Can we "effectivize" spacetime?

Abstract According to *effective realism*, scientific theories give us knowledge about the unobservable world, but not at the fundamental level. This view is justified by the well-received *effective-field-theory* (EFT) approach to physics, according to which our best physical theories are only applicable up to a certain energy scale and expected to break down beyond that. In this paper, I explain the motivations for the EFT approach and effective realism as well as their benefits. For example, I argue that they can offer a new promising answer to the notorious composition question in metaphysics. I also raise new challenges for this approach. Applying effective realism to *effective quantum gravity* (EQG) reveals its shortcomings: EQG does not give us a realistic theory of spacetime even within its scope of validity. It also exposes a general interpretative dilemma faced by all EFTs concerning their indispensable references to classical spacetime beyond their scope of validity.

Keywords scientific realism, semirealism, spacetime, renormalization, effective field theory, effective quantum gravity.

What is the world like at the fundamental level given our best scientific theories? This is a question often asked by philosophers, and in particular metaphysicians who endorse scientific realism. However, we have good reasons to believe that this question relies on a faulty assumption about science and should be abandoned. No, I do not mean the reasons given by the traditional foes of realism—in particular, those who argue that science does not aim at providing us knowledge beyond the empirical realm. Rather, I mean the novel challenges presented by a new approach to physics, according to which even our best physical theories like *quantum field theories* (QFTs) are considered as only applicable to the presently experimentally accessible energy levels and are expected to break down beyond that level. Such theories are called the *effective field theories* (EFT) and the approach, *the EFT approach*. According to this approach, we may never be able to plausibly assert that we have found the fundamental theory. This approach is widely adopted by the physics community, and rightfully so, as I shall argue (Section 1). What is the implication of this approach for scientific realism and our worldview?

At first, it may sound like a triumph of anti-realism: we are only licensed to believe in the empirical predictions of our best theories because they are merely *effective*. But this is not so. EFTs include a wide range of theoretical statements about entities that are standardly recognized as unobservable: electrons, neutrons, quarks. The fact that EFTs are expected to break down beyond a certain scale does not automatically entail that we should not believe in the truth (or approximate truth) of the theoretical statements within the scope of the theories. As it turns out, reconciling the EFT approach with realism results in a new implementation of restricted realism (or semirealism)—call it *effective realism*—which has important benefits. I will argue, building on the work of Williams (2019), that it offers attractive answers to traditional ontological questions, such as the composition question (Section 2). In general, this approach provides handy ways to single out entities worthy of ontological commitment within the domain of a scientific theory.

Nonetheless, I will point out some important problems facing the strategy of effective realism. First, I shall apply this strategy to *the effective theory of quantum gravity* (EQG). In the classical picture, spacetime metrics are well defined for arbitrarily small regions, and larger distances are obtained by integrating over local metrics.

It has been long realized that this classical picture is inaccurate for the small realm when quantum physics takes over—metrics too are governed by quantum dynamics. In the philosophical literature, we have not talked about this picture much, because it is commonly assumed that we know very little about spacetime beyond general relativity due to the incompatibility between general relativity and quantum physics. This assumption needs to be corrected because the incompatibility in question is true only if we want the unified theory to be a fundamental theory—a theory amenable to empirical tests however small scales we probe—a desire we should forsake according to the EFT approach. At currently experimentally accessible scales, we do have a physically well-defined unification of general relativity and quantum theory, namely EQG.

Can we extract a realistic theory of spacetime metrics at accessibly small scales from EQG under the strategy of effective realism? My answer is overall negative (Section 3). The problem has to do with the EQG's reliance on a classical background metric, which is defined to arbitrary accuracy. First of all, if we follow the standard prescription that we use in interpreting other EFTs, we will commit to an undesirable dualism between the graviton field and the background metric. Moreover, we face a dilemma in whether to take the background metric realistically because it is defined beyond the validity range, and yet plays an indispensable role in the theory.

The second difficulty is not limited to the interpretation of EQG, but present to all EFTs, since they all involve references to the classical background metric (Section 4). While it may be tempting to exclude spacetime from the ontology of a typical EFT as a theory of *matter*, which is under no obligation to offer an exhaustive description of reality, the references to background spacetime play an explanatory role in the theory and therefore should not be dispensed with in our interpretation. I conclude that we should address these important challenges to effective realism, which is otherwise attractive and even a necessary adaptation of realism to the EFT approach to physics.

We can also think of these as challenges to the very EFT approach insofar as it is a goal of physics to provide realistic stories of the world.

Here's a roadmap for the paper. In Section 1, I will provide a brief exposition on the technique of renormalization and how it leads to the framework of EFTs. I will offer some arguments for the EFT approach to physics while rejecting others. In Section 2, I will explain why we have good reasons to endorse realism towards EFTs, and how the EFT approach provides principled answers to ontological questions that are otherwise troubling. In Section 3, I introduce EQG as an effective unification of general relativity and quantum field theory, and argue that we cannot extract from EQG a realistic theory of spacetime metrics at the experimentally accessible level. In Section 4, I examine the general implications of the problematic case of EQG for the EFT approach. In particular, I argue that the references to background classical metrics constitute a general interpretative problem for all EFTs.

The paper contains quite a bit technical details for the general reader. As often is the case, technicality is a double-edged sword—it helps the discussion to be more scientifically accurate and non-superficial, but it can also unnecessarily distract or intimidate the readers away from the philosophical content. In the hope of dulling its bad edge, I would like to emphasize that the heavy-handed technical details (e.g., Section 1.1, 1.2, 3.1) are entirely skippable or skimmable if the reader can accept the relevant technical claims for the philosophical discussion.

