The Unruh Effect and Theory Interpretation in an Effective Framework

Marco Maggiani

University of Pittsburgh

Abstract

I discuss the ontological implications of the Unruh effect if quantum field theory is taken to be an *effective* theory. In the context of the "algebraic" approach to the philosophy of quantum field theory, the Unruh effect can be exploited to construct arguments against particle interpretations. I argue that, since those arguments make use of the notion of fundamentality in a possible world, they cannot be understood in a framework that takes quantum field theory to be an effective theory. I then propose a reformulation that is valid for effective field theories. I conclude by noting that, given that analogous arguments against field interpretations can be made in the algebraic context but not in the effective one, arguments against particles from the Unruh Effect are much more powerful in the latter. I also present a method for interpreting effective theories along the way.

1 Introduction

Outside of the "algebraic" approach, there has been precious little discussion within the philosophical literature on quantum field theory (QFT) of the *Unruh effect*: the prediction of quantum field theory in curved spacetime that an accelerated observer in the Minkowski vacuum will detect a thermal bath of quanta. In the context of the algebraic approach, the Unruh effect can be exploited to construct arguments against the particle interpretation of QFT. The purpose of this paper is to explore if and in what form these arguments can be transferred to the "effective" approach to the philosophy of QFT, which regards QFT as an effective field theory (EFT). I will argue that one argument against the particle interpretation survives in the effective context, and moreover that it carries more weight there than in the algebraic one.

I start, in section 2, by presenting the Unruh Effect, some of the initial arguments made by physicists concerning its ontological implications, and a regimentation of these arguments by philosophers. In section 3, I argue that this regimentation makes use of the notion of fundamentality in a possible world, and that therefore, for it to be relevant for interpreting QFT, must be committed to the "Standard Account" of theory interpretation (Williams 2019). The core tenets of the Standard Account are that theories provide a true and exhaustive description of certain possible worlds in all respects, and that the goal of theory interpretation is the identification and characterization of their fundamental ontological features. These are incompatible with the effective field theory approach to the philosophical study of QFT, and for this reason I introduce, in section 4, an alternative account of theory interpretation that can be used to interpret effective theories. At the heart of this account is the idea that the entities fit for interpretation are chosen if they conform to certain metaphysical principles, frame independence being one of them. This account does not have the problems of the Standard Account because it does not employ the notion of fundamentality in a possible world, and can be used to construct an argument against particle interpretations because, given the Unruh effect, particles are not frame independent.

I conclude the paper by assessing, in section 5, the strength of this argument against particles for effective field theories. In the algebraic framework, the argument against particles from their lack of frame independence is not the only argument against particles that makes use of the Unruh effect. It is also possible to construct an argument against particles taking as a starting point the unitary inequivalence of the Fock space corresponding to an accelerating observer with that of an observer moving inertially. Moreover, as argued in Baker 2009, we can also construct a similar argument against the wavefunctional interpretation, arguably the leading field interpretation of QFT. However, I argue that these two arguments do not work if we adopt the effective approach to the study of QFT, because inequivalent representations are unphysical according to the effective approach. We are left only with the argument against particles from frame dependence, and therefore I conclude that, given the lack of a compensating argument field interpretations (since, as I argue, there are field theoretic quantities that are not frame dependent), this argument is stronger in the effective context than in the algebraic one.

2 Particles and the Unruh Effect

Let us briefly introduce the reasons why QFT might seem to be about particles.[1] Consider the radiation field (i.e., the electromagnetic field). For simplicity, assume the idealization that the radiation resides inside a large cubic enclosure, and impose periodic boundary conditions at the surfaces of the cube. The most straightforward way of quantizing the radiation field in this situation works as follows.[2] We first Fourier analyze the radiation field into normal modes, and, given that each mode is described by the harmonic oscillator equation, we apply the harmonic oscillator treatment to each mode. The result of this procedure is the following radiation Hamiltonian for the radiation field:

$H_{rad} = \sum_{\mathbf{k}} \sum_{r} \hbar\omega_{\mathbf{k}}(a_r^{\dagger}(\mathbf{k})a_r(\mathbf{k}) + \frac{1}{2})$

Where the summations are over all the allowed momenta $\mathbf{k}$ and both polarization states $r = 1, 2$ for each $\mathbf{k}$, and the $a_r^{\dagger}(\mathbf{k})$ and $a_r(\mathbf{k})$ operators satisfy the following commutation relations

$[a_r(\mathbf{k}), a_s^{\dagger}(\mathbf{k}')] = \delta_{rs}\delta_{\mathbf{k}\mathbf{k}'}$

$[a_r(\mathbf{k}), a_s(\mathbf{k}')] = [a_r^{\dagger}(\mathbf{k}), a_s^{\dagger}(\mathbf{k}')] = 0$

Now, consider the operators

$N_r(\mathbf{k}) = a_r^{\dagger}(\mathbf{k})a_r(\mathbf{k})$

Given the commutation relations above we find that the $N_r(\mathbf{k})s$ have eigenvalues $n_r(\mathbf{k}) = 0, 1, 2, ...$, and eigenfunctions

$|n_r(\mathbf{k})\rangle = \frac{[a_r^{\dagger}(\mathbf{k})]^{n_r(\mathbf{k})}}{\sqrt{n_r(\mathbf{k})!}}|0\rangle$

The eigenfunctions of the radiation Hamiltonian are clearly products of

---

[1] I will be largely following Mandl and Shaw 2010 here.

[2] Similar procedures can be applied to other bosonic fields.

these eigenfunctions, i.e., they are states of the following form

$|...n_r(\mathbf{k})...\rangle = \prod_{\mathbf{k_i}} \prod_{\mathbf{r_i}} |n_{r_i}(\mathbf{k_i})\rangle$

whose energy is

$\sum_{\mathbf{k}} \sum_r \hbar\omega_{\mathbf{k}}(n_r(\mathbf{k}) + \frac{1}{2})$

The interpretation of this result is straightforward: we just need to generalize the interpretation of similar results for a singular harmonic oscillator to a system constituted by a superposition of harmonic oscillators. The effect of $a_r(\mathbf{k})$ acting on one of the eigenstates of the radiation Hamiltonian is that of reducing the eigenvalue of the operator $n_r(\mathbf{k})$ (the *occupation number* of the mode $(\mathbf{k}, r)$) by one. We then interpret $a_r(\mathbf{k})$ as an "annihilation" operator, which annihilates a photon in mode $(\mathbf{k}, r)$ (i.e., a photon with momentum $\hbar\mathbf{k}$, energy $\hbar\omega_{\mathbf{k}}$, and polarization vector $\varepsilon_r(\mathbf{k})$). Similarly, $a_r^\dagger(\mathbf{k})$ is viewed as a "creation" operator of a photon in mode $(\mathbf{k}, r)$.

