programme. In V. Allori, et al. (Eds.), *Do wave functions jump?* forth: Springer. preprint https://philsci-archive.pitt.edu/16061/1/GhirardiFS.pdf [accessed 2/6/2019].

Esfeld, M. (2019b). Against the disappearance of spacetime in quantum gravity. *Synthese*. https://doi.org/10.1007/s11229-019-02168-y (2019).

Esfeld, Michael, Hubert, Mario, Lazarovici, Dustin, & Dürr, Detlef (2014). The Ontology of Bohmian Mechanics. *The British Journal for the Philosophy of Science, 65*(4), 773–796. https://doi.org/10.1093/bjps/axt019

Esfeld, Michael, Lazarovici, Dustin, Lam, Vincent, & Hubert, Mario (2017). The Physics and Metaphysics of Primitive Stuff. *The British Journal for the Philosophy of Science, 68*(1), 133–161. https://doi.org/10.1093/bjps/axv026

Falkenburg, B. (2007). *Particle Metaphysics. A critical account of subatomic reality*. Heidelberg: Springer.

Fankhauser, Johannes, & Dürr, Patrick (2021). How (not) to understand weak measurements of velocities. *Studies in History and Philosophy of Science, 85*, 16–29.

Fine, A. (1996). On the interpretation of Bohmian mechanics. In J. T. Cushing, et al. (Eds.), *Bohmian mechanics and quantum theory: An appraisal*. Springer.

Flores, F. (1999). Einstein's theory of theories and types of theoretical explanation. *International Studies in the Philosophy of Science, 13*(2), 123–134. https://doi.org/10.1080/02698599908573613, 01 July 1999.

Frigg, R. (2009). Typicality and the approach to equilibrium in Boltzmannian statistical mechanics. *Philosophy of Science, 76*. https://doi.org/10.1086/605800

Frigg, R. (2011). Why typicality does not explain the approach to equilibrium. In M. Suárez (Ed.), *Probabilities, causes and propensities in Physics*. Berlin: Spinger. preprint https://philsci-archive.pitt.edu/11213/1/typicality.pdf.

Frigg, R., & Hoefer, C. (2007). Probability in GRW theory. *Studies in History and Philosophy of Modern Physics, 38*(Issue 2), 371–389. https://doi.org/10.1016/j.shpsb.2006.12.002

Gao, S. (2016). *The meaning of the wave function: In search of an ontology for quantum mechanics*. https://arxiv.org/abs/1611.02738 (accessed 1/7/2018).

Goldstein, S. (2011). Typicality and notions of probability in physics. In Y. Ben-Menahem, & M. Hemmo (Eds.), *Probability in Physics*. Heidelberg: Springer.

Goldstein, S. (2017). Bohmian mechanics. In *Stanford encyclopedia of philosophy* (accessed: 3/3/2018) https://plato.stanford.edu/entries/qm-bohm/.

Goldstein, Sheldon, Taylor, James, Tumulka, Roderich, & Zanghì, Nino (2005a). Are all particles identical? *Journal of Physics A: Mathematical and General, 38*, 1567.

Goldstein, Sheldon, Taylor, James, Tumulka, Roderich, & Zanghì, Nino (2005b). Are all particles real? *Studies in History and Philosophy of Modern Physics, 36*(1), 103–112. https://doi.org/10.1016/j.shpsb.2004.11.005

Goldstein, S., & Struyve, W. (2007). On the uniqueness of quantum equilibrium in Bohmian mechanics. *Journal of Statistical Physics, 128*, 1197–1209. https://doi.org/10.1007/s10955-007-9354-5 (2007).

Goldstein, Sheldon, Tumulka, Roderich, & Zanghì, Nino (2009). *Bohmian Trajectories as the Foundation of Quantum Mechanics*. arXiv. https://arxiv.org/pdf/0912.2666.pdf.

Greaves, H. (2006). Probability in the Everett interpretation. *Philosophy Compass, 2*(1), 109–128. https://doi.org/10.1111/j.1747-9991.2006.00054.x. January 2007.

Hájek, A. (1997). 'Mises redux' — redux. Fifteen arguments against finite frequentism. *Erkenntnis, 45*, 209–227. https://www.jstor.org/stable/20012727.

