

Extracting New Physics from the CMB

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We review how initial state effects generically yield an oscillatory component in the primordial power spectrum of inflationary density perturbations. These oscillatory corrections parametrize unknown new physics at a scale M and are potentially observable if the ratio H_{infl}/M is sufficiently large. We clarify to what extent present and future CMB data analysis can distinguish between the different proposals for initial state corrections.

I. TRANSPLANCKIAN PHYSICS — OR, CAN QUANTUM GRAVITY BE SEEN IN THE SKY?

There is much about the early universe that remains beyond the reach of today's most refined theoretical tools. Among the many intertwined and as yet poorly understood issues are the nature and resolution of the big bang singularity, the correct form of physical laws in the extreme environment of the Planck era, and the full specification of initial conditions for all physical degrees of freedom. Even without answers to these questions, however, cosmology has made great strides in recent years. This is at least partly due to the happy fact that inflationary cosmology — viewed as an effective theory that describes the dynamics of the universe at sufficiently “late” times — has a tendency to suppress dependence on unknown physics of the very early universe.

Nevertheless, there are features of inflationary cosmology that retain a memory of conditions and dynamics of the very early universe, and a growing cadre of researchers have, in recent years, tried to exploit this to provide a cosmological window on the Planck era — a body of work that is often referred to as *transplanckian physics* [1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12]. In this note, we emphasize one such approach: seeking transplanckian signatures in the cosmic microwave background radiation (CMB).

In the following sections, we will review potential transplanckian signatures, emphasizing observational consequences over technical details (which are covered in the references we cite). But first, we give a quick sketch of the essential physics.

The standard, and highly successful, calculations of the CMB power spectrum [16], rely on two essential assumptions:

- (1) the standard dynamics of flat spacetime quantum field theory is applicable on arbitrarily short scales (and hence arbitrarily high energies) and
- (2) the standard boundary conditions used in flat spacetime quantum field theory are applicable when a mode's wavelength is sufficiently small (the intu-

ition here is that the smaller a mode's physical wavelength — the more blueshift its corresponding comoving mode experiences — the less sensitive it is to any background spacetime curvature).

Transplanckian studies of the CMB challenge one or both of these assumptions, and the literature is now replete with many specific alternative proposals — alternative dynamics and/or alternative boundary conditions. We have argued [2, 9] that a generic signature of such proposals is a new *oscillatory* feature overlaid on the usual primordial power spectrum. It is straightforward to understand why: regardless of the primordial dynamics and primordial boundary conditions, at sufficiently late times (for any given mode) the successful standard dynamics — essentially Einstein's equations (or Einstein's equations with couplings to a scalar field theory) — must be the controlling framework. At this late time, we can summarize the unknown primordial dynamics and primordial boundary conditions through the specification of boundary conditions to the Einstein equations. Of course, an arbitrary choice of boundary conditions will result in arbitrary results. The data, however, winnow the possibilities since the boundary conditions must yield results that do not differ significantly from the observed scale invariance. This suggests two physically well-motivated classes of boundary conditions.

(a) For each comoving mode k , set boundary conditions when the physical momentum $k/a(t)$ is redshifted to a physical cutoff scale M_{cutoff} (e.g. the string scale in string theory), and choose the boundary conditions to be nominally scale invariant by making them depend only on the physical scale $k/a(t_k) = M_{cutoff}$, or

(b) At a chosen time t_{cutoff} (essentially, the earliest time for which we can trust standard general relativistic dynamics), set the boundary conditions for all modes k on this equal time hypersurface, and choose these boundary conditions to include one-loop corrections to the standard (scale invariant) flat spacetime boundary values.

In either case, the modified boundary conditions on each mode amount to a Bogoliubov rotation of

positive and negative frequency components of that mode (relative to the standard vacuum choice). Since the power spectrum is proportional to the square of a given mode's amplitude, this rotation leads to a positive/negative mode mixing, yielding the oscillatory behaviour referred to above. In case (a), though, the argument of the oscillatory terms will depend on $H_{inf}/(k/a(t_k)) = H_{inf}/M_{cutoff}$, which is constant in de Sitter space, and hence truly oscillatory behaviour only occurs in the physically relevant case of backgrounds with non-constant Hubble parameter. In case (b), the oscillatory behaviour is already present in de Sitter space as $k/a(t_{cutoff})$ is explicitly k dependent.