This seems to show that the formalism of QFT contains discrete (i.e., countable) quantities, which moreover have the same energy of classical particles. Some have taken this to be a definitive proof of the viability of a particle interpretation for QFT.[3]

However, this conclusion is premature. At the very least, we must recognize that our ordinary concept of a particle must be revised, for several reasons. For instance, a number of no-go theorems shows that in this context "particles" cannot be localized in any finite region of space-time,[4] and in the case of interacting fields, not even the "particle number" representation

---

[3] Ryder, for instance, argues that the calculations above provide the "justification for interpreting $N_r(\mathbf{k})$ as the number operator, and hence for the particle interpretation of the quantized theory". See Ryder 1996, p. 131).

[4] See for instance Malament 2006 and Halvorson & Clifton 2002.

delineated above is available.[5]

Importantly, particles come under pressure also from the Unruh effect, which can be described as follows. Let $|0; M\rangle$ be the Minkowski vacuum. A detector moving inertially in $|0; M\rangle$ would detect no particles. However, if the same detector starts moving in a uniformly accelerated motion with acceleration a instead, and the state is still $|0; M\rangle$, it will observe a thermal bath of quanta (called *Rindler quanta*) with temperature $T = \frac{\hbar a}{2\pi c k_b}$.[6]

Multiple derivations of the Unruh effect are possible; we can derive it for instance using Bogoliubov methods, path integrals, and as a rigorous result in algebraic quantum field theory (see Harlow 2016 for an helpful derivation via path integrals and Crispino *et al.* 2008 for a more general review; for philosophical discussion, see Wallace 2018 and Earman 2011).

Qualitatively, we can explain the Unruh effect in the following way.[7] The raising and lowering operators for the Minkowski quanta are obtained by quantizing the positive frequency solutions of the Klein-Gordon equation, $(\Box + \mu^2)\phi(x) = 0$, where $\mu \equiv \frac{mc}{\hbar}$. What is regarded as a positive frequency solution, and therefore the space of the positive frequency solutions, depends on the time parameter we use. Hence, if we use the proper time parameter for an accelerating observer, the space of positive frequency solutions will change, and after quantization we will then obtain raising and lowering operators different from those we obtain for the Minkowski quanta. We call

---

[5] For a presentation of this argument, see Fraser 2008. For a possible response which relies on the notion of asymptotically free states in scattering theory, see Bain 2000.

[6] In this formula, a is the acceleration of the observer, c the speed of light, and k_b Boltzmann's constant. Therefore, if $a = 2.47 \cdot 10^{20}\mathrm{m} \cdot \mathrm{s}^{-2}$, the temperature of the observed thermal bath will be about 1K.

[7] See Teller 1995 pp. 110-113.

these operators the Rindler rising and lowering operators, as opposed to the Minkowski raising and lowering operators we obtain for inertial observers. For this reason, the particle number operator for the acceleration observer will be different from the particle number operator for the inertial observer, too.

The Unruh effect has originated much discussion in the literature on the philosophy of QFT. One of the first physicists to describe it, Paul Davies, concluded that it shows that "particles do not exist" (Davies 1984). Robert Wald, more modestly, concluded that particles should be demoted from a *fundamental* to a *derivative* status

> It simply happens that the natural notion of "particles" defined by accelerating observers ... differs from the natural notion of particles defined by inertial observers ... . No paradox arises when one views quantum field theory as, fundamentally, being a theory of local field observables, with the notion of "particles" merely being introduced as a convenient way of labeling states in certain situations. (Wald 1994, p. 116)

Arageorgis *et al.*, in an attempt to make the content of Wald's remark explicit, formulated the following argument (Arageorgis *et al.* 2003, p. 166)

(A1) If the particle notion were fundamental to QFT, there would be a matter of fact about the particle content of quantum field theoretic states.

(A2) The accelerating and inertial observers differ in their attributions of particle content to quantum field theoretic states.

(A3) Nothing privileges one observer's attributions over the other's.

(C4) Therefore, there is no matter of fact about the particle content of quantum field theoretic states. (From (A2) and (A3))

(C5) Therefore, the particle notion is not fundamental. (From (A1) and (C4))

Arageorgis *et al.* end up denying the soundness of this argument by rejecting (A3), but in the philosophy of QFT (A3) is usually regarded as true. And for good reasons: in the case of the Unruh effect, it might indeed be possible to argue that the physical states corresponding to the accelerating observer are in some way less "real", but for less symmetric spacetimes there is no preferred class of observers, and therefore no preferred definition of particle (see Wallace 2001, and Wald 1994 for details).

3 Fundamentality and Theory Interpretation

The idea that facts about fundamental entities, in the unqualified metaphysical sense, must be observer independent is an intuitive metaphysical principle. Following Wald 1994, I here take this to mean that the fundamental facts must be frame independent, although, as I will discuss later, Arageorgis *et al.* had something slightly different in mind.

At any rate, this principle cannot be the one expressed by the assumption (A1) in the argument above. Why? The reason is that, after all, particle and field ontologies are supposed to provide an interpretation for QFT, which is surely *not* fundamental. The argument made by Arageorgis *et al.*, is not supposed to show that particles and fields are not fundamental *simpliciter*, but only that they are not fundamental *according to QFT*.

It remains to explain how even this weaker sense of fundamentality is related to theory interpretation. The link between interpretation and fundamentality is provided by what Porter Williams (Williams 2019) calls the "standard account" of theory interpretation, a set of assumptions concerning how to correctly interpret scientific theories shared by many practitioners in the philosophy of physics (the "standard interpreters"). Williams provides us with a list of five principles that, taken together, constitute the standard account. They are (Williams 2019, pp. 211-212)

(1) The theory to be interpreted is assumed to provide a true and exhaustive description of the physical world in all respects, including at all length scales.

(2) A theory is to be interpreted in isolation. It is illicit to appeal to, e.g., the inevitability of gravitational effects at short distances to resolve an interpretational difficulty in quantum field theory.

(3) An interpretation of a theory consists of the set of all worlds nomologically possible according to that theory.

(4) This set of possible worlds is determined by generic structural features of the theory in question, such as, e.g., its dynamical laws. Information about empirical applications of the theory is largely or entirely ignored.

(5) The goal of interpreting a physical theory is to identify and characterize its fundamental ontological features.

Of course, Williams does not claim that all authors normally thought as working under the "standard account" paradigm accept all the five principles in all their papers. The standard account is merely thought as a summary of assumptions, many of which, but not necessarily all, are shared by a substantial group of philosophers of physics.[8][9] I will discuss these matters more in the next section, since for now I am mostly interested in principles (1) and (5), which all the standard interpreters share.