1 A short introduction to EFTs

The technique of *renormalization* is at the core of the framework of QFTs. It was once perceived as a necessary criterion for physical theories that they are *pertubatively renormalizable*. In this section, I will explain what this means, why our attitude towards it has changed, and how this change leads to the EFT approach to physics.

I will argue that our best scientific theories should be considered EFTs—valid up to a certain scale. (For detailed expositions on EFTs, see Costello 2011, Butterfield and Bouatta 2014, Crowther and Linnemann 2017, and Williams 2021)

1.1 What is pertubative renormalizability? Consider a scalar field ϕ with mass m and an interaction coupling constant λ, which is needed for describing how the field interacts with itself. In the framework of QFT, we can calculate the probabilistic correlation between certain values of ϕ at four spacetime points. We can think of this as the amplitude (which gives us the probability) of two particles scattering with certain energies and angles and producing another two particles with certain energies and angles (the particles are the excitations of the field). This amplitude is given by integrating over all possible configurations of ϕ with the given values at the four spacetime points $\phi(x_1), \phi(x_2), \phi(x_3), \phi(x_4)$. The integrand is given by the Lagrangian $\mathcal{L}$ of the field, which encodes all its dynamic information. We can write it out like this:

$$\mathcal{A} = \int D\phi\phi(x_1)\phi(x_2)\phi(x_3)\phi(x_4)e^{i\int d^4x\mathcal{L}(m,\lambda)}$$

Unfortunately, when we try to calculate this integral by expanding it into a Taylor series ordered by the magnitude of λ, we see that most terms are divergent, and so adding them up is not mathematically well-defined. More concretely, when calculating the amplitude of the aforementioned scattering, we need to integrate over all the possible interactions happening in the process, such as the two particles exchanging "photons" any number of times. But those virtue "photons" can have arbitrarily high momenta and integrating over them leads to divergence.

Here's where the technique of renormalization comes to the rescue. The first step is called "regularization." There are many ways to regularize, but the most intuitive way is to impose a momentum cut-off. The idea is that if we ignore all the interactions that involve momenta above that cut-off point, then the integral in question becomes finite. (We can also think of it in terms of length, which is inversely related to momentum. The regularization amounts to ignoring all fluctuations of the field within the cut-off length.) After the regularization, the value of the integral would appear to depend on the cut-off points. But this cannot be the case, because the value of the integral is an objective physical quantity while the cut-off point is arbitrarily chosen. The second step of renormalization precisely addresses this problem: we calculate how the parameters of the field m, λ vary with the cut-off points so that the value of the integral remains invariant. If necessary, we can introduce new parameters that depend on the cut-off points. If introducing finitely many such parameters can solve the problem, then we say the theory is *pertubatively renormalizable*. Otherwise, it is non-renormalizable—which is bad because if a theory is defined by infinitely many parameters, we can never verify it with our finite experiments. In the scalar field case, indeed no additional parameter is needed. As such, renormalizability was considered an important criterion for whether a theory is physical (finitely verifiable).

But after the second step, the mass and the coupling constant for interaction would depend on the cut-off point—one may justifiably ask: aren't they physical quantities? Isn't this a problem too? As it turns out, they are indeed not physical quantities but theoretical posits—we call them *bare constants*. In contrast, the *physical constants* that we measure in experiments are functions of the bare constants, the cutoff point, and the energy level of the experiments.[1] So, once we know how the bare constants vary with the cut-off point, we can calculate the values of the physical constants at the energy level of our experiments and compare it with our experimental results. Magically enough, the physical constants are independent from the cut-off point (their dependence on the bare constants and the cutoff "cancel off"). They only depend on

[1]Strictly speaking, physical constants are not directly measurable either; what we measure is just the values of correlation functions. But it's not too long a stretch to say physical constants measurable in the indirect sense.

the energy level of our experiments: for example, the measured charge of an electron depends on the energy we use to probe the electron.

1.2 Why is pertubative renormalizability now considered less important?

The dominant attitude towards renormalizability has changed under the rise of *renormalization group* method (RG) since 1980s. Instead of the bare coupling constants and the cut-off points, RG focuses on how physical coupling constants vary with the energy scale (or inversely, the length scale). For the scalar field ϕ, we already know the value of the physical constant λ_p given any energy scale μ, and from here it is trivial to derive how λ_p changes as a function of μ. For concreteness, the equation is as follows (c is a real number; $\mathcal{O}$ abbreviates less important terms):

$$\mu\frac{d}{d\mu}\lambda_p(\mu) = c\lambda_p(\mu)^2 + \mathcal{O}$$

This equation is called the *renormalization group (RG) equation* for λ_p. More generally, for any theory with physical constants $g_1, g_2..., g_n$, the RG equation for a given g_i involves all coupling constants:

$$\mu\frac{d}{d\mu}g_i(\mu) = \beta(g_1, ..., g_n)$$

If we picture the values of n physical coupling constants being represented by a point in an n-dimensional abstract space, then their varying with energy scales can be pictured as the point moving around in the space as we adjust the energy scales. This "motion picture" is called *running coupling constants* or *renormalization group flow*. If the coupling constants converge into some finite values as μ approaches infinity, then we say the theory is *non-pertubatively renormalizable*. As it turns out, non-renormalizable theories are possibly non-pertubatively renormalizable (for example, see Braun at al. 2011).

An important insight from RG for our purpose is that non-renormalizable terms in a Lagrangian that seem so troublesome in renormalization need not be a problem for the theory at a sufficiently low energy level. The reason is roughly that, because those terms are multiplied by physical coupling constants, which get smaller as the energy level becomes smaller, they become irrelevant at the low energy level. In other words, if we restrict the scope of the theory to the low energy range, then we can ignore the non-renormalizable terms, which are only relevant to higher energy ranges. As a result, we can extract empirical predictions from the theory at the low energy range just like from a renormalizable theory.

