The Cosmological Constant Problem Is Not Meant to Be Solved

Mike D. Schneider

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Abstract

The title of this paper is confused, of course; what is a (scientific) problem if not something intended to be solved? But the "Cosmological Constant Problem" (CCP) is not strictly a problem for our current theories, and so the proposed "solutions" to it cannot be solutions as such. Nonetheless, the CCP is consistently entertained as if it were a problem with a landscape of possible solutions. Given this state of affairs, I discuss how one ought to make sense of the role of the CCP in contemporary theoretical physics and generalize some lessons from it.

1 Introduction

The "Cosmological Constant Problem" (CCP) has occupied the attention of theoretical physicists and cosmologists for several decades, often glamorized in popular science as the "vacuum catastrophe" or "the worst prediction in the history of physics". According to INSPIRE, the High Energy Physics online information system, Weinberg's 1989 paper that first formally outlined the subject has been cited nearly 3300 times (only 71 citations short of INSPIRE's 2015 list of the top 40 most highly cited papers of all time). Efforts to confront the CCP have proliferated, resulting in a vast landscape of theoretical projects that purport to have potentially solved the problem (or that purport to offer a solution just around the corner).

Despite all of this activity, what is actually meant by the CCP is ambiguous. Roughly, the CCP concerns a tension between the value assigned to the cosmological constant ("Λ") in the standard model of cosmology and the values of certain quantities predicted in quantum field theory (QFT) that are thought to influence Λ. But the status of the CCP as a problem is made complicated by two observations. First, it is unclear by what merits the quantities from QFT are relevant to the standard model of cosmology built on classical (i.e. not quantum) physics. Second, even if such quantities are relevant, the current standard model of cosmology can accommodate them: one needs only to fine-tune a new parameter available in the standard model, usually denoted Λ_0, to counteract their presumed effects on Λ. Consequently, not only is there no explicit conflict concerning Λ in the current standard model of cosmology, but moreover the model is robust in the face of the empirical predictions from QFT that are usually offered as credible threats. As such, the CCP cannot be understood as a problem for the current standard model of cosmology. (Section 2 will formally develop this claim.)

The situation is quite different when one leaves behind present, well-evidenced physical theory and speculates about what a quantum theory of gravity will entail for the future of cosmology. Under certain ordinary assumptions about the relationship between cosmology and any local theory of matter, the CCP could become an actual conflict between theory and observation in the next generation of physical theory. But competing semiclassical intuitions about what our current theories imply about future theories of quantum gravity make it unclear how to assess that conflict. Granting different assumptions about what quantum gravity will ultimately entail gives rise to different characterizations of the CCP, and as a consequence the proposed "solutions" offered to the CCP are segregated into several pairwise incompatible categories that differ in their assumptions about the nature of the problem. This makes it difficult to compare the individual virtues of the proposed solutions across categories, but it also suggests a new way of understanding the role of the CCP in shaping future physical theory.

The immediate goal of the present paper is to explain how it is that such incompatible theoretical proposals can all simultaneously count as plausible solutions to the CCP. In other words, by virtue of what do the proposals in each of the categories count as approaches to solving the CCP? Generalizing from the case of the CCP, section 4 will argue that some problems in theoretical physics are not meant to be solved; instead, their primary function is to sketch out new avenues of theoretical research. Under this view, what constitutes a possible "solution" to such a problem is any possible schematic for the next generation of physical theory that is well-suited to reproduce the virtues of the present theory and improve upon it in at least one precise regard: by providing an explanation for how it is that the problem (now articulable) is already taken care of in the new theory. In this way, the activity of solving such a problem amounts to scientific progress of an exclusively theoretical kind, which is nonetheless grounded in empirical considerations that follow as consequences of our best contemporary physical theories.

2 The "Cosmological Constant Problem" Is Not a Problem (For Current Theory)

This section ought to begin with a statement of the CCP, but there is no statement of it that is both concise and wholly satisfying. This is primarily because on multiple occasions, the content of the CCP has shifted, giving rise to distinctions in the literature between terms such as the "old" CCP, the "new" CCP, and the "cosmic coincidence problem". Moreover, the relationships between each of these variants of the CCP are dubious, including the extent to which the later ones replace or augment the earlier ones (e.g. when is a solution to one necessarily a solution to the others?). There is indeed a simple characterization of the CCP that encapsulates each of its variants, but some background will be needed in order to state it.

Let a cosmological model be a triple (M, g_{ab}, T_{ab}), where M is a hausdorff, paracompact manifold that is smooth and connected, g_{ab} is a smooth, non-degenerate, pseudo-Riemannian metric on M, and T_{ab} is the stress-energy tensor of a collection of matter fields over M. The induced pair (M, g_{ab}) defines the general relativistic spacetime underlying the cosmological model (c.f. Malament (2012)).[1] Via the dictates of general relativity (GR), the geometry of spacetime wholly determines the distribution of matter throughout spacetime (as represented by T_{ab}) via the Einstein Field Equations (EFE), which in geometrized units ($c = G = 1$) can be represented as:

$$R_{ab} - \frac{1}{2}Rg_{ab} = 8\pi T_{ab} \tag{1}$$

where the left-hand side describes the spacetime geometry (i.e. the curvature of spacetime) via the Ricci tensor R_{ab} and the Ricci curvature R on the metric, and the right-hand side defines the distribution of matter across the spacetime. The conservation of energy-momentum is satisfied by the covariant divergence of T_{ab} vanishing everywhere (i.e. $\nabla^b T_{ab} = 0$). This conservation law is, in fact, guaranteed in standard GR as a consequence of the second Bianchi identity, a purely geometrical fact which requires the covariant divergence of the left-hand side of the EFE to vanish.

[1] Where it is relevant, the standard model of cosmology is defined over a four-dimensional Lorentzian manifold equipped with a perturbed Friedman-Lemaitre-Robertson-Walker (FLRW) metric.