Thus, our main conclusion is that if transplanckian physics is observable in the CMB — admittedly a significant “if” as we need the amplitude of the transplanckian contribution to be sufficiently large — then a prime signature to look for is an oscillatory component to the primordial power spectrum.

In what follows, we spell this out in somewhat greater detail, focusing on the choice of initial conditions in the context of effective field theory — a framework we feel to be both conservative and reliable, but sufficiently rich to allow the calculation of the form of oscillatory power spectrum component. We compare the results found in the two cases (a) and (b), above, and note significant qualitative differences.

II. INITIAL STATE EFFECTS IN THE CMB AND THEIR RELATION TO NEW PHYSICS

The initial state problem can be turned into an opportunity to probe new high energy, or ‘transplanckian’, physics, *if* initial state selection proves to be related to physics at the high energy scale, typically corresponding to the string or Planck scale. Although many proposals have been put forward suggesting such a link, they typically rely on highly particular models of Planck scale physics that are predominantly ad hoc and contain specifics whose justification can be questioned [1, 2, 3, 4]. However, the *generic* features of Planck scale physics ought to be describable by an effective field theory [5]. Inspired by [6], [7] showed how initial conditions are translated into the language of effective field theory (EFT) through the introduction of a boundary action. This spacelike boundary action is located at an initial time surface t_0 where the initial conditions are set for *all* the bulk modes. Primarily for phenomenological reasons[17] the boundary action is chosen to describe small corrections to the Bunch-Davies (BD) state. The BD state corresponds to a specific choice for a (relevant) operator on the boundary. The effect of unknown Planck scale physics on the initial conditions is parametrized in terms of irrelevant boundary operators. Their presence induces small corrections to the BD state suppressed by powers of the ratio of the physical mo-

mentum scale $p = k/a_0$ over the cut-off scale M . This necessarily leads to initial states that break the (approximate) scale invariance of the CMB spectrum, i.e. for every comoving momentum k mode the initial state correction is slightly different, simply because they correspond to different physical momenta at the initial time t_0 . Clearly, this is an example of the type (b) boundary conditions discussed in the last section.

By contrast, this generic breaking of scale invariance in boundary EFT differs from the type (a) approaches in which bulk modes are treated identically by imposing an initial condition, without explicit momentum dependence, for all modes at some fixed physical cut-off scale M_{cutoff} . Momentum dependence is only implicitly allowed through dependence on the background geometry, i.e. through a time-varying H . In this framework, therefore, one enforces the breaking of scale invariance via the slow-roll behaviour of the background, which itself breaks de Sitter scale invariance in the bulk. Hence, this approach also preserves near-scale invariance of the spectrum of perturbations.

It is worth emphasizing that whereas the boundary effective field theory method introduces a spacelike hypersurface ($t = t_0$) in spacetime on which boundary conditions are specified, in the approach just described, boundary conditions are specified on a hypersurface in energy-momentum space, $E = M_{cutoff}$, which can be referred to as the New Physics Hypersurface (NPH). Notice too that the NPH approach does not conflict with boundary EFT per se (one can always evolve/devolve boundary conditions specified at different times on the NPH, to one chosen time t_0), but it will not conform to generic predictions from a boundary EFT point of view due to the *special* requirement of near-scale invariant initial conditions. The EFT and NPH methods can thus be said to represent two separate classes of boundary conditions[18]. General (observational) consequences of initial state modifications in this class have been described in [9].

In light of these formal considerations of both the expectation and relevance of initial state effects in the CMB, the pressing question is how initial state effects alter the standard predictions based on the Bunch-Davies state. Given a basis u_k, u_k^* for the two linearly independent solutions to the wave equation in the inflationary background spacetime, the initial conditions determine a unique linear combination

$$\begin{aligned} v_k &= N(k) [u_k + b(k)u_k^*], \\ v_k^* &= N(k)^* [u_k^* + b(k)^*u_k]. \end{aligned} \quad (1)$$

Klein-Gordon normalization of the mode functions v_k implies that $|N(k)|^2 = \frac{1}{1-|b(k)|^2}$. The power spectrum of perturbations is proportional to the absolute value $P(k) \propto |v(k)|^2$. The (complex) parameter b is known as the Bogoliubov parameter, and we shall follow the convention that the standard Bunch-Davies choice of initial conditions corresponds to $b = 0$. Compared

to the standard Bunch-Davies form one thus obtains for the power spectrum (defining the phase δ through $u_k = e^{i\delta} |u_k|$)

$$P(k) \propto \frac{1}{1 - |b(k)|^2} \left[(1 + |b(k)|^2 + e^{2i\delta} b(k)^* + e^{-2i\delta} b(k)) |u_k|^2 \right]. \quad (2)$$