1.3 What is the EFT approach to physics? The RG method naturally leads to EFTs. Suppose we only care about the energy level μ_0 that we currently have access to. Then, we can impose a momentum cut-off point Λ_0 suitably beyond μ_0 ($\Lambda_0 \gg \mu_0$) which allows us to ignore all interactions that involve energies beyond Λ_0. For example, if we try to model the scattering of protons at the energy level of about 1 GeV, then we can impose a cutoff point suitably larger than 1 GeV but smaller than the energy level of quarks and gluons (about 10^{15} GeV). This allows us to ignore the quarks and gluons and in general higher-energy degrees of freedom so that we can optimize parameters to model the system efficiently at the low-energy range. This is very intuitive: for example, we know that in describing the heat transfer of a macro-system, it is sufficient to use macro-parameters like temperature and conductivity of the material—the micro-parameters like the Brownian motions of the molecules are largely irrelevant. The resulting theory is only valid up to an energy level suitably below Λ_0. If we conduct an experiment at the energy level near or beyond the cut-off point, then we can expect the theory's predictions become very inaccurate, as the finer details blurred out by the cut-off point become relevant.

1.4 Why should QFTs be considered EFTs? The physics community has largely shifted from the attitude that renormalization is a necessary condition for a physical theory to the attitude that even QFTs, our best physical theories so far, are just EFTs. I shall argue that this shift is warranted because we should exercise high energy humility.

First, it might be worth mentioning that Butterfield and Bouatta (2014) argued that we should consider QFTs as EFTs because otherwise it would be a very lucky coincidence that QFTs happen to be pertubatively renormalizable. The idea is that nonrenormalizable theories (such as the fermi theory of the weak interaction) are perfectly conceivable. Indeed, according to Dyson's power-counting method, a theory is renormalizable only if the Lagrangian does not contain coupling constants with a negative dimension of mass, but we can conceive many theories that have such constants (see Peskin and Schroeder 1995: 315-323). Taking QFTs as EFTs can explain away this lucky coincidence, because within low energy level all non-renormalizable terms are suppressed by being multiplied by a small factor associated with the low energy level and therefore do not contribute to the result (see Wilson 1979).

However, this argument seems incompatible with the wide acceptance of renormalizability as a necessary condition for a fundamental or final theory.[2] As long as we do not want to necessarily avoid the "lucky coincidence" of having a final theory, renormalizability isn't exactly a coincidence that has to be explained away. For one thing, having conceivable and coherent alternatives does not necessarily mean our physically well-behaved theory requires a miracle—it shouldn't be too much to ask of our physical reality to be well-behaved! I think the real rationale for taking QFTs as EFTs is that we should not take QFTs as our final theories, not that their renormalizability is a miracle.

[2] More precisely, nonpertubative renormalizability is considered a criterion for a fundamental theory (see Crowther and Linnemann 2017). However, which notion of renormalizability is used here is not important, as either needs not be a coincidence to be explained away,

We know that atoms, once considered basic, are composed of neutrons, protons and electrons, and neutrons and protons in turn are composed of quarks. There is no reason to think that quarks, which are considered fundamental particles in the standard model of QFTs, are not composed of smaller entities. We do not know whether new particles and interactions will appear at a higher energy level, so the most responsible epistemic attitude is to exercise high energy humility—that is, to remain agnostic about what physics is like at the high energy level. Indeed, recent experimental results indicate a decent chance that we have found new degrees of freedom beyond the standard model: the B-meson decays observed in LHCb seem to deviate from the predictions of the standard model, and some researchers have cautiously suggested the phenomena to be explained by new particles called leptonquarks and charged singlets (Marzocca and Trifinopoulos 2021).

More formally, the fact that QFTs are empirically successful at the low energy level that we have access to is no indication of how they will apply to higher-energy levels because the low energy theories are "decoupled" from their higher energy counterparts: two very similar EFTs that are practically indistinguishable at their validity range can have very different underlying higher-energy theories—and vice versa. In terms of RG flow, closely grouped points that represent theories at a certain energy level can flow in diverging ways not only as the energy level goes higher but also as it goes lower. For example, theories that belong to "a universality class" converge to a fixed point in their RG flow (see Butterfield and Bouatta 2014). Note, however, that EFTs are still in principle reducible to their higher-energy counterparts, and though this reduction is often extremely difficult in practice, it has been done in some cases (see Petreczky et al. 2018). So, the decoupling in question is not radical. Yet this does not matter for the argument: our empirical measures are not fine enough to differentiate between similar EFTs with different higher-energy versions. In particular, we do not have enough empirical evidence to differentiate between QFTs that apply to all energy levels and their slightly modified counterparts QFTs* that are similar in the low energy level but run in diverging courses as the energy level increases.

Not only a particular QFT as EFT is decoupled from higher-energy theories, but also the framework of QFTs itself is decoupled from higher-energy ones. Weinberg (1995, 1999) has shown that any quantum theory satisfying Lorentz invariance at the low energy level and one other plausible assumption called "cluster decomposition" must be a QFT at the low energy level (see Butterfield and Bouatta 2014). So the fact that the framework of QFTs is empirically successful at our experimentally accessible energy level is not an evidence for that its applicability to higher-energy levels.

2 Effectivizing Ontology

Contrary to what one might initially think, considering physical theories as EFTs does not mean that we cannot interpret them realistically. In this section, I will explain—following Williams (2019)—how we can reconcile the EFT approach to physics with scientific realism through *effective realism*. I will also argue that effective realism can offer attractive answers to vexing ontological questions such as the composition question.