Moreover, it is not difficult to show that the left-hand side of the EFE can be modified to include an additional "cosmological" term Λg_{ab} without losing the conservation law over T_{ab}, as long as Λ is a constant across all solutions:

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = 8\pi T_{ab}$$

where the cosmological term is naively interpretable as the inherent elasticity of the spacetime (repulsive when, by sign convention, Λ is positive). Historically, this was the form in which Einstein first presented it. Just as easily though, the term may instead be absorbed into the stress-energy tensor that governs the right-hand side of the EFE as a contribution $T_{ab}^{(\Lambda)} = -\frac{\Lambda}{8\pi}g_{ab}$:

$$R_{ab} - \frac{1}{2}Rg_{ab} = 8\pi(T_{ab} - \frac{\Lambda}{8\pi}g_{ab}) = 8\pi T_{ab}^{(total)}$$

The two modifications of the EFE are equivalent, but in the latter case we can understand the cosmological term as the stress-energy tensor of a perfect fluid defined everywhere in spacetime, which just happens to be massless (i.e. the cosmological term is an isotropic pure pressure term).[2] Even when the rest of T_{ab} goes to zero (i.e. in vacuum regions), there is a constant energy density defined over the region. By sign convention, when Λ is positive, that region has associated with it a negative pressure. In this way, the "repulsive force of spacetime" or "spacetime's elasticity" is interpreted locally as the negative pressure term that arises from the vacuum being endowed with a non-zero energy density. Since the 1990s, the standard model of cosmology has included a positive Λ to recover empirical observations about the accelerating expansion of the universe. That the standard model of cosmology requires a positive Λ is normally taken as evidence that there is such a thing as a (classically available and gravitating) energy of the vacuum (c.f. Zel'dovich (1968), Frieman et al. (2008)). This sets the stage for theoretical considerations about what physical mechanisms give rise to that energy.

[2]Curiel (2016) offers an argument based on a novel uniqueness proof for the EFE that the cosmological constant ought only to be understood in the latter context, as a component of the stress-energy tensor with physical dimensions of $(\text{mass})^2$ when G is assigned its ordinary dimensions (because, following Curiel's proof, the addition of constant multiples of the metric, such as Λg_{ab}, to the left-hand side of the equation is not permitted). Although relevant to the subject matter of the present paper, such an argument should not affect the particular claims about methodology and theory development that I will make. For this reason, I leave off a study of its potential implications on desired solutions to the CCP for another time.

At this point, it is crucial to note that nothing in the theory of general relativity nor in the standard model of cosmology prohibits hypotheses concerning a new classical term Λ_0 which behaves like a contribution to Λ in the form $T_{ab}^{(0)} = -\frac{\Lambda_0}{8\pi} g_{ab}$. This term could be a new constant of nature (or less presumptuously, a new constant in the theory), or else it could represent a new kind of (classical) matter field. In either case, if Λ is considered the total value of all pure-pressure contributions and Λ_0 is just some particular new contribution, then the only constraint we can place on the quantity Λ_0 is whatever empirical access we have to the effective value taken by Λ, minus whatever values are assigned to any other contributions to Λ that are thought to emerge from other domains of physical theory. Consequently, the justification that Λ_0 equals any particular value (even $\Lambda_0 = 0$) must take the following form:

1. By empirical considerations via the standard model of cosmology coupled with astrophysical observations, the effective cosmological constant must take on a value of Λ.

2. Results from the rest of our corpus of physical theory suggest that there are certain quantities (call them γ, δ, $\zeta, \ldots, \theta$) that behave as ordinary, classical contributions to the effective cosmological constant (i.e. they gravitate in the same way as other vacuum energy sources with equivalent values would gravitate). Their total contribution can be represented as $-T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}$ (where a sign convention is set merely for convenience below).

3. Further results from the rest of our corpus of physical theory suggest that there are no other quantities beyond those listed above that also contribute to the effective value of Λ.

4. Therefore, the value given to Λ_0 is determined by the following expression:

   $$T_{ab}^{(0)} = -\frac{\Lambda_0}{8\pi} g_{ab} = T_{ab}^{(\Lambda)} - (-T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}) = -\frac{\Lambda}{8\pi} g_{ab} + T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}$$

   from which it follows that the new term ought to be assigned the value Λ_0 such that

   $$\frac{\Lambda - \Lambda_0}{8\pi} g_{ab} = T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)} \tag{2}$$

Several claims about the standard model of cosmology immediately follow from Equation 2. If the effective term Λ is entirely accounted for by the contributions γ, δ, $\zeta, \ldots, \theta$, then Λ_0 is simply 0. If the effective term is not entirely described by those contributions, then Λ_0 is non-zero and also contributes. If there are no other contributions γ, δ, $\zeta, \ldots, \theta$ to the effective term, the right-hand side of the equation goes to zero and it is easy to see that Λ_0 simply equals Λ. Finally, per the stipulation above that the effective term must be constant as it appears in the EFE, if one wants Λ_0 to be a dynamic quantity (under some preferred foliation), it is easy to see that other contributions would have to directly cancel with it to maintain Λ. (If empirical observations turn out to warrant a dynamic Λ, then this takes us beyond that which is allowed by the standard model of cosmology formulated in GR; more on this possibility will be said in section 3.)

We are almost to a characterization of the CCP (and the renunciation of its classification as a problem for current theory follows immediately from its characterization, by the lights of what we have just said). But before then, we must briefly address the notion that Λ might receive contributions from other domains of physical theory (i.e. γ, δ, $\zeta, \ldots, \theta$ above). There are restrictions on what could count as such a contribution: they cannot be ordinary matter sources (though they still must in total obey the conservation law that insists that the covariant divergence vanish), but rather must resemble massless perfect fluids whose rest frames belong to the equivalence class of the comoving frames of the vacuum (in the standard model of cosmology, these are the comoving frames of matter in an FLRW metric). All of the current candidates for these contributions are the expected zero-point energy densities that emerge from the fields described by the standard model of particle physics (i.e. in the framework of QFT on flat spacetime). I will say a little bit about these zero-point expectation values, but this is not the place for an extended conversation about them (for slightly more, see section 3; otherwise, for more careful treatments of zero-point energies, consider Rugh et al. (1999); Rugh and Zinkernagel (2002); Martin (2012) and Kragh (2012)).

Speculations about vacuum energy conditions in the context of quantum theory date nearly as far back as they did in (general relativistic) cosmology.[3] In the 1920s, work that would eventually culminate in quantum electrodynamics (the first successful QFT) made coherent for the first time the notion that quantum fields feature non-zero ground state energy levels, called the "zero-point energies" of their respective fields.[4] Today, arguably

[3]In fact, as early as 1916 (a year before Einstein's introduction of Λ), Nernst proposed that considerations of black body radiation and Planck's law lead one to consider the vacuum as a energetic medium filled with radiation (Rugh and Zinkernagel, 2002).

[4]There are technical difficulties that would emerge if we were to make this point more

every quantum field implicated in the standard model of particle physics is thought to have associated with it such a zero-point energy.