Hájek, A. (2009). Fifteen arguments against hypothetical frequentism. *Erkenntnis, 70*, 211–235. www.jstor.org/stable/40267419.

Held, C. (2018). The Kochen-specker-theorem. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/entries/kochen-specker/. (Accessed 6 January 2018).

Hoefer, C. (2011). Physics and the humean approach to probability. In C. Beisbart, & S. Hartmann (Eds.)*, 2011. Probabilities in Physics*. Oxford: Oxford University Press.

Holland, P. (1993). *The quantum theory of motion. An account of the deBroglie-Bohm causal interpretation of quantum mechanics*. Cambridge: Cambridge University Press.

Holland, P., & Philippidis, C. (2003). Implications of Lorentz covariance for the guidance equation in two-slit quantum interference. *Physical Review A, 67*(6). https://doi.org/10.1103/PhysRevA.67.062105

Hossenfelder, S. (2018). *Lost in math: How beauty leads Physics astray*. New York: Basics Books.

Howard, D. (1989). Holism, separability and the metaphysical implications of the Bell experiments. In J. Cushing, & E. McMullin (Eds.), *Philosophical consequences of Bell's theorem* (pp. 224–253). Notre Dame: University of Notre Dame Press.

Howard, D. (1992). Locality, separability and the physical implications of the bell experiments. In A. van der Merwe, F. Selleri, & G. Tarozzi (Eds.), *Bell's theorem and the foundations of modern Physics*. Singapore: World Scientific.

Howard, D. (2004). Who invented the 'copenhagen interpretation? A study in mythology. *Philosophy of Science, 71*(Issue 5), 669–682. https://doi.org/10.1086/425941

Hubert, M., & Romano, D. (2018). The wavefunction as a multifield. *European Journal for Philosophy of Science, 8*(3), 521–537. https://doi.org/10.1007/s13194-017-0198-9 (2018).

Ivanova, M. (2014). Is there a place for epistemic virtues in theory choice? In A. Fairweather (Ed.)*, 2014. Virtue epistemology naturalised: Bridges between virtue epistemology and philosophy of science* (pp. 207–226). Cham: Springer.

Kitcher, Ph. (1995). The advancement of science. In *Science without legend, objectivity without illusions*. Oxford: Oxford University Press.

Koslicki, K. (2013). Ontological dependence: An opinionated survey. In M. Hoeltje, et al. (Eds.), *Varieties of dependence: Ontological dependence, grounding, supervenience, response-dependence* (pp. 31–64). München: Philosophia Verlag, 2013.

Kukla, A. (1994). Non-empirical theoretical virtues and the argument from underdetermination. *Erkenntnis, 41*, 157–170. https://doi.org/10.1007/BF01128825

Lam, V., Wüthrich, & Chr. (2018). Spacetime is as spacetime does. In *Studies in History and Philosophy of modern Physics (forth.)*. preprint https://arxiv.org/abs/1803.04374.

Lazarovici, D. (2019). Position measurements and the empirical status of particles in Bohmian mechanics. *Philosophy of science (forth.)*. preprint: https://arxiv.org/abs/1903.04555.

Lazarovici, D., & Reichert, P. (2015). Typicality, irreversibility and the status of macroscopic laws. *Erkenntnis, 80*(Issue 4), 689–716. https://doi.org/10.1007/s10670-014-9668-z

Lazarovici, Dustin, Oldofredi, Andrea, & Esfeld, Michael (2018). *Observables and unobservables in quantum mechanics: How the no-hidden-variables theorems support the Bohmian particle ontology*. arXiv. https://arxiv.org/abs/1805.07120.

Le Bihan, B., & Read, J. (2018). Duality and ontology. *Philosophical Compass (forth.)*. https://doi.org/10.1111/phc3.12556

Lehmkuhl, D. (2017). Introduction. Towards a theory of spacetime theories. In D. Lehmkuhl, et al. (Eds.)*, 2017. Towards a Theory of spacetime theories. Einstein Studies 13*. Basel: Birkhäuser.

Maudlin, T. (1995a). Why Bohm's theory solves the measurement problem. *Philosophical Studies, 62*(Issue 3), 479–483.

Maudlin, T. (1995b). Three measurement problems. *Topoi, 14*(Issue 1), 7–15.