As evidence for the existence of the standard account, Williams cites several philosophers of physics, among whom we find John Earman and Laura Ruetsche, who were involved in formulating the argument of section 3. Moreover, David Baker, who made a closely related argument against the wave-functional interpretation (to be discussed in section 6), also explicitly adheres to the standard account. For consider the following passages

> "Whatever else it means to interpret a scientific theory, it means saying what the world would have to be like if the theory is true". (Earman 2004 p. 1234)
>
> "To interpret a physical theory is to say what the world would be like, if the theory were true. A realist about a theory believes that theory to be true". (Ruetsche 2008, p. 199)[10]
>
> "To give a theory a field interpretation is to claim that the physically possible worlds described by the theory are configurations of one or more fundamental fields". (Baker 2009, p. 586)

---

[8] An example of a philosopher that does not accept all the assumptions that constitute the Standard Account is Gordon Belot (see Belot 1998), as noted in Williams 2019, p. 212, note 6. I will discuss Belot's paper in the next section. An example of a standard interpreter that, on the other hand, *accepts* (2) and (4) is Doreen Fraser. See Fraser 2009, p. 552, where, when discussing whether theories of quantum gravity could do interpretative work in effective field theories, Fraser writes: "the fact that quantum gravity indicates that space is discrete would not help settle the question of how to interpret the cut-off variant of QFT because gravitational considerations are *external* to QFT" (my italics).

[9] Whether, e.g., Belot would reject (3) likely depends on how we should understand the notion of nomological possibility that (3) makes use of, which is philosophically controversial.

[10] Currently, Ruetsche is not a standard interpreter (see Ruetsche 2011). I report this earlier quote merely as evidence that at an earlier time, including where she cowrote Arageorgis *et al.* 2003, she likely was.

For additional evidence, I can do not better than referring the reader to Williams 2019, pp. 212-213.

Of course, principle (5) is the one that connects fundamentality and theory interpretation. Its acceptance by the "standard interpreters" explains why it is commonly accepted that it is possible to argue against a particular interpretation by showing that the entities pertaining to that interpretation are not fundamental.

Many compelling objections can be raised against the standard account. For instance, an adherence to the standard interpretation can lead to a lack of flexibility when evaluating arguments. Consider for example the following argument that Doreen Fraser (in Fraser 2009, section 4) uses to argue that quantum field theory in four dimensions is not fit for interpretation. Fraser considers an effective field theory (EFT) which breaks down at a short distance L; generally, in this case we reduce the theory to a finite number of degrees of freedom by defining the fields on a spatial lattice with lattice spacing L. Her adoption of the standard account leads then her to conclude that the EFT under consideration attributes a lattice structure to space. Since no one believes that QFT implies that space has a lattice structure, she concludes that EFTs cannot be interpreted. However, if we reject the standard account, we can deny the EFTs really "assigns" space a lattice structure (for such a structure might be, e.g., a mathematical artefact). Therefore, it might well be the standard account, not the interpretational fitness of EFTs, that must be rejected (Williams 2019, p. 217).

However, given that we could reject the standard account by rejecting each of principles (1)-(5), and the connection between fundamentality and interpretation depends only on principle (5), we must assess whether there is a valid objection specifically against principle (5). And what is arguably the strongest objection against the standard interpretation attacks precisely this principle. This objection is that *there is no empirically successful quantum field theory that identifies and characterizes fundamental ontological features*, and surely, in the philosophy of physics, we want to be at the very least able to interpret theories that are empirically successful, especially if there are no alternatives.

Let me explain. It follows from principle (1) of the standard interpretation that a theory necessarily has a rigorous mathematical structure defined on all lengthscales. This is strictly related to principle (5), since the fundamental ontological features of a theory are normally taken to be those at the smallest scales.[11] And there is a research program with the aim of putting QFT in a mathematically precise formulation valid at all scales: I am referring to the program nowadays know as algebraic quantum field theory (AQFT). AQFT was developed in the 1960s, after Feynman, Schwinger, Dyson, and Tomonaga introduced the method of renormalization as a solution to the problem of infinities in QFT, which at the time made little mathematical sense. In that context, a group of mathematical physicists tried to put QFT on a solid axiomatic foundation, by laying down seemingly necessary axiom that any QFT would have to satisfy. And almost immediately, Glimm and

---

[11] At least, this is assumed by the standard interpreters. Famously, in Schaffer 2010, Jonathan Schaffer argued that the entire Universe, and not its parts that exist at the smallest scales, is fundamental. As promised, later I will adapt Arageorgis et al.'s argument to the effective field theory context, and I will not need the standard interpreters' assumption, but only the much weaker assumption that neither particles nor fields are fundamental.

Jaffe (1968), constructed a two-spacetime dimensional scalar quantum field theory without cutoffs, with an interaction term $\lambda\phi^4$.

There also exist rigorous algebraic formulations of free quantum field theory in four dimensions. However, to this day, after more than fifty years of research, we lack a physically realistic algebraic formulation of the most important kind of quantum field theory, i.e., four-dimensional field theories *with interactions*, which are the kind of theories we use in particle physics.

Therefore AQFT, which would be compatible with principle (1), has the important defect of not being an empirically successful theory. This renders it unfit for interpretative work, insofar as such work has to do with finding out at least something about the nature of *our* world, until a four-dimensional formulation of AQFT for interacting theories is found, or at least until we have compelling reasons for believing it can be found. We cannot defend principle (5) by noting that is compatible with AQFT.

How does principle (5) fares with respect to empirically satisfactory QFTs? Badly, for empirically satisfactory QFTs are *effective* field theories.

To understand why the adoption of effective QFTs implies a rejection of principle (5), it is useful to start by considering condensed matter physics and its employment of QFT methods.[12]

Condensed matter physics is the branch of physics dealing with the study of the physical properties of matter, in its solid and liquid phases. At large scales, the solid bodies it studies (such as, e.g., metals and crystals) look like continuous systems, so we can treat them as fields.

This means that we can handle them using QFT methods from "particle

---

[12] Here, I will be mostly echoing Wallace 2006 and Wallace 2011.

physics" QFT. The application of these methods, however, leads to divergent integrals at short scales. This is not surprising, however, for we know that at short lengthscales solid bodies have a *discrete* structure. We should *expect* the description of solid bodies as continuous systems to break down at short lengthscales. Hence, it is reasonable to avoid calculating the divergent integrals down to zero length scales: they should instead be cut off around the atomic lengthscale (i.e., around 0.1 nm).

Of course, the precise way in which the continuum description of solids fails at atomic length scales is going to be much more complicated than the adoption of any such crude "cutoff" can incorporate. Hence there are going to be multiple ways of implementing the cutoff, none of which will be exact.