Sakharov (1967), in correspondence with Zel'dovich (1968) was the first to show how these zero-point energies resemble contributions to Λ. Nonetheless, it is important to note that these quantities are quantum mechanical expectation values, which is to say that they are not quantities of energy in the classical sense of the term. Any treatment of these expectation values as classical quantities applicable to a general relativistic model of cosmology depends on semiclassical approximations that render quantum mechanical quantities as classically gravitating substances. But lacking a mature theory of quantum gravity which can be shown to reduce to GR in the appropriate limiting cases, it is unclear by which merits the predicted zero-point energy values from QFT on flat spacetime can be assumed to gravitate like otherwise classical energy contributions in curved spacetime. The simplest presentation of this point that I have found is given by Saunders (2002), who expresses it in terms of the standard measurement problem that has plagued quantum mechanics since its conception:

> "In point of fact, on every other of the major schools of thought on the interpretation of quantum mechanics - the Copenhagen interpretation, the pilot-wave theory, and the Everett interpretation - there is no reason to suppose that the observed properties of the vacuum, when correlations are set up between fields in vacuo and macroscopic systems, are present in the *absence* of such correlations" (p. 24).

The semiclassical assumption that seems to be doing work is that the zero-point energies couple to the (quantum field theoretic conception of the) gravitational field so that they can be expected to gravitate at all, whereupon the (classical conception of the) gravitational field is considered a suitable stand-in for the sort of macroscopic system that is necessary to repeatedly "measure" this particular quantum system and render it as a classical quantity of energy. Moreover, it must be taken as a further assumption that the zero-point energies as they are currently computed yield expectation values of that classical quantity, rather than eigenvalues of it.

Nonetheless, physicists regularly equivocate between the vacuum energy implied by Λ in the standard model of cosmology and the sum of all the

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explicit, but at its core are the same principles that arise in non-relativistic quantum mechanics to render the harmonic oscillator incapable of falling to a state of complete rest.

zero-point energies that arise in QFT. Different heuristics to compute the total value of the collection of zero-point energies suggest that the quantity is between 60 orders of magnitude (Frieman et al., 2008) and 120 orders of magnitude (Weinberg, 1989) larger than Λ. If this is interpreted (lazily) as a direct prediction of Λ, it truly is the biggest disparity between prediction and observation in the history of physics. When the collection of zero-point energies is instead considered as the "matter contribution" to Λ, then (by the outline sketched above) Λ_0 assumes the difference between the empirically determined Λ and the total computed value of its matter contribution.

Finally, we are in the position to characterize the three common variations of the CCP in as few sentences. The "old" CCP suggests that there is a problem in cosmology that Λ in the standard model is effectively 0, despite the seemingly overwhelming presence of matter contributions that arise as consequences of the standard model of particle physics. The "new" CCP suggests that the problem is that Λ is not precisely 0, while also being many orders of magnitude smaller than the total computed value of the (quantum) matter contributions. The "cosmic coincidence problem" suggest that the worry is augmented by the fact that the particular value of the not-quite-zero Λ resembles the mass-density of the universe in the present cosmic epoch.

But we have already seen that none of these variations of the CCP constitute strict problems for the standard model of cosmology because the standard model permits the inclusion of a new term Λ_0, whose assumed value provides, by construction, the difference between the effective term Λ and whatever other vacuum contributions are identified. Moreover, according to current theory, the zero-point energies that emerge in the context of QFT are not classical, and so they are not the sorts of quantities that can readily act as contributions to Λ. But then if the CCP is to be understood as a worry in the present theory, it must really be about how the standard model of cosmology permits the new term Λ_0 without any other constraints, such that the question of whether zero-point energies count as contributions to Λ does not affect the status of the overall model. Indeed, a typical attitude is that identifying Λ_0 as the difference between the measured value of Λ and whatever are the matter contributions to it amounts to fine-tuning a term to save the theory. Moreover, the fine-tuned term perfectly resembles physical contributions to Λ that are constrained by local physics, even though the term itself is not. That the fine-tuning of Λ_0 needs to be extraordinarily precise only amplifies the dissatisfaction.

But what is actually meant by fine-tuning in this context?[5] On a standard reading, the fine-tuning of a parameter is taken to mean that its value must be tweaked in a certain *ad hoc* way, so as to save the model from some ready conflict (rather than discarding the model for a future, more well-behaved alternative). The concern with fine-tuning must be that the assigned value entails additional physical consequences in the model, and that such *ad hoc* procedures will subsequently lead us astray (e.g. to future incorrect predictions or misguided applications of the theory, understandings of the universe, etc.).[6]

To this comment, the point has already been made that Λ_0 only appears once in the standard model, which is to say that it can only ever be determined by the procedure summarized in Equation 2. Consequently, there is no particular assignment of a value to Λ_0 that appears any more *ad hoc* than any other assignment, even in the case where one concludes that Λ_0 ought to be assigned the value of 0. But it seems highly unlikely that anyone would be alarmed by the discovery that Λ_0 ought to be "fine-tuned" to 0 (indeed, depending on the historical circumstance, we might never have noticed that we did so). Such an assignment would not seem *ad hoc*. But in this case, it follows that no other assignment of a value to Λ_0 can be considered *ad hoc* either. Another way of expressing this point is to recall that Equation 2 is a function of just the effective term Λ and the sum of the effects of all known vacuum contributions to Λ. So the claim that Λ_0 must be set to the value needed to reconcile the effective term Λ with all known vacuum contributions is tautologous: Λ_0 is a bound variable and this is the only way to set it. Moreover, there is no threat down the road, because this is the only role the term plays in the theory.

Alternatively, the concern of fine-tuning could also be entertained in terms of the robustness of the physical consequences that follow from assigning Λ_0 its precise value. If the physical predictions do not smoothly

[5] Or in the titular words of Bianchi and Rovelli (2010), "Why all these prejudices against a constant?".