Since the spectrum is evaluated for modes $p > H$ we know that the phase δ is k -independent and therefore just corresponds to an overall phase. Assuming that the corrections are small, i.e. $|b(k)| \ll 1$, the final expression for small initial state modifications to the (BD) primordial spectrum of inflationary perturbations is

$$P(k) \approx P_{BD}(k) \left[1 + 2|b(k)| \cos(\alpha(k) + \delta) \right]. \quad (3)$$

The *distinctive* feature of generic initial state modifications is thus the appearance of an oscillatory signal on top of the standard BD spectrum with the period and amplitude determined by the complex Bogoliubov parameter $b(k) = |b(k)| \exp(i\alpha(k))$. Throughout the rest of this proceeding we will drop the appearance of (arbitrary) constant phases δ .

A. Corrections to the primordial spectrum from scale-invariant initial conditions

The above expression for the corrections to the power spectrum directly shows the effect of near scale-invariant initial conditions. They correspond to explicitly k -independent Bogoliubov parameters b , though they may have implicit k -dependence through the background value of the Hubble parameter H . In a pure de Sitter background with constant H the scale invariance is exact. In scenarios where the size of the Bogoliubov parameter is tied to the New Physics Hypersurface where $p(t) = M = M_{cutoff}$, the minimal choice (i.e. the minimal uncertainty/‘empty’ state at the NPH) is $b = \frac{H}{2iM} e^{-2iM/H(1-\epsilon_H)}$ with ϵ_H the (Hubble) slow roll parameter of the inflationary background [9]. Any k -dependence in these near-scale invariant scenarios is induced by the time dependence — and therefore k dependence — in the Hubble parameter H . For a quasi-de Sitter background H depends on the momentum scale as $H \propto k^{-\epsilon_H}$.

There is some reason to believe that these New Physics Hypersurface scenarios, with a generalized Bogoliubov parameter $b = \tilde{\beta} \frac{H}{2iM} e^{-2i\frac{M}{H}}$, are the only consistent scale invariant modifications to the Bunch-Davies initial state [19]. The power spectrum in this consistent subclass is described by the expression

$$P(k) \approx P_{BD}(k) \left[1 + \tilde{\beta} \frac{H(k)}{M} \sin \left(\frac{M}{H(k)} \right) \right] \quad (4)$$

We will consider this case only from now on and compare it to the generic predictions made by the boundary EFT formalism.

B. Corrections to the primordial spectrum from boundary EFT

In the boundary EFT formalism one finds instead that the amplitude and phase of b are k -dependent functions. This requires a bit more explanation (for all the details we refer to [7], see also the related work [8]), because the Bogoliubov parameter $b(k)$ is not a natural parameter in the effective action. The starting point in this case is the boundary action,

$$S_B = \int_{t=t_0} d^3x \sqrt{g} \left(-\frac{1}{2} \kappa_{BD} \phi^2 \right), \quad (5)$$

introduced at some initial time or scale factor $a_0(t_0)$. Using the machinery of effective field theory, starting with a bare coupling reproducing the Bunch-Davies initial state, one can calculate corrections to this bare coupling κ_{BD} by considering the effect of higher-derivative (irrelevant) operators in the boundary theory. The assumption of new physics at some physical cut-off scale M — close to the Planck scale — naturally introduces these irrelevant operators. They encode the particulars of the unknown high energy physics order by order in an expansion in the physical momentum $p_0 = \frac{k}{a_0}$ over the cut-off scale M . On the basis of straightforward dimensional analysis we *generically* expect the leading correction to the bare Bunch-Davies coupling constant κ_{BD} to be of the form (note that κ has dimensions of mass)

$$\kappa(k) \approx \kappa_{BD} + \beta \left(\frac{k^2}{a_0^2 M} \right), \quad (6)$$

Under the assumption of naturalness the coefficient β is moreover expected to be of order 1 (although, it is entirely possible that β is fine-tuned in the real world).