Given the strength of the interactions at short length scales, we should expect this fact to have consequences at large scales. And it does, but, astonishingly, modern renormalization theory tells us that the only effects at large lengthscales will be changes in finitely many interaction terms called the renormalizable interactions. These cannot be derived from first principles but can be measured empirically.

As this works perfectly well in condensed matter physics, we can tell the same story in the case of quantum field theory, if there is a way of freezing out the degrees of freedom on lengthscales far below those that are currently accessible in experimental physics (this could be done, for instance, by a deeper theory that does not give rise to infinities).[13] This is the sense in which empirically successful QFTs are effective field theories. They, because of their very nature, *do not* describe the world at arbitrary length scales. And

---

[13] See Wallace 2011, p. 118, for other possibilities.

since the world's "fundamental ontological features" are supposed to occur at the shortest lengthscales, effective QFTs do not describe them either. Therefore, we cannot interpret effective QFTs and at the same time accept principle (5) of the standard account of theory interpretation.

For this reason, principle (5) should be rejected. This shows that if we want to use the Unruh effect to argue against particle interpretations in the effective context, we cannot just argue that particles are not fundamental: we must offer a reformulation of the argument in Section 3. To do so, we can take inspiration from the "standard interpreters" and the methods they use to deal with metaphysical matters.

4 Fundamental Structures in Possible Worlds vs Candidate Ontologies

Suppose you adhere to the standard account, and you subscribe to at least principles (1) and (5) of Williams' formulation. And you still want to hold out hope that the AQFT program will succeed in the end, and it will be possible to extract from the quantum theory of fields a description (i.e., a possible world) that is complete at all scales and can be formulated using rigorous mathematics. How can we understand the assumption (A1) of the argument against particles provided by Arageorgis *et al.*

(A1) If the particle notion were fundamental to QFT, there would be a matter of fact about the particle content of quantum field theoretic states.

In that case? Well, as we noted above, the field and particle notions might be fundamental in a possible world in which QFT holds exactly at all scales, but we know that they are not *actually* fundamental (in other words, they are not fundamental in the actual world), since QFT itself is not fundamental in the actual world. Hence, even for a standard interpreter, (A1) must involve a notion of fundamentality distinct from the metaphysical one. In fact, (A1) will say something about a possible world. More specifically, it will say that if the particle notion were fundamental *in the (merely) possible world in which QFT holds exactly*, there would be a matter of fact about the particle content of quantum field theoretic states *in that possible world.* So, the acceptance of (A1) (necessary for the argument of Arageorgis *et al.* to go through) implies a restriction on the logically possible worlds that are fit for interpretation. And as (A1) does not seem to follow from the *laws* of QFT, it also implies, perhaps, the need to restrict the set of the logically possible worlds that make up the interpretation of QFT beyond the set of all the possible worlds that are nomologically possible according to QFT.[14]

Do the standard interpreters have the means of accomplishing such a restriction? Some of them surely seem to. In *Understanding Electromagnetism* (Belot 1998), Gordon Belot presents what is arguably the best description of how the standard account is supposed to work.[15] We start, Belot tells us, to think about the content of a theory by considering the set of possible worlds in which the theory is true, and this follows purely from the formalism of the theory. However, this is only a first approximation: not all possible

---

[14] Therefore, it might be neccessary to reject principle (3) of Willliams' summary.

[15] I focus on Belot's account since it is the most fleshed out, but note that none of the quotes presented as evidence for the existence of the standard account on pages 2012-2013 of Williams 2019 supports, as far as I can tell, principles (2)-(4) of Williams's characterization of the standard account.

worlds are created equal. For Belot, an interpretation consists in the possible worlds picked out by the formalism together with additional structure which stands for our evaluation of the virtues of each possible world, and the main task of the interpreter of a scientific theory consists in spelling out what this additional structure consists of. Sometimes, but not always, there will be a single favored interpretation (Belot believes this to be the case for electromagnetism).

What does the additional structure consist of? Purely metaphysical views, and beliefs about the structure of our world constitute part of it. For instance, we might want an interpretation of electromagnetism to be deterministic, and that would imply that gauge-invariant interpretations of electromagnetism are preferable. And we might want a theory of electromagnetism to satisfy one or both of the following kinds of *locality*: *synchronic* locality, according to which the state of a system S at time t can be specified by specifying the states of the subsystems of S in each region of space, and *diachronic* locality, which says that what will happen in a certain region of space s in a finite amount of time Δt from now will only depend on the state of the world in a finite neighborhood of s, and that the size of this neighborhood approaches zero as $\Delta t \to 0$.

The intertheoretic relations between different theories will also play an important role. Consider, for instance, the traditional interpretation of classical electromagnetism in terms of electric and magnetic fields. This interpretation, if considered in isolation, satisfies all the three metaphysical desiderata listed above: it is deterministic, and synchronically and diachronically local. However, the consideration of quantum mechanical effects such as, e.g., the

Aharonov–Bohm effect challenges this interpretation. The Aharonov–Bohm effect occurs when the wave function of a charged particle passing around a long solenoid undergoes a phase shift as a result of the behavior of the magnetic field inside the solenoid, despite the fact that the magnetic field in the region in which the particle passes, and the wavefunction of the particle inside the solenoid, are negligible. This phenomenon has been verified experimentally, and has led many to interpret electromagnetism in terms of the vector potential instead. This interpretation is arguably indeterministic, since it is not gauge invariant, and diachronically nonlocal, since changing the magnetic field in a region of space can change the vector potential in a different region of space instantaneously, but it enables us to keep synchronic locality (Belot 1998).[16]

Moreover, if when we interpret a scientific theory we are supposed to identify the fundamental ontological structure of a certain possible world, there will also be some metaphysical constraints on our interpretations that follow from the fundamentality of this structure. Hence, we will look for entities that are, e.g., independent and explanatory, and from which all other structures, and their properties and relations, can be deduced. As a constraint on what the fundamental entities in certain possible worlds can be, I propose we understand (A1) as one of these metaphysical constraints on the fundamental entities.

So, according to the standard interpreters, our beliefs about our world are reflected in our interpretations of our various physical theories. It follows

---

[16] Belot, then, as noted above, is not committed to Williams' principle (4), and is not committed to principle (2) either.

that, by getting clear on the fundamental structure of certain possible worlds, they believe they can clarify and make explicit beliefs about our world.