Maudlin, T. (2010). Can the world be only wavefunction? In S. Saunders, et al. (Eds.), *Many worlds? Everett, quantum theory, and reality*. Oxford University Press.

Maudlin, T. (2011). Three roads to objective probability. In C. Beisbart, & S. Hartmann (Eds.), *Probabilities in Physics*. Oxford University Press.

Maudlin, T. (2012). Critical study; David Wallace, the emergent multiverse. *Noûs, 48*, 794–808.

Maudlin, T. (2013). The nature of the quantum state. In A. Ney, & D. Albert (Eds.), *The wave function: Essays on the Metaphysics of quantum mechanics*. Oxford University Press.

Maudlin, T. (2016). Local beables and the foundations of physics. In M. Bell, & S. Gao (Eds.), *Quantum nonlocality and reality: 50 Years of Bell's theorem*. Cambridge University Press.

Mittelstaedt, P. (1995). Constitution of objects in classical mechanics and in quantum mechanics. In *, Vol. 34*. *International journal for theoretical Physics* (pp. 1615–1626). https://doi.org/10.1007/BF00676274 (1995).

Muller, F. A. (1997a). The equivalence myth of quantum mechanics – Part I. In *, Vol. 28*. *Studies in history and philosophy of science Part B: Studies in history and philosophy of modern Physics* (pp. 35–61). https://doi.org/10.1016/S1355-2198(96)00022-6 (1).

Muller, F. A. (1997b). The equivalence myth of quantum mechanics – Part II. In *, Vol. 28*. *Studies in history and philosophy of science Part B: Studies in history and philosophy of modern Physics* (pp. 219–247). https://doi.org/10.1016/S1355-2198(97)00001-4 (2).

Myrvold, W. (2003). On some early objections to Bohm's Theory. In *International Studies in philosophy of science*. https://doi.org/10.1080/02698590305233, 17,1, 2003.

Myrvold, W. (2016). Probabilities in statistical physics. In A. Hájek, & C. Hitchcock (Eds.), *Oxford handbook of probability and philosophy*. Oxford: Oxford University Press, 2016, preprint http://philsci-archive.pitt.edu/11019/.

Myrvold, W. (2017). Ontology for collapse theories. In Sh. Gao (Ed.), *Collapse of the wave function*. Cambridge: Cambridge University Press, 2018; preprint http://philsci-archive.pitt.edu/13318/.

Ney, A. (2012). The status of our ordinary three dimensions in a quantum universe. *Noûs, 46*(3), 525–560. https://doi.org/10.1111/j.1468-0068.2010.00797.x (2012).

Ney, A., & Albert, D. (2013). *The wave function: Essays on the Metaphysics of quantum Metaphysics*. Oxford: Oxford University Press.

Ney, A., & Philipps, K. (2013). Does an adequate physical theory require a primitive ontology? *Philosophy of Science, 80*(3), 454–474. July 2013 https://www.doi.org/10.1086/671076.

Norsen, T. (2014). The pilot-wave perspective on spin. *American Journal of Physics, 82*, 337–348. https://doi.org/10.1119/1.4848217

Norton, J. (2008). Must evidence undermine theory? In M. Carrier, D. Howard, & J. Kourany (Eds.), *The challenge of the social and the pressure of practice: Science and values revisited*. Pittsburgh: University of Pittsburgh Press, 2008; preprint https://www.pitt.edu/∼jdnorton/teaching/1702_jnrsnr_sem/1702_jnrsnr_seminar_2005/docs/underdet_thesis.pdf.

Norton, J. (2018). *Simplicity as a surrogate*. Unpublished manuscript. University of Pittsburgh https://www.pitt.edu/∼jdnorton/papers/material_theory/6.%20Simplicity.pdf [accessed: 5/5/2019].

Oldofredi, A. (2020). Stochasticity and Bell-type quantum field theory. *Synthese, 197*, 731–750. https://doi.org/10.1007/s11229-018-1720-0 (2020).

Oldofredi, A. (2021). Beables, primitive ontology and beyond: How theories meet the world. In V. Allori (Ed.), *Quantum mechanics and fundamentality: Naturalizing quantum theory between scientific realism and ontological indeterminacy*. forth: Synthese Library. Springer. preprint https://arxiv.org/abs/2104.13859.