[6] In laboratory physics, fine-tuning is not usually a concern: specifying that a term in a given theory needs a particular value to produce results in one experiment is precisely what is needed to falsify the theory in later independent experiments (because the theory yields incorrect predictions in the context of those later experiments, by virtue of the value assigned to that term). In cosmology though, as well as in other contexts where coming up with novel tests is difficult, there are often no other easily accessible and independent tests to perform whereby the theory could be falsified by virtue of the value assigned to that term. On the other hand, the point could be made that what one cosmologist views as an act of fine-tuning, another cosmologist could view as the achievement of a new precision measurement.

transform as the value is approached from upper or lower limits, then there is a concern that the value is, in some sense, uniquely determined, even while supposedly being unconstrained by any local physics. Fortunately, in the context of Equation 2 it is clear how there is at least one sense in which the physical consequences of Λ_0 deform smoothly as Λ_0 departs from its assigned value.[7]

Perhaps one might like to claim on the grounds of parsimony, naturalness, or some other metaphysical or aesthetic consideration that a parameter like Λ_0, which resembles the contributions of various physical sources but might itself not represent one, should be expected to be 0, in which case any deviation from that value to another particular value constitutes fine-tuning in the worrying sense of the term.[8] But such a position seems mysterious. The presumed privileging of one value over another value that a parameter in a physical model ought to take must be grounded in some deeper philosophy concerning one's particular conception of physical theory as it relates to the world, but the specifics of such a deeper philosophy are opaque and it is by no means clear that everyone would agree on the specifics that would justify the privileging of 0 over other values.[9]

Nonetheless, in framing the subject in these more foundational terms, one begins to get the sense that the CCP is not strictly an issue of fine-tuning a parameter that lacks physical constraints, but is more so an issue of how the physical parts of a theory connect up to the parts of the theory that carry no physical interpretation. Λ is physical (the total gravitating energy of the vacuum), all of the quantum matter contributions to Λ are thought to be physical in their origins (putting aside, for the moment, our comments above about the questionable emergence of classical quantities from the quantum zero-point energies), but the remaining contribution to Λ (Λ_0) may not be. (Unless, of course, one simply postulates the presence of a constant, classical field on the basis of Λ_0, a proposal that will be considered in section 3.)

[7] This situation is made more difficult in the context of semiclassical gravity, but such is not an issue for the present cosmological model. At best, it is an issue for what theorists believe will be the case in a future, as-of-yet undiscovered theory. This point will be considered in the following section.

[8] Or alternatively, one might like to claim that merely by placing Λ on the stress-energy side of the EFE, one is committed to assigning it exclusively physical sources. But we are free to separate Λ_0 from the other contributions to Λ and put it on the curvature side, if this is the only complaint (results from Curiel (2016) notwithstanding).

[9] Sometimes, for instance, being able to tune certain values to 0 enhances the symmetry of the theory, which is subsequently held as a virtue of the theory. Since this is not true of Λ anyway, now is not the time for a discussion of this view.

But identifying the CCP as a problem of how different components of the present theory interlink cannot be the whole story, because there is a way to circumvent the issue when it is understood exclusively in these terms, using resources only from within the context of GR and the standard model of cosmology. This is done via unimodular formulations of GR, which render Λ_0 as a mere constant of integration in the theory, rather than as a term meant to counteract possible vacuum energies.[10] That this ready option is not, in fact, taken to be *the solution* to the CCP by the vast majority of cosmologists suggests that there is something more interesting afoot. To be more precise, recall from the Introduction that the different solutions to the CCP can be categorized according to their mutually incompatible assumptions about the nature of the problem. Unimodular gravity is a prime example of the first category:

1 The relationship must be severed between the effective term Λ that arises in the standard model of cosmology and the ordinary gravitational effects of any approximately classical vacuum energies.

While unimodular gravity presents an interesting approach to some, many cosmologists do not endorse it. A core claim of the present paper is that one underlying reason for the lack of interest in unimodular gravity as a solution to the CCP is that for many cosmologists, it is not the CCP's status as a perceived problem for current theory that has the discipline so preoccupied with searching for supposed solutions to it. Rather, those "solutions" are in the service of something else entirely, which will begin to be teased out in the following section.

3 Why The "Cosmological Constant Problem" Still Matters

It might be tempting, in light of everything that has been said so far, to dismiss the CCP outright, and declare the physics community's reactions to it philosophically lazy, misguided, or even agenda-driven. This is the view implied by Earman (2001), who writes:

> "Steven Weinberg (1989), who believes that physics thrives on crises, has been instrumental in promoting this problem to the status of a crisis for contemporary physics. I want to explain

[10] See Appendix A for a brief presentation of how unimodular formulations accomplish this task.

why this crisis needs to be viewed with some skepticism." (p. 207)

I do not dispute Earman's claims in these remarks (the beginning of Weinberg's (1989) paper, by the way, bluntly states that "Physics thrives on crisis" and goes on to suggest that it is the "want for other crises to worry about" that leads people to consider the CCP), but I confess that Earman's general attitude here[11] strikes me as backward. The philosophical point to be made is not that the physics community might be in error about a concern that is central to their field and that the CCP is actually, in point of fact, a pseudoproblem (i.e. that "this 'crisis' needs to be viewed with some skepticism"). Rather, the point to be made is that the physics community's persistent worry about the CCP *as a problem* (alternatively, as a "crisis") suggests that there might be something else going on. There is something interesting, that is, about the fact that the depiction of the CCP as a problem for contemporary cosmology has not diminished over the past several decades in light of all of the potential "solutions" that have been offered for it.

There is an explanation for this state of affairs. As rehearsed above, the standard model of cosmology is formulated in the framework of GR. The model is therefore classical (i.e. not quantum), which means its domain of applicability only extends over classical quantities. Zero-point energies, meanwhile, are explicitly quantum phenomena without well-understood analogs in the classical limit. As such, their quantities are outside of the classical domain, and so their computed values are technically irrelevant to the standard model of cosmology. In other words, since the zero-point energies that arise in QFT are quantum and Λ is only understood classically, our current best theories of physics are silent as to how they interact.

However, if the zero-point energies that arise in QFT are understood as concrete predictions of vacuum energy sources that will arise in some future physical theory which unifies GR and QFT (i.e. the theory of quantum gravity), and if, moreover, vacuum energies in that future theory continue to contribute to some effective term that reduces to classical Λ, then that future theory (but *not* any present theory) is thought to have to reckon with the apparent disparity between the quantum contributions in current QFT and the effective term Λ in the standard model of cosmology.

Subsequently, solving the CCP consists of endorsing a possible frame-

[11] In a more recent work, Earman (2016, p. 11) expresses a similar sentiment: "Before being swept up in this stampede towards crisis and desperate searches for solutions, it is well to try for a more sober perspective."

work for future physical theory and subsequently demonstrating that within such a framework, the CCP is an ordinary problem with an ordinary solution already built into the theory. Since each of these solutions depends on conjectures about what future theory will entail, the CCP has remained (and will continue to remain) an open problem until some of these conjectures gain sufficient empirical grounding to warrant adoption into the corpus of established physical theory. But this entire conversation presupposes some resolution to a fascinating methodological conundrum: how do we talk about what future, as-of-yet undiscovered theories *ought to do*, and on what grounds do we make such claims?