2.1 Effective realism How do we read an ontology from a scientific theory? *Naive realism* prescribes that we should commit to every entity the theory quantifies over, which may include numbers, functions, manifolds, bundles, structures, etc. While it is very intuitive that we should commit to some non-observational entities in our best theory, it is excessive to endorse every object it quantifies over, not only because our best theories have some speculative aspects that are highly susceptible to revision by future theories, but also because they contain many uninterpreted statements that we cannot straightforwardly commit ourselves to realistically. For example, general relativity talks about tangent bundles, but it is not clear what aspects of reality these notions refer to (e.g., physical entities or Platonic abstracta). Semirealism, which requires us to believe only in some aspects of our best theory, comes into rescue (Chakravartty 1997). The general idea is that we should believe only in those aspects of a theory that are unlikely to be rejected by future theories, those that are considered "mature" and "robust" (see Worrall 1989, Psillos 1999). According to *entity realism*, we should restrict ontological commitment to entities that have sufficient explanatory or causal power. *Structural realism* says that we should only believe in certain relational structures between entities. (*Ontic structural realism* is somewhere in-between since it treats entities themselves as structures.) But what entities (or structures) have sufficient explanatory or causal power in a given scientific theory? There is little practical guide—barring hindsight—to discern the inventory of a theory worthy of ontological commitment.[3]

The framework of EFTs provides semirealism with rigorous and applicable principles, because every EFT has built in a demarcation criterion between physical objects and mathematical artefacts among its domain, just as it has built in its own scope of validity. In a (pertubatively or nonpertubatively) renormalized theory, the physical coupling constants associated with a particular field are invariant under the arbitrary choice of cut-off points and regularization schemes—which is why they are considered physical, while the bare coupling constants that vary with the cut-off points and the cut-off points themselves are non-physical (see Section 1.1). In an EFT, where bare constants do not play a role, there are also quantities that are induced by—and thereby dependent upon—a cut-off point and the choice of a regularization scheme. For example, as Williams points out, in describing a free fermion field propagating in four-dimensional spacetime, we will have to posit 16 "mirror fermions" in the effective Lagrangian due to the cut-off point. These mirror fermions, like the bare constants,

[3]For example, Hacking (1982) argued that we commit to the existence of an unobservable entity only if it can be manipulated to produce new experimental data, such as electrons. But the criterion in question is subsequently loosened to include entities that we do not interfere or intervene, like sun neutrinos, or the core of the sun.

are part of the heuristic device to yield empirical predictions that are invariant under our arbitrary provisional choices. Thus, whether an entity in an EFT varies with its regularization scheme and cut-off point constitutes a concrete criterion for its physical reality.

Let's turn to how this new approach to realism—*effective realism*—can offer new promising answers to vexing ontological questions. I will take the composition question as an example.

2.2. The composition question There needs no introduction to the famous (or infamous) composition question raised by van Inwagen (1990), which asks under what conditions material objects compose a further object. There are three mutually exclusive and jointly exhaustive positions. *Universalism* says that material objects always compose, while *nihilism* says that there are no composite things. These two are principled answers, but are extreme and at odds with our ordinary and scientific ontological attitudes. For example, contra universalism, the nose of a dog and a bike do not compose a further object—or so it is commonly held—nor does a cell of my body with one of yours. Against nihilism, we commonly believes that many entities studied by special sciences exist, including atoms, molecules, cells, dogs and cats, even though they are composite objects. Between these two extremes, there is the position of *restricted composition*, which says that things compose but not always. There are many attempts to answer the composition question, but it is highly controversial whether any satisfactory answer is—or can be—given (see Korman and Carmichael 2016). For example, van Inwagen's original answer that life systems are the only composite objects defies belief nearly as much as the two extreme positions. Markosian's (1998) *brute composition*, which says that the notion of composition is (almost) basic, does not illuminate what restricted ontology we should believe in.

It is often lamented—sometimes ridiculed—that this debate is too removed from any scientific context (see Ladyman and Ross 2007). Contra this, it is argued that it is unclear how particular scientific theories are relevant (Dorr 2010). But fortunately in this case, science can indeed provide help. The EFT approach offers a new attractive answer to the composition question and, more generally, a principled guide for our ontological commitment at the nonfundamental level. To illustrate, an example discussed by Williams comes handy. Quantum chromodynamics (QCD)—a QFT about the strong force—describes quarks and gluons (the force carrier) and their interactions at a relatively high energy range. At this range, the interactions are relatively weak, and an explanation in terms of quarks and gluons is appropriate. But at a lower energy range (corresponding to the length scale above $10^{-15}m$), the interaction between quarks and gluons becomes so strong that an explanation of phenomena in terms of individuals states of quarks and gluons becomes intractable. Rather, they are *confined* (a technical term referring to this kind of situation where interaction is very strong) into hadrons—particles that constitute nuclei such as neutrons and protons—and explanations of larger particles in terms of hadrons become more appropriate.

Now, appealing to confinement may sound very similar to a much discussed composition principle based on unity and cohesive force: for instance, atoms compose molecules in virtue of their chemical bonds, or the components of a car compose a car because they are held together by mechanical force. Indeed van Inwagen himself has considered the principle. But it is difficult to flesh this intuitive criterion into a full-fledged principle for composition that saves our commonsense—after all, a dog and a mug glued together do not compose a new thing. Can the EFT approach do better? Confinement by itself is just a special phenomenon of hadrons, and would not help with the more general situation. However, this phenomenon illustrates a more general ontological principle. The EFT approach provides a general prescription of imposing a high-energy cut-off point and dispensing with the degrees of freedom beyond the cut-off point so that the higher-energy interactions play no role in low-level empirical predictions. In this sense, every EFT offers its own set of "basic" ontology and physical laws.[4] Blurring out the extra degrees of freedom of the quarks and gluons when they are confined into hadrons is just an example of this. A dog and a cup glued together do not compose a new object because this new object would not feature in any "basic" laws by the prescription of EFT.[5]

To highlight:

> Effective Composition. For disjoint material objects xs, they compose a new object y iff the interactions among xs are decoupled—through y—from all empirical predictions below a certain energy scale (or beyond a length scale).