Oldofredi, A., & Esfeld, M. (2018). *On the possibility of a realist ontological commitment in quantum physics* (accessed: 29/6/2018) https://arxiv.org/abs/1801.05307.

Passon, O. (2006). *What you always wanted to know about Bohmian Mechanics but were afraid to ask* (accessed: 3/8/2017) http://arxiv.org/abs/quant-ph/0611032.

Passon, O. (2010). *Bohmsche Mechanik: Eine elementare Einführung in die deterministische Interpretation der Quantenmechanik*. Frankfurt a.M: Harri Deutsch.

Psillos, S. (1999). *Scientific realism. How science tracks truth*. London: Routledge.

Read, J., & Møller-Nielsen, T. (2020). Motivating Dualities. *Synthese, 2020*(197), 263–291. https://doi.org/10.1007/s11229-018-1817-5

Redhead, M. (1987). *Incompleteness, non-locality, and realism: A prolegomenon to the philosophy of quantum mechanics*. Oxford: Oxford University Press.

Saunders, S. (2021). *The Everett interpretation: Probability*. https://arxiv.org/abs/2103.03966 (accessed: 10/07/2021).

Scheibe, E. (2007). *Die Philosophie der physiker. München: C.H. Beck*.

Schlosshauer, M. (2014). The quantum-to-classical transition and decoherence", forthcoming. In Aspelmeyer, et al. (Eds.), *Handbook of quantum information*. Berlin/Heidelberg: Springer. https://arxiv.org/abs/1404.2635.

Sebens, Ch. (2015). Quantum mechanics as classical physics. *Philosophy of Science, 82*, 266–291. https://doi.org/10.1086/680190 (April, 2015).

Solé, A., & Hoefer, C. (2019). The nomological interpretation of the wave function. In A. Cordero (Ed.)*, Vol. 406. Philosophers look at quantum mechanics. Synthese library (Studies in epistemology, logic, methodology, and philosophy of science)*. Cham: Springer. https://doi.org/10.1007/978-3-030-15659-6_9.

Stanford, K. (2017). Underdetermination of scientific theory. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/win2017/entries/scientific-underdetermination [accessed 2/7/2018].

Suárez, M. (2007). Quantum propensities. *Studies in History and Philosophy of Modern Physics, 38*(Issue 2), 418–438. https://doi.org/10.1016/j.shpsb.2006.12.003

Suárez, M. (2009). Propensities in quantum mechanics. In D. Greenberger, et al. (Eds.), *Compendium of quantum Physics*. Berlin: Springer. https://doi.org/10.1007/978-3-540-70626-7_152.

Suárez, M. (2013). Propensities and pragmatism. *The Journal of Philosophy, 110*(Issue 2), 61–92. https://www.jstor.org/stable/43820751.

Suárez, M. (2014). A critique of empiricist propensity theories. *European Journal for the Philosophy of Science, 4*, 215. https://doi.org/10.1007/s13194-014-0083-8 (2014).

Suárez, M. (2016). The chances of propensities. *The British Journal for the Philosophy of Science, 69*(4), 1155–1177. https://doi.org/10.1093/bjps/axx010. December 2018.

Tahko, T. (2018). Fundamentality. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/fall2018/entries/fundamentality/ (accessed: 3/2/2020).

Tahko, T., & Lowe, E. J. (2015). Ontological dependence. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/win2016/entries/dependence-ontological (accessed: 2/1/2019).

Thornton, S. (2004). Solipsism and the problem of other minds. In *Internet encyclopedia of philosophy*. https://www.iep.utm.edu/solipsis/. (Accessed 2 January 2018).

Tumulka, R. (2017). *Bohmian mechanics*. https://arxiv.org/abs/1704.08017 (accessed: 10/5/2018).

Uffink, J. (2011). Subjective probability and statistical physics. In C. Beisbart, & S. Hartmann (Eds.)*, 2011. Probability in Physics*. Oxford: Oxford University Press.

Vaidman, L. (2014). The many worlds interpretation of quantum mechanics. In *Stanford encyclopedia of philosophy*. https://plato.stanford.edu/entries/qm-manyworlds/ (accessed: 5/7/2015).

Valentini, A. (2020). Foundations of statistical mechanics and the status of the Born rule in de Broglie-Bohm pilot-wave theory. In V. Allori (Ed.), *Statistical mechanics and scientific explanation. Determinism, indeterminism, and laws of nature*. Singapore: World Scientific. preprint https://arxiv.org/abs/1906.10761.