I am very sympathetic to this picture of what the interpretation of a scientific theory consists in but, unfortunately, as we have seen in the previous section, its talk of possible worlds specified in terms of certain fundamental physical structures makes it untenable when we try to interpret an effective field theory. And there is something strange about trying to learn about our world by articulating the structure of merely possible worlds.[17]

Here is a better picture of what goes on when we interpret a scientific theory, which can be applied to the interpretation of an EFT and preserves what was right about the standard interpretation. Rather than many candidate possible worlds, the formalism of our theories will select between different *candidate ontologies.* These ontologies will contain non-fundamental entities or structures; in this way, this procedure gives us a notion of theory interpretation that not only avoids talk of possible worlds but is also able to decide between competing interpretations in terms of different non fundamental entities, such as particles and fields. The ontologies that will end up *not* being chosen as those in terms of which the theory under consideration should be interpreted will either be excluded from the ontology of the theory or will be understood as emergent or derivative from the ontology that gets ultimately chosen (the latter will maybe be the fate of particles). Other than that, we will select the right ontology in the same way in which the standard interpreters selected the fundamental structure of their possi-

---

[17] Even Belot admits that "admittedly, this is a strange way to learn about the world" (Belot 1998, p. 551).

ble worlds. Metaphysical principles (which even the standard interpreters regard as beliefs about our world) and intertheoretic relations will again play an important role. And as the standard interpreters look for independent and explanatory fundamental structures from which the other structures can be deduced, we will try to select an ontology with those properties, too.

The requirement that this ontology should be independent, in particular, ties in this discussion of theory interpretation with the ontological significance of the Unruh effect. It is natural to understand the metaphysical independence requirement, in the context of a discussion of physical theories, as a requirement that our ontology should be frame independent. For if it a desideratum that the entities that are picked out as those fit for an interpretation of QFT be frame independent, then we can make the following argument against particles, that does not make use of the notion of fundamentality in any form

(B1) If there is no fact of the matter about the particle content of field theoretic states, there are reasons against particle interpretations of QFT.

(B2) The accelerating and inertial observers differ in their attributions of particle content to quantum field theoretic states.

(B3) Nothing privileges one observer's attributions over the other's.

(D4) Therefore, there is no matter of fact about the particle content of quantum field theoretic states. (From (B2) and (B3))

(D5) Therefore, there are reasons against particle interpretations of QFT. (From (B1) and (D4))

In this argument, (D5) only states that we have *reasons* against particle interpretations of QFT; of course, this reflects the fact it might still be the case that the frame independence requirement might need to be abandoned in the end, in the same way in which, maybe, we have to abandon diachronic locality in the case of electromagnetism.

Note that this frame independence requirement on interpretations is not unique to QFT. In classical electromagnetism, electric and magnetic fields need to be relativized to a reference frame, but it is the invariant electromagnetic tensor that represents the "deepest" ontology of electromagnetism. However, it's probably helpful to attempt a more general justification. I can, at this stage, imagine two possibilities.

The first exists in the context of a layered ontology. The layers that are "deeper", or more fundamental, might be naturally more likely to be frame independent. This was perhaps the justification that the pioneers of QFT in curved spacetime had in mind when they argued that QFT is best formulated in terms of local field observables (see Wald's quote above). However, while I have some sympathy for the idea that the entities that are fundamental in the metaphysical sense might in fact be frame independent, it is hard to justify the thesis that *fields* have this property in the effective field theory context, which assumes them to be non-fundamental.

The second is pragmatic in nature. According to this possibility, an interpretation is the best rendition of a theory in terms of the language of objects, properties, and relations, where the best rendition is the one that fares better in terms of simplicity, explanatory power, intelligibility, and the metaphysical constraints discussed above. This is closely related to Wallace's version of structural realism (Wallace 2023), in which the ontological description of a mathematized physical theory is its most useful description in the object/predicate language.[18] In this context, arguably, the imposition of a frame independence requirement on the objects fit for interpretation does not require a *deep* metaphysical explanation, for when we interpret a theory we are merely, in some sense, selecting the best *metaphor* for a mathematized theory, and the best and most intelligible such metaphor should not be dependent on our perspectives.[19]

Now that we have in hand an argument that attacks particle interpretations adequate to our setting, I want to explore how strong this argument is. If the problem with particles is that the particle content of a field theoretic state must be relativized to a reference frame, this problem will be much more severe if their main competitors, *fields*, do not need to be so relativized. But in Baker 2009, David Baker has argued that fields suffer from problems similar to those of particles. Let us then see if these results, obtained in framework of AQFT, hold for EFTs.

5 The Wavefunctional Interpretation

The procedure sketched in section 2 (called *second quantization*) is not the only way of obtaining a QFT for a free field. The so-called *field quantization* is also an option.

---

[18] However, we do not need to assume structural realism here (since we do not strictly need it as an assumption to "pick out" non-fundamental entities following certain metaphysical and non-metaphysical desiderata).

[19] A further question (and a possible avenue for further research) concerns whether the best precisification would preserve particles as derivative or emergent entities (following Wald 1984) or dispense with them entirely (more in the spirit of Davies 1984).

We know that a field consists in the specification of the value of physical quantities (e.g., scalars, vectors, or tensor quantities) to space-time points. In the literature, these quantities are often called *determinables*. More specifically, determinables are sets of properties, and only one of the elements of these sets (sometimes referred to as the *determinates* of the sets) can be assigned to an individual, i.e., to a space-time point, in this case. Sometimes we need to consider an assignment of determinates to all spacetime points, in which case we get a field *configuration*, defined in Teller 1995 as follows

> *A Field Configuration for a determinable* (*or collection of determinables*) is a specific assignment in which each space-time point gets assigned a value of the determinable (or a value of each determinable in the collection).[20]

Following Teller 1995, let us provide an example of how this is supposed to work by considering the electric field. The electric field is a field; specifically, a vector field. A configuration of the electric field is then an assignment of a vector, representing the magnitude and direction of the field, to each space-time point. Hence it is straightforward to interpret the electric field of classical electromagnetism as a field in the sense defined above.

Things are more complicated in the case of QFT. Field quantization leads to the association of an *operator-valued* quantum field, $\hat{\phi}(\mathbf{x}, t)$ to each space-time point $(\mathbf{x}, t)$. To $(\mathbf{x}, t)$ we also associate a conjugate field $\hat{\pi}(\mathbf{x}, t)$, and certain commutation relations hold between $\hat{\phi}(\mathbf{x}, t)$ and $\hat{\pi}(\mathbf{x}, t)$.

Since in the case of classical fields we also associate a mathematical entity (be it a scalar, vector, or a tensor) $\phi(\mathbf{x}, t)$ to each $(\mathbf{x}, \mathrm{t})$, there is a tantalizing

---

[20] We also say that we have a field theory if we possess field equations that constrain the values that the determinates can take in each space-time point.

parallel between these fields and the quantum field. However, this parallelism is limited. For classical fields associate a determinate – a property – to each space-time point.