In other words, a composite object is admitted into our ontology if it has sufficient or relatively basic explanatory, predictive, causal power with respect to a wide range of empirical phenomena—that is, being featured in the basic laws of an EFT. According to this criterion, we can indeed commit to the existence of atoms, molecules, cells, (perhaps) dogs and cats—and quarks and suns—without committing to any number of compositions among them. Note that this does not save our commonsense inventory completely, since it does not include everyday objects like tables and chairs.[6] But I think it's a good thing: that our commonsense is not a reliable guide to truth is

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[4] Cao and Schweber (1993) have expressed a similar point:

> The necessity, as required by the decoupling theorem and EFT, of an empirical input into the theoretical ontologies applicable at the lower energy scales - scales to which the ontologies at the higher energy scales have no direct relevance in scientific investigations - is fostering a particular representation of the physical world. In this picture the latter can be considered as layered into quasi-autonomous domains, each layer having its own ontology and associated "fundamental" laws. (p.72)

[5] Indeed any artificial objects would not count as objects by this criterion. The ontological questions about artificial objects may be separated from that of natural objects.

[6] One could—if one wants to—modify the principle to apply to only natural kinds while treating artifacts separately so that we do not have to necessarily rule out artifacts. As far as I am concerned, whatever principles we come up with for artifacts, it would have to be relative to the perspectives or ways of living of some conscious beings or communities.

a touchstone for any respectable discipline (although we should guard against going too far as dismissing commonsense altogether).

In summary, the EFT approach provides a concrete strategy for semirealim on how to read an ontology from an EFT, and how we can have a restricted realism about entities at intermediate (i.e., nonfundamental) levels. Given empirically successful scientific theories treated as EFTs, we should commit to the entities (which are usually unobservable!) that feature in the laws of these theories, and are invariant under the arbitrary choices of cut-off points and regularization schemes. This way, what makes EFTs "effective" (as opposed to "realistic" in the traditional vocabulary), namely that they deliberately ignore more fundamental degrees of freedom and include certain mathematical artefacts, is not a problem for permitting a realistic reading. On the contrary, these features provide a helpful implementation of semirealism and a robust doctrine of nonfundamental ontologies that offers a promising answer to ontological questions that are otherwise troubling.

3 Can We "Effectivize" Spacetime?

In the last section, I explained the general prescription of effective realism on how we can have realistic interpretations of EFTs. Does this prescription work for *the effective theory of quantum gravity* (EQG), an EFT of the spacetime metric within the experimentally accessible range?

3.1 The effective theory of quantum gravity (EQG) Let me explain why applying the technique of QFT to general relativity yields a pertubatively nonrenormalizable theory, and how the EFT approach leads to EQG. (See also Burgess 2003, Donoghue 1995, 2012, Shomer 2008 and Crowther 2013, 2016)

The Einstein-Hilbert action for general relativity, from which Einstein's field equations are derived, can be extended into the following full action including potentially relevant terms:

$$S_{EH} = \int d^4x\sqrt{g}(\Lambda + 2/\kappa^2 R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + ... + \mathcal{L}_{matter})$$

Here, g is the determinant of the metric tensor, Λ is the cosmological constant, R is the Ricci scalar curvature, $R_{\mu\nu}$ is the Riemann curvature tensor, and κ, c_1, c_2 are coeffients where $\kappa^2 = 32\pi G$. The cosmological constant is relatively tiny, and so are $R^2, R_{\mu\nu}R^{\mu\nu}, ...$ such that these terms are typically irrelevant for physics (see Donogue 2012). So the action is typically taken as $\int d^4x\sqrt{g}(2/\kappa^2)R$, ignoring the matter fields. This can be expanded into a pertubative series by taking the metric tensor $g_{\mu\nu}$ as the sum of a fixed background metric $\bar{g}_{\mu\nu}$ and a graviton field $h_{\mu\nu}$. $\bar{g}_{\mu\nu}$ is usually taken to be the Minkowski metric because for the scale of experimental setting where the scattering takes place, Minkowski spacetime is usually a good enough approximation for the background spacetime.[7] Let h be the canonically normalized graviton field $h = h_{\mu\nu}M_p$, where M_p is the Planck mass. Then, expanding the Einstein-Hilbert action in terms of h results in this:[8]

$$S_{EH} = \int d^4x(\partial h)^2 + 1/M_p(\partial h)^2 h + 1/M_p^2(\partial h)^2 h^2 + ...$$

As mentioned in Section 1, Dyson proposed a simple criterion called *power counting* to determine whether a QFT defined on spacetime of a certain dimension is renormalizable. According to this criterion, if a coupling constant entering the Feymann diagram has a negative dimension of mass, then the theory in question is non-renormalizable; in contrast, if all coupling constants have a positive dimension of

[7]When a strong gravitational field is in question, then we need to work with a curved background spacetime. EFTs in curved spacetime is much less worked out and may be subject to difficulties depending on the properties of the curvature involved. See Burgess 2003.