Lacking a mature theory of quantum gravity that formally interprets both the gravitational properties of energy sources and the zero-point energies of the vacuum, the standard move is to introduce a semiclassical theory of gravity that is meant, in principle, to approximate such an unknown future theory. Via semiclassical gravity, one may formulate semiclassical interpolations of contemporary, well-evidenced physical models and draw conclusions of a similar form as one does from the contemporary models.

The most basic account of semiclassical gravity assumes that matter fields are quantum mechanical, while the gravitational field is classical. That is, semiclassical gravity consists of modifying the EFE (i.e. either Equation 1, or after the inclusion of Λ) to read:

$$R_{ab} - \frac{1}{2}Rg_{ab} = 8\pi < \hat{T}_{ab}^{(total)} >_{\psi}$$

where the left-hand side of the equation describing spacetime curvature remains untouched, while the the stress-energy tensor representing the classical matter fields (and, perhaps, Λ) has been replaced with a quantum mechanical operator to the same effect ($<>_{\psi}$ signals the expectation value of that operator in state ψ). In the context of semiclassical gravity, a cosmological model can be suitably transformed

$$(M, g_{ab}, T_{ab}) \rightarrow (M, g_{ab}, < \hat{T}_{ab} >_{\psi})$$

In this way, the right-hand side of the transformation is the semiclassical interpolation of the left-hand side. Since the approximate nature of semiclassical gravity is ambiguous, a well-evidenced model of cosmology (e.g. the standard model of cosmology) does not necessarily transform into a well-evidenced interpolation of the model. Nonetheless, in a very practical sense, this is what cosmologists have to work with in their attempts to develop an approximate understanding of what a future quantum theory of cosmology might look like.

The claims made on the basis of semiclassical interpolations of classical gravitational models are therefore not consequences of current physical theory. Rather, they are claims about what we might infer from contemporary physics about approximations of future physics. This answers the first part of the conundrum voiced above (how do we talk about what the future theories ought to do: by semiclassical interpolations of current theories), but it does not answer the second part of the conundrum (what are the grounds for these claims about such future theories). Notice that justifications for the methods used to interpolate future theories from current theories can only ever consist of claims which derive from the current theories, which (by setup) are silent precisely in those contexts where the semiclassical theory is needed. Thus, the assumptions that go into these methods are open to expert disagreement: there are disputes about what semiclassical gravity entails for the future of cosmology, which means that there can be no obvious answer to the second part of the conundrum.

In fact, competing assumptions about the semiclassical interpolation of the standard model of cosmology give rise to the second and third categories of solutions to the CCP:

2 The relationship between Λ in standard cosmology and the vacuum energies from QFT will be intact in the next generation of theory (and moreover the physical sources of Λ must be wholly accounted for within the framework of QFT), so the relevant predictions from QFT must be undermined by new theoretical considerations about particle theory.

3 The relationship between Λ in standard cosmology and the vacuum energies from QFT will naturally have come apart in the next generation of theory, and so Λ must be ultimately understood as originating from a new physical source (e.g. a new approximately classical field).

Note that both categories take for granted that Λ in the current theory is naturally interpreted as the direct gravitational manifestation of any and all (classical) vacuum energy sources. In this way, they are incompatible with category **1** solutions, which assume the opposite. To see that this is the case, recall the example offered of category **1**, unimodular gravity. Unimodular approaches to gravity were presented as straightforward examples of category **1** solutions because they reinterpret the classical term Λ as a mere constant of integration. Similarly, consider another example of category **1** solutions: cascading gravity models which realize *degravitation*, the theoretical notion that additional large spacetime dimensions can effectively degravitate vacuum energies (Dvali et al., 2007; De Rham et al., 2008; Moyassari and Minamitsuji, 2013). These approaches take seriously the question "why does the vacuum energy gravitate so little?" (Dvali et al., 2007) and try to answer it by demonstrating feasible mechanisms by which Λ can be decoupled from any computed values of vacuum energies. The goal of these projects is to dilute the relationship between the observed value of Λ and any computed vacuum energies in precisely the right way to reconcile observations and/or predictions of the two in conjunction. A final example of solutions in this category is that of gravitational aether (Afshordi, 2008), in some sense a combination of approaches in both unimodular gravity and degravitation. Like the spirit of degravitation, the motivation of gravitational aether is to decouple vacuum terms and gravity wholesale. Like unimodular gravity, this is accomplished by considering only the trace-free restriction of the matter fields and subsequently introducing new assumptions to rebuild a consistent theory.

By contrast, both categories **2** and **3** assume that insofar as classical vacuum energies relate to Λ, they gravitate in the usual way. But whereas category **2** accepts the usual semiclassical assumption that zero-point energies in QFT will come to factor into Λ, category **3** disputes it. More formally, category **2** assumes the usual semiclassical interpolation of the standard model of cosmology, in which the term that reduces to Λ is in part determined by those terms that reduce to the zero-point energies in QFT. Given this as a starting point, approaches in category **2** focus on undermining the plausibility of the particular values handed over from QFT as contributions to Λ. Category **3**, by contrast, doubts the usual semiclassical interpolation of the standard model of cosmology that renders the zero-point energies as contributions to Λ. Instead, approaches in category **3** begin with the assumption that zero-point energies are irrelevant to considerations of Λ (either because Λ ought to be featured, at least in part, as a purely geometrical quantity on the left-hand side of the semiclassical EFE, or else because zero-point energies ought not to contribute as matter sources to the right-hand side of the semiclassical EFE) and subsequently seek out alternative physical explanations for its particular non-zero value. Hopefully it is clear how approaches in these two categories are thus incommensurable from the start.