Teller 1995 argues from this fact to the conclusion that the reading of $\hat{\phi}(\mathbf{x}, t)$ as a field is unjustified (Teller calls such a reading "perverse"). For Teller, field operators are, as other quantum operators, more correctly viewed as a quantum version of classical determinables (as defined above), since they determine a spectrum of eigenvalues.[21] Nothing less than a full field configuration – an assignment of a value of a determinable in the classical case, and of a possible value of the quantum operator in the quantum one, to each space-time point – can, for Teller, properly count as a physical field.

Considerations like this open the way for the *wavefunctional interpretation*, which is arguably the most straightforward field interpretation of QFT, and the most frequently discussed in a foundational context (see, for example, Arageorgis 1995, Huggett 2003, Wallace 2006, Halvorson & Müger 2007, and Baker 2009). According to the wavefunctional interpretation, it is possible to obtain a proper configuration of the operator-valued quantum field: a proper assignment of physical properties arises when we consider not only the quantum field operators but also the quantum *state* of the system.

The basic idea behind the wavefunctional interpretation is inspired by a powerful analogy between quantized one particle states in ordinary quantum mechanics and quantum fields since both result from imposing canonical

---

[21] Teller notes that, however, the analogy between classical determinables and quantum operators is limited "given the dual circumstance of the absence of exact values and the noncommutative structure of the representing mathematical objects" (Teller 1995, p.97). So, Teller is only arguing that quantum operators are the object that most resembles classical determinables in the quantum world, not that the analogy is perfect.

commutation relations on classical quantities. Hence, they should be interpreted in similar ways. In the context of non-relativistic quantum mechanics, states can be described as a wave function $\psi(x)$, which maps the position x to probability amplitudes; $|\psi(x)|^2$ represents the probability of finding the particles in x, and the state is interpreted as a superposition of classical localized particles. In QFT, instead of positions, we have classical field configurations $\phi(x)$, that assign the value of a field to a point x. If the analogy with ordinary quantum mechanics is to be complete, then, quantum fields should be viewed as functions (of a function) $\psi(\phi)$ from classical field configurations $\phi(x)$ to probability amplitudes (the wave functionals). The quantum state in QFT can then, keeping up the analogy with the nonrelativistic quantum case, be naturally interpreted as a superposition of classical field configurations.[22]

In Baker 2009, David Baker has persuasively argued that if we can construct an argument against particle interpretations using the Unruh effect, the algebraic approach to QFT has the resources to show that a similar argument can be made against the wavefunctional interpretation.

We have observed in section 3 that the inertial and accelerating observers attribute different particle contents to the Minkowski vacuum $|0; M\rangle$. But working in the framework of AQFT we can show more: we can prove that, as shown by Halvorson and Clifton (see Halvorson and Clifton 2001, p. 463, Proposition 7) the Rindler Fock space $\mathcal{F}_R$ proper to the accelerating observer is *unitarily inequivalent* to the Minkowski Fock space $\mathcal{F}_M$ of the inertial

---

[22] Of course, this superposition and the probabilities involved will be understood differently according to one's interpretation of quantum mechanics (Everett, De Broglie-Bohm, collapse theories, etc.). However, according to all of them, a quantum superposition implies a probability distribution over classical (or approximately classical) states.

observer.

Here is a sketch of the problem posed by unitarily inequivalent representations in QFT. In quantum mechanics, the possible states of a system are represented by vectors in an Hilbert space $\mathcal{H}$, and the properties of the systems are represented by operators that act on vectors in $\mathcal{H}$. In the non-relativistic case, the Stone-von Neumann theorem (conjectured by Marshall Stone and proved in von Neumann 1931) guarantees that for any two apparently different representations of a system there is a *unitary transformation* that translates between the two.

However, the Stone-von Neumann theorem applies only to physical systems with finitely many degrees of freedom. And quantum field theories defined on continuous spacetimes have infinite degrees of freedom: this follows from the continuity of the spacetime and, possibly, from the fact that the background spacetime is assumed to be infinite in extent. Therefore, we are no longer guaranteed that different representations of the same physical system are translatable using a unitary transformation.

From the unitary inequivalence of the Rindler and Minkowski Fock spaces it follows that there will be some observables defined on the inertial observer's Fock space that are not defined on the space of the accelerating observer. It is, in fact, possible to show that the Minkowski observer's total particle number operator N_M is not defined on the Rindler Hilbert space. This is the reason why Arageorgis *et al.* argue that the Minkowski and Rindler Hilbert spaces correspond to incommensurable theories (see Arageorgis *et al.* 2002, p. 180).[23]

---

[23] However, note that the AQFT framework has the resources to draw connections be-

Now, it is possible to prove that the wavefunctional space is the same Hilbert space representation (i.e., it is unitarily equivalent) as the Fock space used in applications of free QFT (Baez et al. 1992, p. 57, Corollary 1.10.3 and Theorem 2.3). But then, Baker notes, if the Minkowski Fock space $\mathcal{F}_M$ is unitarily inequivalent to the Rindler Fock space $\mathcal{F}_R$, the Minkowski wavefunctional space $L_2(\mathcal{H}_M, d)$ is unitarily inequivalent to the wavefunctional space $L_2(\mathcal{H}_R, d)$.

Recall that, while the Fock space represents a state as a superposition of n-particle states, the wavefunctional space represents a superposition of field configurations. Therefore, just as from the unitary inequivalence of $\mathcal{F}_M$ and $\mathcal{F}_R$ it followed that the inertial and the accelerating observer have inequivalent definitions of "particle number", then it should follow from the unitary inequivalence of $L_2(\mathcal{H}_M, d)$ and $L_2(\mathcal{H}_R, d)$ that the inertial and the accelerating observer have inequivalent definitions of field configuration, too!

It seems that AQFT then can show that, if the Unruh effect shows that there isn't an "objective matter of fact" about particles, then there isn't an objective matter of fact about fields (or at least wave functionals) either. Hence, fields do not seem to be better suited as an interpretation of QFT as far as the Unruh effect goes.

Baker's result, however, does not hold if QFT is an effective field theory. As noted above, inequivalent representations can arise either because the background spacetime is continuous or because spacetime is assumed to be infinite in extent. Accordingly, we distinguish between two kinds of in-

---

tween the two. For instance, Halvorson and Clifton show that the expectation value for N_R is infinite for the state that the Minkowski observer would call the vacuum (see Halvorson and Clifton 2001, pp. 448–52).

equivalent representations: the ones associated with short distance (and high energy) degrees of freedom (the UV, or ultra-violet, representations), and the ones associated with long distance degrees of freedom (the IR, or infra-red, representations).