[8]This is a schematic expansion without specific details. In the next section, I will mention some details in this expansion relevant to the discussion in that section.

mass, then the divergence can be absorbed by finitely many coupling constants, which means the theory is renormalizable. In the case of gravity, the interaction terms have the coupling constant $1/M_p$ which has a negative dimension of mass. So the resulting theory is non-renormalizable.

But this does not undermine the theory as an EFT. When the energy level E that we use to probe the graviton field is far less than the Planck mass, then the non-renormalizable terms are suppressed by orders of (E/M_p) and do not contribute much to the empirical results at the low energy level. In this case, we can still extract low-energy empirical predictions from the theory and match them with experimental data. For example, the amplitude of two gravitons scattering has been calculated up to two-loop approximation (Abreu, S., et al 2020; for one loop approximation, see Dunbar and Norridge 1995). (It may be worth mentioning that the pertubative corrections to the leading terms are very small. So, as Donoghue 2012 argues, if small corrections are a positive feature of a QFT due to its resulting in more reliable calculations, then the quantum theory of gravity is the best QFT, not the worst.) As in other EFTs, what happens at higher energy levels does not affect the scattering amplitude at the low energy level. So the effective theory of gravity seems as good as a renormalizable one within its validity range. Since we have independent reasons to endorse the EFT approach to physics, appealing to EQG is not an ad hoc move. This is why, as mentioned at the beginning of the paper, the blanket claim of incompatibility between general relativity and quantum theory is considered misleading.

3.2 The Ontology of EQG The effective theory EQG just sketched is a partially successful quantization of gravity in the sense that it is a coherent mathematical machinery that yields empirical predictions within the experimentally accessible range. For this reason, many authors think that the crisis in physics pertaining to quantum gravity is overstated. On the other hand, despite the change of attitude towards

EFTs in physics, many people still hold an instrumentalist attitude towards EQG, namely that the theory is merely a tool for yielding certain empirical predictions. For example, Crowther (2013) wrote that this approach "sustains no illusions" and is "just a means of combining GR and QM to make predictions in the regimes where we are able to." (p.327)

It is certainly true that EQG, like other EFTs, is not a final theory. But an important question is left unaddressed: can we have a realistic reading of EQG in the spirit of effective realism?

The quantization of the metric field that leads to EQG involves dividing it into a fixed background metric and a graviton fluctuation field:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

As explained in Section 3, the background metric $\bar{g}_{\mu\nu}$ is typically taken to be the Minkowski metric as a good approximation for the actual background metric where experiments take place. It is not yet completely clear in the physics literature that I know what conditions the background metric needs to satisfy in order for the formalism of EQG to work, but for the sake of argument, I will grant that this formalism would work for any sufficiently well-behaved background metric, including some curved backgrounds. The resulting theory is about the graviton field propagating in a fixed background spacetime. What realistic theory can we extract from it? Can we specify the "basic" ontology and laws of EQG that describe an intermediate level of reality? Let's consider the following options.

a. Standard interpretation An obvious candidate for being in the basic ontology of EQG is the graviton field $h_{\mu\nu}$. The reason for interpreting it realistically is that it is technically analogous to the particle fields in QFTs that we typically consider real. Graviton is an excitation of the metric field in the same formal sense as (say) a photon being an excitation of an electromagnetic field in QED (quantum electrodynamics). In particular, the graviton field would pass the "robust" test in Williams' proposal, namely that the properties of the field do not depend on arbitrary choice of renormalization schemes and cut-off points. It can be similarly distinguished from mathematical artifacts analogous to the "mirror fermions" in QCD (quantum chronodynamics) in Williams' example. In QCD, formulating the EFT on a spacetime lattice (namely, choosing a certain length as a cut-off point) would result in mirror fermions, the properties of which depend on the particular spacing of the lattice. As Williams explains, this can be illustrated in terms of actions:

$$S_{lattice} = S_{continuum} + S_{mirror}$$

Here, the total action formulated in terms of the lattice can be split into the action about fermions that do not depend on lattice and those that do. The mirror fermions are captured in the latter, i.e., S_{mirror}, allowing us to interpret the former realistically. Similarly, gravitons can be distinguished from mirror gravitons and do not depend on particular choices of cut-off points.

One may note that in the case of matter theories, there is usually no mention of the fixed background field unlike in the case of EQG. This is because the background field is often the vacuum state of the field that one omits mentioning. Analogously, the Minkowski metric may be considered the vacuum state of the metric field, except that the metric field cannot vanish anywhere unlike a matter field. Also, QFTs are typically formulated in Minkowski spacetime rather than curved spacetime. If they are to be formulated in the latter, then we will need to posit a corresponding background matter field as in the case of EQG (see Burgess 2003).

Nevertheless, it seems to me problematic to consider the graviton field as part of the basic ontology for EQG. After all, it is a *fluctuation* of the background field.

If we take this claim literally, then the graviton field is ontologically dependent on the background field (since the fluctuation if a quantity is less fundamental than a quantity). But why should we take this claim literally? Because the graviton field does not play any independent explanatory role in physical theories. It is the metric field as a whole that determines the spacetime geometry and symmetries of dynamic laws.

Moreover, if we do admit the graviton field as a basic entity separately from the background metric, then it would lead to an unattractive "dualistic" reading of EQG: the background metric is naturally interpreted as representing fixed spacetime (fixed in the sense of not being subject to quantum effects, not in the sense of not entering dynamic equations in classical general relativity) whereas the graviton field represents a quantum field propagating in spacetime. Such a dualism is typically rejected in interpreting general relativity, in which case we either consider a manifold or the metric field (or both) as representing spacetime. (For example, Norton and Earman (1987) rejected the approach according to which spacetime is represented by the manifold equipped with Minkowski metric and the disturbance on the Minkowski metric represents a physical field.) For one thing, it would be less ontologically parsimonious by having two kinds of basic entities, namely the spacetime metric and the graviton field.[9] At the very least, if we adopt this dualistic interpretation of EQG, we cannot say that EQG is a quantum theory of *spacetime* since it is not spacetime or its metric property that is treated quantum-theoretically.