Valentini, A., & Westman, H. (2005). Dynamical origin of quantum probabilities. *Proceedings of the Royal Society A, 461*(2053), 253–272. https://doi.org/10.1098/rspa.2004.1394 van Fraassen, B. (1980). *The scientific image*. Oxford: Oxford University Press.

Vickers, P. (2017). Understanding the selective realist defence against the PMI. *Synthese, 194*(9), 3221–3232. https://doi.org/10.1007/s11229-016-1082-4

Vickers, P. (2018). Disarming the ultimate historical challenge to scientific realism. *The British Journal for the Philosophy of Science, 71*(Issue 3), 987–1012. https://doi.org/10.1093/bjps/axy035. September 2020.

Vickers, P. (2019). Towards a realistic success-to-truth inference for scientific realism. *Synthese, 196*(2), 571–585. https://doi.org/10.1007/s11229-016-1150-9

Von Neumann, J. (1932). *Mathematische grundlagen der Quantenmechanik*. Berlin: Springer.

Wallace, D. (2002). Worlds in the Everett interpretation. *Studies in History and Philosophy of Modern Physics, 33*(2002), 637–661. https://doi.org/10.1016/S1355-2198(02)00032-1

Wallace, D. (2003). *Everett and structure. Studies in History and Philosophy of science Part B: Studies in History and philosophy of modern Physics* (Vol. 34, pp. 86–105). https://doi.org/10.1016/S1355-2198(02)00085-0 (2003).

Wallace, D. (2008). Quantum mechanics. In D. Rickles (Ed.), *The ashgate companion to the philosophy of Physics*. Ashgate, preprint https://arxiv.org/pdf/0712.0149v1.pdf.

Wallace, D. (2010). Decoherence and ontology: Or, how I learned to stop worrying and love FAPP. In S. Saunders, J. Barrett, A. Kent, & D. Wallace (Eds.), *Many worlds? Everett, quantum theory, and reality*. OUP. preprint https://arxiv.org/abs/1111.2189.

Wallace, D. (2011). *Decoherence and its role in the modern measurement problem*. https://arxiv.org/abs/1111.2187 (accessed 4/7/2017).

Wallace, D. (2012a). Decoherence and its role in the modern measurement problem. *Philosophical Transactions of the Royal Society of London A, 370*, 4576–4593. https://doi.org/10.1098/rsta.2011.0490

Wallace, D. (2012b). *The emergent multiverse: Quantum theory according to the Everett interpretation*. Oxford: Oxford University Press.

Wallace, D. (2013). The Everett interpretation. In R. Batterman (Ed.), *The oxford handbook of philosophy of Physics*. Oxford: Oxford University Press. preprint http://philsci-archive.pitt.edu/8888/1/Wallace_chapter_in_Oxford_Handbook.pdf.

Wallace, D. (2020). On the Plurality of Quantum Theories: Quantum Theory as a Framework, and its Implications for the Quantum Measurement Problem. In Steven French, & Juha Saatsi (Eds.), *Scientific Realism and the Quantum* (pp. 78–102). Oxford University Press.

Wilson, A. (2018). Super-humeanism: Insufficiently naturalistic and insufficiently explanatory. *Metascience, 27*, 427–431. https://doi.org/10.1007/s11016-018-0326-y (2018).

Zeh, H.-D. (2000). The meaning of decoherence. In Philippe Blanchard, Erich Joos, Domenico Giulini, Claus Kiefer, & Ion-Olimpiu Stamatescu (Eds.), *Lecture Notes in Physics: 538*. *Decoherence: Theoretical, Experimental, and Conceptual Problems* (pp. 19–42). Springer. preprint https://arxiv.org/abs/quant-ph/9905004.

Zeh, H. Dieter (2003). Basic Concepts and Their Interpretation. In Erich Joos, H. Dieter Zeh, Claus Kiefer, Domenico Giulini, Joachim Kupsch, & Ion-Olimpiu Stamatescu (Eds.), *Decoherence and the Appearance of a Classical World in Quantum Theory* (2nd, pp. 7–40). Springer. https://arxiv.org/abs/quant-ph/9506020. preprint.