If we take QFT to be an effective theory in the sense of outlined in section 4, UV representations can be ignored: UV representations originate if there are degrees of freedom at arbitrarily short length-scales, and the imposition of a cutoff explicitly excludes short-distance degrees of freedom. In particular, discretized QFTs (see Wallace 2006, section 3.3) have a finite number of degrees of freedom for each spacetime point, and renormalization theory tells us that on scales long compared to the grid size of such discretized QFTs, any QFT will be equivalent to them. For this reason, UV inequivalent representations are not physically significant if QFT is an effective theory.

Let us now consider IR representations. Here, inequivalent representations arise because the field configuration space may have arbitrary large-distance boundary conditions. We can then deal with them by imposing boundary conditions at infinity. So, as Wallace (Wallace 2006, p. 58) notes, there could indeed be representational ambiguities in an open universe, but they are "respectable", and analogous to the imposition of boundary conditions at infinity in classical physics. Once we impose those boundary conditions, we dissipate the representational ambiguity associated with an open universe.

Moreover, when the standard interpreter argues that, if the universe is infinite, we must take the mathematical descriptions offed by QFT at arbitrarily large distances seriously, she is conflating two senses of infinity: the infinite spatial volume of the universe, and the idealized infinite volume of the spacetime on which EFTs are formulated (Williams 2016).

The descriptions of scattering experiments in EFTs treat the incoming particles as being at an infinite spatiotemporal distance from each other, for in this way they can be treated as non-interacting prior to the scattering event. For the same reasons, they are treated as ending up infinitely far apart after the scattering event.

Nevertheless, if we pay attention to the application of EFTs, we can see how the mathematical expedience of taking this infinite volume limit is independent from the possibility of an infinitely extended universe. For instance, the experiments at the Large Hadron Collider (LHC) constituted an impressive confirmation of the Standard Model of particle physics. However, the LHC tunnel has a circumference of about 27 km and a tunnel diameter of 3.8 m; and if the taking of the infinite volume limit implied that we need to regard our field theoretical description as a description of an entire (infinite) universe, we could not have obtained that confirmation. The reason why, in this case, we can formulate an EFT on an infinite spacetime is that the distances characteristic of the LHC scattering experiments are much smaller than 3.8 m, therefore modelling the background spacetime as infinitely large is an inoffensive idealization. Whether the universe is infinite or not is beside the point – we define EFTs on arbitrary long lengthscales to render them more mathematically tractable, and this does not compel us to treat their mathematical structure at those scales with “ontological seriousness” (Williams 2016).

Finally, note that we cannot construct an argument against field interpretations just from a supposed lack of frame independence because, unlike in the case of particles, there are field theoretic quantities that are not frame dependent. In fact, this is the reason why many of the pioneers of QFT in curved spacetime adopted a field interpretation: after the discovery of the relativity of the vacuum, some of them reacted by attempting to develop a frame independent formulation of QFT, by considering *local* measurable quantities rather than globally defined particle observables ("one must find something else [than particles] to play the role of the basic observables of the theory..." (Fulling 1973, p. 2857)). And what they found is that the field currents, in particular the energy momentum tenson $T^{\mu\nu}$, or its expectation value $\langle\phi|T^{\mu\nu}|\phi\rangle$ in a quantum state ϕ, could serve as observables in this sense. For instance, for the inertial observer, the renormalized energy momentum tensor for the Minkowski vacuum state is $\langle T^{\mu\nu}\rangle_{ren} = 0$, and for the accelerating observer that sees a Rindler vacuum state plus Unruh thermal radiation it is $\langle T^{\mu\nu}\rangle_{ren} = 0 = \langle T^{\mu\nu}\rangle_{thermal} + \langle T^{\mu\nu}\rangle_{Rindler\ vacuum}$, where the expectation value for the energy momentum tensor for the Rindler vacuum is negative. Thus, these physicists regarded the field themselves, or rather the fields currents, as the fundamental observer-independent existing entities (this also can serve as a clarification of what Wald had in mind when he spoke of QFT as being "fundamentally, a theory of local field observables").[24][25]

Relating this point back to the discussion of the wavefunctional approach,

---

[24] For more details, see Rüger 1989.

[25] Other physicists reacted by developing the *detector approach*, which attempts to solve the problem of the relativity of the vacuum by making the observables of QFT more local not by replacing particles by fields, but by relativizing the particle concept to the worldline of a given detector (Unruh 1976). However, the "extreme operationalism" (Isham 1977) of this proposal makes it unfit to investigate the ontological issues I am considering in this paper. See Rüger 1989 for more details.

note that, of course, we do not expect (globally defined) field configurations to be frame independent. However, given the "pragmatic" approach I am taking here, field interpretations still fare better than particles interpretations because, in contrast to the particle case, there are objective matters of fact about field theoretic *quantities* in terms of frame independence.

In conclusion, for EFTs, the inequivalent representations on which Baker's argument relies are unphysical. Therefore, we have a convincing argument that, because of the Unruh effect, there isn't an objective matter of fact about the particle content of field theoretic states but, if QFT is an EFT, we do not have a corresponding argument for fields. It follows that fields seem to be indeed more "independent" than particles, and therefore more fit for being the right interpretation of QFT. This situation can be contrasted with that in which the algebraic approach is in, where *we can* make an argument against there being a matter of fact about the field content of field theoretic states. Arguments against particle interpretations of QFT that exploit the Unruh effect are then stronger if we adopt the EFT framework.[26]

6 Conclusion

Working within algebraic QFT we can utilize the Unruh effect to construct three arguments endowed with ontological significance: two of them, respectively against particles and against fields, follow from the unitary inequivalence of the Rindler and Minkowski Fock spaces, and the third follows from

---

[26] Baker presents other arguments against field interpretations in his 2009 paper. They all involve inequivalent representations, and therefore we can respond to them along the lines presented here.

the frame dependence of particles (arguments against fields from frame dependence are unavailable because fields, in contrast to particles, are not frame dependent). Due to the lack of physical significance of unitarily inequivalent representations within the EFT framework, I have argued that the first two arguments cannot be transferred if we are working within that framework. Then, to show how to translate the argument against particles from frame dependence, I had to give an account about how effective field theories should be interpreted: in short, I proposed that the entities fit for interpretation should be picked according to their being compatible with certain metaphysical principles, frame independence being one of them. I also suggested that the reason why the satisfaction of these metaphysical principles is required lies in the fact that the ontological interpretation of a non-fundamental theory is the best rendition of a mathematized physical theory in terms of objects, properties, and relations, where the "best" rendition is chosen in terms of simplicity, explanatory power, intelligibility, and said metaphysical principles. I concluded by noting that this argument against particles, given the lack of a counterbalancing argument against fields, is stronger in the EFT framework than in the algebraic one.