Theorists working in category **2** have two avenues available to them to undercut the apparent fine-tuning implicated in the CCP (but the two avenues often overlap in practice). Both avenues consist of challenging the heuristics used to compute the zero-point energies in contemporary theory (i.e. the standard model of particle physics). The first avenue usually involves disputing the assumption that the eventual formulation of QFT on curved spacetime will resemble current QFT (on flat spacetime) in approximately vacuum regions. If the former does not smoothly approach the latter in low-energy limits, then there is little reason to take the present calculations based on the latter as indicative of what values the zero-point energies ought ultimately to contribute to Λ. Instead, heuristic accounts of QFT on curved spacetime are explored to determine whether the computed zero-point energies are sufficiently suppressed so that the CCP does not appear. In other words, this avenue is motivated by the possibility that the necessary generalization of the standard model of particle physics to curved spacetimes, on route toward a theory of quantum gravity, will happen to remove the worry of the CCP.[12]

The other avenue consists of suggesting potential modifications to standard particle physics on flat spacetime, even before considering how that model would be generalized to curved spacetimes. Work along this avenue explores what sorts of modifications would, in effect, cancel out the currently computed values. The idea here is that the standard model of particle physics is incomplete, even in the low-energy regime of approximately flat spacetime. Improving upon the model, even still in the framework of QFT on flat spacetime, might happen to resolve the discrepancy between Λ and the total contributions from the zero-point energies. The most common work along these lines concerns supersymmetry, the idea that the standard model of particle physics ought to be augmented to include an additional symmetry group relating fermions and bosons. Theories that satisfy supersymmetry as a local gauge symmetry are theories of supergravity with gravity multiplets comprised of spin-$\frac{3}{2}$ gravitinos (fermions) and spin-2 gravitons (bosons). Among various theoretically attractive features of supergravity is the observation, historically made by Zumino (1975), that the zero-point energies could ultimately be suppressed to 0 in precisely the right way to remove the worry of the CCP. Generalizations of this idea have become quite popular in the context of supersymmetric string theories (see, e.g., Kachru et al. (2003)). There are many theoretical difficulties with this approach, especially if Λ is constant and non-zero (Witten, 2001), but its pursuit as a possible solution to the CCP is noteworthy. The standard model of particle physics is incredibly well supported by empirical data, so the idea is not that the standard model *ought to be* modified so as to address the CCP. Rather, the idea is that there is value in determining which sorts of modifi-

[12] For examples of efforts of this sort, start with DeWitt (1975) and Hollands and Wald (2008, 2010).

cation to the standard model of particle physics happen to cause the CCP to vanish. In the case of such modifications, if in the future it were to turn out that such modifications to the standard model were justified, then the community would no longer be worried about the CCP.[13]

Along both of the theoretical avenues, notice how the CCP, not an ordinary problem in its present context, is transformed into an ordinary, defeasible problem in the languages of the new, as-of-yet undeveloped theories. This suggests that the role of the CCP in its present form is to provide a heuristic by which new theoretical initiatives are judged. Once suitably transformed, the defeasibility of the CCP (as it is rendered in the terms available to the new theoretical initiative) is viewed as a strength of the theoretical initiative: because were it the case that future physicists turn out to need the new theoretical initiative, a (future) problem has both already been formulated and subsequently solved. This could explain the intense spotlight that has been awarded to the CCP over the past several decades: for as long as theoretical physicists have been seriously pursuing a new theory of quantum gravity (and the standard model of cosmology was sufficiently mature so as to warrant talk of Λ), the CCP has provided a heuristic by which to evaluate proposals in the field. Amongst those who think that the new theory ought eventually to respect zero-point energies as approximately classically gravitating sources of vacuum energy, solutions to the CCP in category **2** highlight which theoretical initiatives are most attractive.

We can be more explicit. A solution to the CCP by appeal to some new theoretical initiative X can be understood as consisting of a demonstration that the CCP would be a solved problem in the next generation of physical theory, were the next generation of physical theory to include X. In category **2** (pursued by those who believe that zero-point energies ought to gravitate), X is any generalization of the standard model of particle physics, which is presently formulated in QFT on flat spacetime, to a new particle theory compatible with curved spacetimes. In such a generalization (which is necessary along the route to an eventual theory of quantum gravity), the question of the CCP is transformed into an ordinary problem with an ordinary solution: do the new zero-point energies (which reduce to the current zero-point energies) resemble, in sum, the new effective vacuum energy term (which reduces to the current term Λ)?

[13] Another approach along this second avenue would consider the plausibility of new, previously undetected matter fields with zero-point energies that contribute to Λ as $-\frac{\Lambda_0}{8\pi} g_{ab}$. For technical reasons relating to the maturity and success of the standard model of particle physics, this approach is unlikely to be fruitful.

Contrast this transformation of the CCP with that which emerges from solutions in category **3**. Recall that category **3** assumes that semiclassical gravity is wrong to suppose that the currently recognized zero-point energies count as contributions to the vacuum energy term. For this category, X is the next generation of semiclassical gravity (on the way to a theory of quantum gravity) in which the connection between the current zero-point energies on the quantum side and the spacetime geometry on the classical side has somewhere come apart. Beginning with the assumption that this is to be the next new theoretical initiative, the CCP is transformed into a different ordinary problem with a different ordinary solution: what is the local physics of the gravitating phenomena Λ? Approaches in this category consider the physics of new dynamic fields or modifications to the equivalence principle in GR that would reduce to the effective Λ term in the current model. In short, this is the "dark energy" category.

The first of these two avenues takes seriously the popular interpretation that Λ represents a "dark energy" that couples in atypical ways with the other matter fields implicated in standard particle physics (formulated in the framework of QFT). In other words, one expects there to be an effective classical field theory that can characterize the accelerating expansion of the universe. If it turns out to be a constant scalar field, then it is empirically indistinguishable from Λ in the classical regime, but should be empirically distinguishable from predictions of the standard model of particle physics in a high-energy regime described by quantum field theories. If it turns out to be any other sort of field (e.g. the model of quintessence given by Zlatev et al. (1999), or else that of an exotic fluid as given by Kamenshchik et al. (2001)), then it is empirically distinguishable from the current theories in both regimes. Either situation carries implications for an eventual theory of quantum gravity.