Now, what if we read not the graviton field $h_{\mu\nu}$ but the whole metric field $g_{\mu\nu}$ realistically? The problem with it is that $g_{\mu\nu}$ includes the background metric and is thus defined at arbitrarily small scales. But the ontology of an EFT according to

[9]One may argue that the graviton field $h_{\mu\nu}$ is still part of spacetime because it is still part of the metric field $g_{\mu\nu}$ that we use to calculate distances in the larger scale. But the situation here is like the scenario of Poincare's disk where there is a background spacetime with its intrinsic flat metric and a universal force that distorts rigid rods and light rays such that spacetime *appears* to be curved. Such a picture is more complicated than that of general relativity by its re-introduction of a universal force field eliminated by the latter.

our prescription is restricted to its validity range. For example, in the confinement example (Section 2), gluons and quarks are part of the basic ontology of QCD which governs the physics at short distances within the experimentally accessible range. But at a sufficiently large length scale ($\approx 10^{-15}m$) at which their interactions get so strong that the individual particles become intractable, it is more appropriate to appeal to hadrons composed of quarks and gluons as part of the ontology for a lower-energy theory. Similarly, in EQG, we can admit only those entities whose sizes and interactions are at the appropriate length scale given by the validity range of the theory, which is well above the Planck level.

b. Truncating small distances Facing this problem, one solution is to only extract the metric field above a certain length scale appropriate for EQG into our ontology. The idea is that we keep only the distance relations between spacetime points determined by the metric field within the validity range. More precisely, let spacetime be modeled by $\langle \mathcal{M}, D \rangle$, where $\mathcal{M}$ is a classical manifold and D assigns a length to every path c between manifold points in the usual way except that it has a minimal value given by the validity range of the theory: e.g., for spacelike paths, $D(c) = \int_c ds$ with $ds^2 = \sum g_{\mu\nu} dx_\mu dx_\nu$, iff $\int_c ds \geq minimal$. The distance between two points is given by the length of the extremal path as usual.

But this strategy alone does not get rid of arbitrarily fine-grained distances. For example, consider two points that do not have a distance relation under the above prescription, i.e., whose pre-interpretation distance is smaller than the minimal value. They can still have different distances to other points, and the difference could be a fragment of the minimal valid scale for EQG. If we do not assign distances to "overly close" points, then why should we distinguish between such minuscule distance differences or between those points to begin with?

But a second problem is that it is unclear we can actually deal away with classical background metric defined at arbitrarily small scales. For example, when we calculate scattering amplitudes in EQG, we need to calculate the energy of the graviton field, which involves the classical background metric. More specifically, the Lagrangian for general relativity expanded in terms of the energy of the graviton field includes the following terms (Donoghue 1995, 10):[10]

$$\mathcal{L}_{grav} = \sqrt{\bar{g}}(... + \frac{1}{2}D_\alpha h_{\mu\nu}D^\alpha h^{\mu\nu} - \frac{1}{2}D_\alpha h D^\alpha h + ...)$$

Here we can already see that the Lagrangian depends on the classical background metric in a number of ways. First, D is a covariant derivative with respect to the background metric. Secondly, $D_\alpha h_{\mu\nu}D^\alpha h^{\mu\nu}$ is the inner product of $D_\alpha h_{\mu\nu}$ with itself, which depends on the background metric (the metric is used to raise the index of $D_\alpha h_{\mu\nu}$ before it can be contracted with the original). Similarly, $D_\alpha h D^\alpha h$ and even h alone (which is the contraction of the graviton field with itself) depend on the background metric. Of course, there is also the explicit mention of the classical volume form $\sqrt{\bar{g}}$. Thus, if we truncate the classical metric field in the suggested way, then we won't be able to carry out these calculations needed in EQG. Note that I am not arguing that it is impossible to revise the formalism so that the calculation only relies on the truncated field—which I do not know—but at the very least the point is that truncating the classical field has undesirable ramifications for the formalism of EQG.

Furthermore, the framework of renormalization group method (RG) also involves a classical background metric (though not necessarily the same one as in EQG). In Section 1, I have talked about how physical coupling constants depend on the scales, but the scales are determined by the background metric. Insofar as the appeal of EQG (and the idea of tower of EFTs) is dependent on this framework, EQG is indirectly

[10]This is a more detailed expansion than the schematic expansion of $\mathcal{S}_{EH}$ mentioned in the previous section.

dependent on the background metric of RG. Thus, even if we can truncate $g_{\mu\nu}$ in EQG in the suggested way, we haven't eliminated altogether the theory's dependence on a classical metric defined at arbitrarily small distances. While for a semi-realistic reading of EQG advocated by the refined scientific realism, we do not need to register all the things it quantifies over, there is something particularly unsatisfying in that when we extract a theory of metric from EQG, we are unable to interpret the classical background metric that does robust work in the theory.

It may be possible to purge EQG—and in general the EFT framework—of all references to classical background metrics by developing a new framework of EFTs on lattice spacetime points. Instead of truncating small distances, we start with spacetime lattice with a minimal spacing, and define all quantum fields including the metric field on it (for lattice QFTs, see for example Montvay I. and G. Münster 1997). But this attempt is better described as developing an alternative framework rather than an interpretation of EQG. Indeed this is part of the work of developing a full theory of quantum gravity (for example, loop quantum gravity is in its vicinity; see Rovelli and Viditto 2015). So it seems that we are running out of options for extracting a realistic ontology of spacetime metrics from EQG.