Acknowledgement

I wish to thank David Wallace, Robert Batterman, and Porter Williams for many valuable comments and suggestions.

References

[1] Arageorgis, A. (1995), *Fields, Particles, and Curvature: Foundations and Philosophical Aspects of Quantum Field Theory in Curved Spacetime*, Ph.D. thesis, University of Pittsburgh.

[2] Arageorgis, A., Earman, J., Ruetsche, L. (2002) "'Weyling the Time Away: The Non-unitary Implementability of Quantum Field Dynamics on Curved Spacetime", *Studies in History and Philosophy of Modern Physics* 33, 151-184.

[3] Arageorgis, A., Earman, J., Ruetsche, L. (2003) "'Fulling Non-uniqueness and the Unruh Effect: A Primer on Some Aspects of Quantum Field Theory", *Philosophy of Science* 70, 164-202.

[4] Baez, J. Segal, I., Zhou, Z., (1992), *Introduction to Algebraic and Constructive Quantum Field Theory*, Princeton, NJ: Princeton University Press.

[5] Bain, J. (2000), "Against Particle/Field Duality: Asymptotic Particle States and Interpolating Fields in Interacting QFT (Or: Who's Afraid of Haag's Theorem?)", *Erkenntnis* 53, 375-406.

[6] Baker, D.J. (2009), "Against Field Interpretations of Quantum Field Theory", *British Journal for the Philosophy of Science* 60, 585-609.

[7] Belot, G. (1998), "Understanding Electromagnetism", *British Journal for the Philosophy of Science* 49, 531-555.

[8] Crispino, L.C.B., Higuchi, A., Matsas, G.E.A. (2008), "The Unruh Effect and its Applications", *Reviews of Modern Physics* 80, 787-838.

[9] Davies, P.C.W. (1984), "Particles Do Not Exist", in Christensen, S.M. (eds.), *Quantum Theory of Gravity* 66-77, Oxford: Oxford University Press.

[10] Earman, J. (2004), "'Laws, Symmetry, and Symmetry Breaking: Invariance, Conservation Principles, and Objectivity", *Philosophy of Science* 71, 1227-1241.

[11] Earman, J. (2011), "The Unruh Effect for Philosophers", *Studies In History and Philosophy of Modern Physics* 42, 81-97.

[12] Fraser, D. (2008), "The Fate of 'Particles' in Quantum Field Theories with Interactions", *Studies in History and Philosophy of Modern Physics* 39, 841-859.

[13] Fraser, D. (2009), "'Quantum Field Theory: Underdetermination, Inconsistency, and Idealization", *'Philosophy of Science* 76, 536-567.

[14] Fulling, W.G. (1973), "Notes on Black-Hole Evaporation", *Physical Review D* 7, 2850-2862.

[15] Glimm, J., Jaffe, A. (1968), "A $\lambda\phi^4$ Quantum Field Theory without Cutoffs. I.", *Physical Review (2)* 176, 1245-1951.

[16] Halvorson, H., Clifton, R. (2002), "No Place for Particles in Relativistic Quantum Theories?", *Philosophy of Science* 69, 1-28.

[17] Halvorson, H., Müger, M. (2007), "Algebraic Quantum Field Theory", in Butterfield, J., Earnman, J. (eds.), *Philosophy of Physics* 731-864, Amsterdam: North-Holland.

[18] Harlow, D. (2016), "Jerusalem Lectures on Black Holes and Quantum Information", *Reviews of Modern Physics* 88, 015002.

[19] Huggett, P.C.W. (1984), "Philosophical Foundations of Quantum Field Theory", in Clark, P., Hawley, K. (eds.), *Philosophy of Science Today* 617-637, Oxford: Clarendon Press.

[20] Isham, C.J. (1977), "Quantum Field Theory in Curved Spacetime: An Overview", *Annals of the New York Academy of Sciences* 302, 114-157.

[21] Malament, D. (1996), "In Defense of Dogma: Why There Cannot be a Relativistic Quantum Mechanics of (Localizable) Particles", in Clifton, R. (eds.), *Perspectives on Quantum Reality: Non-Relativistic, Relativistic, and Field-Theoretic* 1-10, Dordrecht et al.: Kluwer.

[22] Mandl, F., Shaw, G. (2010) *Quantum Field Theory*, 2nd edition, Chichester: John Wiley & Sons.

[23] Rüger, A. (1989), "Complementarity Meets General Relativity: A Study in Ontological Commitments and Theory Unification", *Synthese* 79, 559-580.

[24] Ruetsche, L. (1998), "Interpreting Quantum Theories", in Machamer, P., Silberstein, M. (eds.), *The Blackwell Guide to the Philosophy of Science* 199-226, Oxford: Blackwell.

[25] Ryder, L. H. (1996), *Quantum Field Theory*, 2nd edition, Cambridge: Cambridge University Press.

[26] Schaffer, J. (2010), "‘Monism: The Priority of the Whole", *Philosophical Review* 119, 31-76.

[27] Teller, P. (1995), *An Interpretive Introduction to Quantum Field Theory*, Princeton: Princeton University Press.

[28] Unruh, W.G. (1976), "Notes on Black-Hole Evaporation", *Physical Review D* 14, 870-892.

[29] von Neumann, J. (1931), "Die Eindeutigkeit der Schrödingerschen Operatoren [The Uniqueness of Schrödinger Operators]", *Mathematische Annalen* 104, 570-578.

[30] Wald, R.M. (1994), *Quantum Field Theory on Curved Spacetime*, Chicago: University of Chicago Press.

[31] Wallace, D. (2001), "Emergence of Particles from Bosonic Quantum Field Theory", arxiv.org/pdf/quant-ph/0112149v1.

[32] Wallace, D. (2006), "In Defence of Naiveté: The Conceptual Status of Lagrangian Quantum Field Theory", *Synthese* 151, 33-80.

[33] Wallace, D. (2018), "The Case for Black Hole Thermodynamics Part I: Phenomenological Thermodynamics ", *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 64, 52-67.

[34] WALLACE, D. (2023), “ Stating Structural Realism: Mathematics-First Approaches to Physics and Metaphysics”, in HAWTHORNE, J. (eds.), *Philosophical Perspectives Volume 36: Metaphysics* 345-378, Oxford: Wiley-Blackwell.

[35] WILLIAMS, P. (2016), *Philosophy of Science Made Effective: Realism, Reduction, and the Renormalization Group in Quantum Field Theory*, Ph.D. thesis, Columbia University.

[36] WILLIAMS, P. (2019), “Scientific Realism Made Effective”, *British Journal for the Philosophy of Science* 70, 209-237.