The second avenue explores what it would take to capture the accelerating expansion of the universe (whether constant or ultimately dynamic) in terms of Lorentz-violating modifications to GR, where the general relativistic quantity Λ that arises in the current standard model of cosmology is understood as an effective term that captures the Lorentz-violating aspects of the modified theory. The most natural examples of approaches along these lines include MacDowell-Mansouri gravity (Wise, 2010) and the related projects in de Sitter relativity, which consider spacetime theories like GR except where the tangent space at each point is de Sitter-like, instead of Minkowskian (Aldrovandi and Pereira, 1998, 2009; Almeida et al., 2012). In these cases, note that the modifications to GR obviously impact considerations about semiclassical gravity by providing a new classical theory that semiclassical gravity must reduce to. This in turn impacts which strategies toward a theory of quantum gravity are considered viable.[14]

In all of category **3**, it is easy to see that one possible consequence of the CCP in present theory is to suggest previously unforeseen physical constraints on future theories of quantum gravity. In this way, the first avenue can be understood as predominately focused on the quantum side of semiclassical interpolations of standard cosmology, where the CCP in present theory implicates future complications for the quantized matter term that would otherwise be ignored in contemporary particle physics. Meanwhile, the second avenue can be understood as focused on the classical side, where the CCP in present theory implicates future complications for the spacetime geometry that the quantized matter term must induce. But just like in the case of the category **2** solutions to the CCP, both avenues of research in category **3** pave the way for the eventual theory of quantum gravity to have a built-in solution to a technical problem that formally reduces to the CCP.[15]

4 Discussion and Concluding Remarks

The goal of this paper was to discuss the odd state of affairs surrounding the CCP, in the hopes of drawing philosophical lessons about scientific methodology on the cutting-edge of theory development. To that end, great care was given to how the CCP was first presented in section 2: as a quirk of our standard model of cosmology but not technically a problem, which only starts to look more like a problem when one turns one's attention to what future physical theories might entail. How the CCP transforms into an ordinary problem in light of what future theories are thought to entail became the focus of section 3, whereupon it was noticed that the CCP transforms into different problems for future physical theory depending on the assumptions one makes about what the future theory will look like.

[14] One might be confused about why cascading gravity, which was above offered as an example of category **1**, is not instead an example of category **3** based on what has just been said. But recall that cascading gravity is designed to dampen the relationship between vacuum energies and the gravitating term Λ, whereas these other modified theories of gravity offer accounts of Λ independent of any such vacuum energies.

[15] There is a fourth category of solutions to the CCP in the context of future theory that focuses on explaining away the CCP by heuristic arguments concerning probability measures that emerge in the context of several speculative theories, which render the observed value of Λ antecedently probable. Since the backbone of the fourth category, anthropic reasoning, is a source of its own philosophical battles, the details of solutions in this category have not been included in the present work. For more on the subject, see Smeenk (2013) to get a sense of the arguments that plague the general approach.

This unifying feature of both the second and third categories– that the CCP of today will eventually take the form of an ordinary problem with an explicit solution already provided– suggests a general understanding of why it is that the CCP of today is treated by the theoretical physics community as a problem at the forefront of their field. Simply put, it is the reduction to the language of our present theories of (one of) the first theoretical problem(s) that the next physical theory will be expected to solve, above and beyond all of the other problems that it must also already solve (namely, all those that reduce to already-solved problems in our current best theories).

Weatherall (2011) identifies a similar story concerning the equivalence (according to Newtonian physics) of inertial and gravitational mass, where it was viewed as a problem that the two Newtonian quantities were empirically indistinguishable (even though it technically was not a problem for the theory). The solution (that is, an explanation of their observed equivalence) came in the context of GR, even though there is no equivalent problem in the language of GR to be solved (because there is no such thing as gravitational mass). Nonetheless, in the reduction of GR back to Newtonian physics, one may derive the equivalence of the two Newtonian quantities, which seems to count as a satisfying explanation in response to the original Newtonian problem. In this way, the development of GR is characterized as having solved an outstanding problem in physics, even though there was no explicit problem in the framework of Newtonian physics, and there is no coherent statement of the problem in GR (because the solution was somehow already built into the theory).

Weatherall (2011) uses this case to come to the conclusion that at least some problems in physics have the effect of shaping the next generation of research in the field, because their solutions involve departing from present theory and engaging in new theoretical developments. I am inclined to make a slightly stronger claim: some problems in physics are intended to shape the next generation of research in the field, because merely entertaining them *as problems to be solved* requires new theoretical initiatives by which to properly articulate them. The intense focus on the CCP in contemporary theoretical physics supports this claim. As a consequence of the community worrying about the apparent fine-tuning of Λ_0 in light of certain natural semiclassical assumptions about the future of cosmology, multiple independent lines of theoretical inquiry have been developed, each of which features a sketch of future physical theory in which a newly articulated problem has been solved. Moreover, those sketches can be easily grouped, broadly, in terms of the additional assumptions that would warrant them as components of the next generation of physical theory.

But there is a more subtle comment to be made here about the process of theoretical development as it relates to scientific progress. In a landmark paper, Sklar (1975) introduced to the philosophical community the notion of methodological conservatism, which presumes that it is rational to believe a proposition that is largely supported by empirical evidence, but which also depends on the additional (unevidenced) belief that the proposition is *a priori* more plausible than other mutually exclusive propositions. This means that two agents who possess the same empirical evidence but who find different propositions antecedently plausible may rationally disagree. One obvious virtue of methodological conservatism is that it offers a potential justification of expert disagreement. In particular, it provides an account of how scientists engaged in theoretical research may rationally disagree about the future of their discipline. But although it can justify how it is that the ordinary scientific practice of expert disagreement is rationally permissible, it does not explain or contextualize the role of that scientific practice as a generic feature of the ongoing development of scientific theory.

It is in regards to this last point that the present paper can offer some parting philosophical insight. The case study of the CCP and its pairwise incompatible categories of solutions suggests that expert disagreement arises at least in the context of research problems like the CCP, which are not properly problems for our best contemporary theories. Different possible formal articulations of the problem require different assumptions about the next generation of physical theory, which are precisely the sorts of propositions that are largely evidenced by empirical research but whose adoption depends on their perceived plausibility. Thus, the theoretical community's treatment of the CCP can be understood as an instance of methodological conservatism in practice.

But then, we have already pointed out the strategic virtue of problems like the CCP: in the different contexts of having granted the different assumptions, theorists are in the position to explore different possible extensions of contemporary theory that do everything the current theories do plus solve an additional technical problem in the field. Moreover, the additional technical problem in the field now solved was also, by design, never a proper problem before. The theorist who provides a solution to that new problem is therefore in the position to claim that, on the basis of well-evidenced contemporary theory and some antecedently plausible assumption about future theory based on the current theory, they have developed some new theoretical initiative whose solved problems include the current theory's solved problems as a proper subset. That is, the theorist has an obvious claim toward having made progress in the field, conditional on their theoretical initiative being accepted as a part of the next generation of physical theory.

Taking a step back, it is clear that by virtue of being entertained as problems, worries like that of the CCP in our current best theories engender methodologically conservative theoretical initiatives that feature markers of progress in the field. That is to say, the CCP is not meant to be solved; rather, it is meant to illuminate the possible paths forward from current theories to future, more sophisticated theories.