4 The Challenge to Effective Realism

In the last section, I discussed some problems in applying effective realism to EQG. In this section, I would like to examine whether those problems have more general implications for the EFT approach.

Let's reflect on the relevant similarities and dissimilarities between EQG and other EFTs in particle physics, especially QFTs. As EFTs, all these theories are very much on a par. To start with, other EFTs also have the analogous problem of classical background *matter* field. More detailedly, the quantization of a classical matter field in QFTs also involves dividing it into a fixed background field and its fluctuation:

$$\phi = \bar{\phi} + \psi$$

Like in EQG, the background field $\bar{\phi}$ is usually taken to be the classical vacuum state of the field. This can be omitted and thereby does not lead to an interpretative issue (the vacuum state of a matter field vanishes everywhere while that of a metric field is the Minkowski metric). However, those background fields sometimes are not vacuum or zero states (QFTs with non-zero background fields are not commonly considered due to calculation complexity, but entirely possible). In this case, we need to interpret this fixed background matter field. However, this challenge can be met more easily because the references to classical background matter fields in arbitrarily small regions can be truncated using the strategy in 3.2 (b)—unlike classical metrics, classical matter fields are not part of the framework for EFTs.

What's more troublesome, like EQG, other EFTs also involve a classical background *metric* field, which is likewise involved in calculating the energy of matter fields. For example, we may similarly interpret QFTs as describing certain particles propagating in classical Minkowski spacetime (or some suitably curved spacetime), which is defined to arbitrary accuracy. How should we interpret this reference? First, it might be worth noting that the problem here is not exactly analogous with the case of EQG. To remind: interpreting EQG as gravitons propagating in classical spacetime commits an unpleasant dualism between the graviton field and spacetime metric, which we standardly accept to be one and the same entity. In other EFTs, there is no such unwanted dualism. However, we still face a dilemma over whether we should take the background spacetime realistically. On the one hand, classical spacetime does not satisfy the condition for ontological commitment that it fall under the validity range of the EFTs, since arbitrarily small regions are parts of classical spacetime. On the other hand, it also does not satisfy the criterion for a non-entity because it does not vary under different choices of cutoff points or regularization schemes. So it seems that classical spacetime is neither a physical entity not a mathematical artefact by the standards that we have discussed. So how should we think of it?

One move is to consider classical spacetime as part of the heuristic device to get the empirical predictions rather than carrying genuine ontological weight in EFTs. The idea is that being invariant under different choices of renormalization schemes is not a sufficient condition for ontological endorsement, and therefore we are not obligated to endorse spacetime under effective realism. This may seem reasonable at first. As quantum theories of matter, their failure to include a realistic ontology of spacetime is no failure as realistic theories of matter—as long as we do not unreasonably expect a given scientific theory to be an exhaustive description of reality. Nevertheless, this strategy is unsatisfactory. Putting in the words of Ruetsche (2011), an interpretation of a scientific theory should allow it to "discharge all its scientific duties." Clearly, one of the duties that QFTs have is to explain the observable phenomena in terms of the particle fields and their dynamics that are probable at currently experimentally accessible scales. The background spacetime plays an important role in this explanation. If we omit spacetime from the explanation "a ray of electrons of this-and-that properties propagating in Minkowski spacetime in such-and-such a way" for certain electromagnetic phenomenon, the explanation would not be complete.

I would like to briefly distinguish this problem with a very different one that Fraser (2009) raises and that Williams (2019) rejects. Fraser argues that because EFTs impose some cut-off point, a realistic interpretation of an EFT requires us to posit spacetime as composed of lattice point with lattice spacing corresponding to the cut-off point. But since we should not believe that spacetime is composed of lattice points, we should refrain from interpreting EFTs realistically. Here I disagree with Fraser on several different fronts. For one thing, I do not think we should rule out a lattice theory of spacetime. But more importantly, it is quite a jump—an unwarranted one for that sake—to think that a lattice theory of spacetime is implied by realism about EFTs. The rationale behind it has to do with the assumption that a theory needs to describe reality exhaustively. Since an EFT does not say anything below a certain length scale, this means that there is a minimal length. Williams rightfully rejects this assumption in favor of effective realism, according to which a theory only needs to describe reality at a certain level. Besides, even if there is a minimal length, it does not immediately follow that spacetime is composed of lattice points, as discussed in 3.2 (b). In comparison, the problem I raise here is about the interpretative problem of background spacetime, not of the cut-off point.

To take stock, we face a dilemma in interpreting the reference to classical background spacetime in any given EFT: it should not be included in the ontology because it is defined beyond the validity range; but it should be included in the ontology because it plays a necessary explanatory role. For matter fields, the references to their high-energy (or short-length) parts are dispensable—which is part and parcel of the EFT approach. But for spacetime, the references to smaller regions are indispensable, at least in the current framework of EFTs. The EFT approach is otherwise very attractive and promising in answering important ontological questions, which is why I think we should worry about this interpretative dilemma.

5 Conclusion

Do we have a quantum theory of spacetime metrics at the experimentally accessible small scales where quantum effects are prominent? I have argued for "no," despite the fact that the effective theory of quantum gravity (EQG) is celebrated as a satisfactory physical theory at these scales. A natural interpretation of EQG says that the graviton field, which is subject to quantum fluctuations, propagates in classical background Minkowski spacetime—which is not a quantum theory of spacetime metrics. This also raises a general concern for the EFT approach to realism, which is otherwise attractive and provides a useful framework for answering difficult ontological questions. The classical background spacetime involved in EFTs is neither a clear non-entity nor belong to the layered ontology licensed by those EFTs.

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