A If the CCP Were a Problem For Standard Cosmology, Here Would Be a Solution

The purpose of this section is to demonstrate, in brief, that from the position where the CCP would be, truly, a problem for the standard model of cosmology, there is a ready solution available that interprets $\Lambda = \Lambda_0$ simply as a physical constant, explicitly rejecting the notion that vacuum energies gravitate and therefore preventing any problems down the road reconciling new and improved calculations of such quantities with Λ. The exposition primarily follows Earman (2003), Ellis et al. (2011), and Earman (2016) in considering unimodular approaches to classical gravity (where λ in the former's treatment and $\hat{\Lambda}$ in the latter two's treatments are just our lovable Λ_0 in other forms).

First, consider what it would mean for the CCP to be a problem for the standard model of cosmology. I take it that for the CCP to be a problem for a particular theory, there would need to be some empirical observation that is in tension with theoretical expectations that follow from setting Λ_0 to its otherwise necessary value.[16] From Equation 2, it follows that there would be a problem were it the case that some physical theory warrants a restriction on Λ_0 such that:

$$\frac{\Lambda - \Lambda_0}{8\pi} g_{ab} \neq T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}$$

for some range of values for Λ and $T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}$, whereupon both such terms are found to assume particular values within those ranges. If this state of affairs were to obtain, then the observation of Λ and the calculation of $T_{ab}^{(\gamma+\delta+\zeta+\ldots+\theta)}$ would doom the standard model of cosmology. As

[16] This is certainly the intuition behind quotes about skepticism toward the CCP like that given from Earman (2001) above, where the target of skepticism is the extent to which there is a demonstrated conflict between current theoretical predictions and empirical observations.

has already been discussed, insofar as one fears that Λ_0 is fine-tuned, it must be because such a conflict is somehow plausible. But if there were a way to undermine the relationship expressed in Equation 2 between the potential vacuum energy contributions and Λ (and so, subsequently, Λ_0), this supposed problem could be suitably avoided. In fact, this is just what unimodular approaches to GR promise.

Unimodular approaches to GR consider a trace-free restriction of the EFE (as presented in Equation 1, without Λ) in conjunction with the premise that $\nabla^b T_{ab} = 0$.[17] It has often been claimed that as a consequence of this reformulation of GR, vacuum energies are teased apart from the other contributions to the stress-energy tensor (and so for our purposes, it suitably undermines Equation 2). More generally though, it shifts the interpretation of Λ_0 from being a bound variable determined by Equation 2 to being a free variable used to fit the model to data. This works (in brief) as follows.

Taking the trace of Equation 1 yields $R - \frac{1}{2}(n * R) = 8\pi T$ where n is the dimension of the spacetime manifold and $T = Tr(T_{ab})$, the trace of the stress-energy tensor. In the special case of a four-dimensional manifold, this reduces to $-R = 8\pi T$. For convenience, express this as $-\frac{1}{4}R = 8\pi * \frac{1}{4}T$. The trace-free restriction of the EFE without Λ in four dimensions thus yields $R_{ab} - \frac{1}{2}Rg_{ab} - (-\frac{1}{4}Rg_{ab}) = 8\pi T_{ab} - 8\pi\frac{1}{4}Tg_{ab}$. Partially simplifying the expression, we arrive at

$$R_{ab} - \frac{1}{2}Rg_{ab} + \frac{1}{4}(R + 8\pi T)g_{ab} = 8\pi T_{ab} \tag{3}$$

From the second Bianchi identity and the assumed conservation of momentum-energy (which we no longer get for free), differentiating Equation 3 according to ∇^b (and subsequently multiplying through by 4) gives

$$\nabla^a(R + 8\pi T) = 0$$

and so $R + 8\pi T$ is a constant of integration (which we can represent as a constant Λ_0 multiplied by a factor of 4). Returning to the trace-free EFE as represented by Equation 3, one may use this constant of integration in place of the trace of T_{ab} to yield

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda_0 g_{ab} = 8\pi T_{ab}$$

[17] Recall that this constraint represents the conservation of momentum-energy, which was previously guaranteed by the geometry of the full-blown EFE. In unimodular approaches, stipulating it as an independent assumption is needed to recover the full expressivity of GR.

which resembles the full-blown EFE with a cosmological constant in precisely the form as we first introduced it, and so Λ_0 can easily play the role that was originally intended of Λ.

Nonetheless, using Λ_0 in this way requires us to identify models of cosmology in terms of equivalence classes of standard cosmological models with a given metric that satisfy the condition $R + 8\pi T = 4\Lambda_0$. In the case of the standard model of cosmology, now an equivalence class of perturbed FLRW spacetimes satisfying $R + 8\pi T = 4\Lambda_0$, just one of those spacetimes is expected to obtain in our own backyard. And so, empirically detecting the value we ought to assign to the constant parameter Λ_0 amounts to selecting which of the equivalence class is relevant to our particular empirical circumstance. This is no more spectacular than the analogous activity of empirically determining which spring constant correctly reproduces the behavior of one spring, rather than of another.

And meanwhile, any vacuum energy terms can be absorbed into the value assigned to Λ_0. There are two common ways of thinking about what this means. The first way is that vacuum energy terms do not gravitate, because the stress-energy of such vacuum sources is not trace-free (and so any metrical terms decouple from the total stress-energy tensor), but Earman (2016) sheds doubt on this view, arguing that the contributions of such vacuum sources are smuggled in. The second way consists of reasoning in analogy with Equation 2: whatever empirical access we have to Λ_0 is dependent on our theoretical understanding of the presence of vacuum contributions. But unlike what was the case in Equation 2, Λ_0 is no longer interpreted as counteracting the vacuum contributions to result in the effective term Λ; rather, its role is merely in specifying which of the equivalence class of cosmological models represents that which obtains in our present universe, whether or not our present universe is thought to have vacuum energies.

In this way, category **1** solutions can be understood as circumventing the apparent fine-tuning of Λ_0 from current theory onward by undermining the connection between Λ and any contributions to $T_{ab}^{(total)}$ (including those which may arise as predictions in QFT). Approaches in this category come at the cost of formally interpreting $\Lambda = \Lambda_0$ as a freely-varying fit parameter over an equivalence class of cosmological models. As was mentioned in the body of the paper, the most notable feature of this approach is that the cosmological community by and large does not view it as an adequate redress to the CCP, even though it seemingly eradicates any construction of the worry.

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