To connect with the general power spectrum expression (3), we translate this generic boundary EFT correction to an expression for the Bogoliubov parameter $b(k)$. To do so, we remind ourselves that the boundary action was introduced to set the initial condition. Varying the action, one finds that the coupling κ corresponds to the following boundary condition on the scalar inflaton field ϕ

$$\partial_n \phi|_{a_0} = -\kappa \phi(a_0), \quad (7)$$

where $\partial_n = H \frac{\partial}{\partial \ln a}$ corresponds to the normal derivative with respect to the boundary. From (7) it is straightforward to deduce a relation between the coupling κ and the Bogoliubov parameter b . Expand the scalar field in a basis of two independent mode functions, allowing for an arbitrary Bogoliubov rotation,

and substitute this into (7) to obtain

$$b(k) = -\frac{\kappa(k)u_k(t_0) + \partial_n u_k|_{t=t_0}}{\kappa(k)u_k^*(t_0) + \partial_n u_k^*|_{t=t_0}}. \quad (8)$$

This equation relates $b(k)$ and $\kappa(k)$ in general. What we are really interested in is a relation between the Bogoliubov parameter b , as defined with respect to the BD mode functions, and the leading irrelevant correction to the bare BD coupling κ_{BD} (6). Expanding (8) to leading order in corrections to the BD state, using the BD mode functions u_k and the normalization conditions, we get that

$$b(k) = ia_0^3 (u_k(t_0))^2 \beta \left(\frac{k^2}{a_0^2 M} \right) + \dots \quad (9)$$

Now we can use (3) to evaluate the effect of the leading higher derivative correction in boundary EFT to the initial conditions on the primordial inflationary power spectrum. The explicit BD mode functions (for a massless scalar field) will differ depending on the specific inflationary background. The limit where the comoving momentum k is much larger than the comoving horizon size *at the initial time* t_0 , i.e. when $k \gg a_0 H$, is universal, however. For all inflationary backgrounds the $y_0 \equiv k/a_0 H \gg 1$ corrections to the power spectrum are

$$P(k) \approx P_{BD}(k) \left[1 + \beta \frac{k}{a_0 M} \sin(2y_0) \right]. \quad (10)$$

Notice the presence of *two* relevant scales in this expression: $k_H = a_0 H$ and the ‘comoving cut-off scale at the initial time’ $k_M \equiv a_0 M$. One might take issue with this introduction of a second scale $1/\eta_0$. In a most conservative scenario one can think of it as the beginning of inflation or the ‘Planck time’ before which GR breaks down. We will elaborate on the interpretation and theoretical expectation of the (period) scale k_H and the (amplitude) scale k_M in the next subsection.

C. Observable parameters and physical quantities

As explained and emphasized, it is a generic feature that initial state corrections are characterized by oscillations on top of the standard spectrum of fluctuations. This implies that in principle there will be two, a priori, independent observable parameters extractable from (future) CMB data; the amplitude and the period of an oscillatory component of the primordial power spectrum[20]. Preliminary data extraction studies have indicated that these oscillatory features are indeed expected to be decipherable in future CMB experiments (under optimistic assumptions for the ratio H/M) [12]. The distinction between the generic

boundary EFT prediction and the near-scale invariant NPH proposal for initial state corrections is in the k -dependence of these two observable parameters.

For the boundary EFT prediction, the qualitative behaviour of the corrections depends crucially on the relative value of the scale k_H and k_M with respect to the range of comoving momentum modes present in the observable CMB, $k \in [k_{min}, k_{max}]$. As the scale k_M corresponds to the comoving cut-off scale, beyond which the boundary EFT formalism breaks down, we *must* require that $k_{max} < k_M$. Now, the ratio between the period and the cut-off is a physical quantity given by $\frac{k_H}{k_M} = \frac{H}{M}$ [21]. Thus we see that within a consistent boundary EFT description there is a lower bound on the period

$$k_H \gtrsim \left(\frac{H}{M} \right) k_{max}. \quad (11)$$

This theoretical estimate is important because the scale k_H sets the period of the oscillations in the spectrum, which can be read off from (10) to equal

$$\Delta k = \pi k_H \gtrsim \left(\frac{H}{M} \right) \pi k_{max}. \quad (12)$$

Extrapolating these constraints to constraints in multi-pole space l , i.e. $\Delta l = \pi l_H \gtrsim \left(\frac{H}{M} \right) \pi l_{max}$, we can deduce a lower bound on H/M beyond which the oscillations are too frequent and are washed out of the data. Since we know that the current $\pi l_{max} \lesssim 10^4$ and assuming that a period $\Delta l \gtrsim 10$ is observable, we find that $H/M \gtrsim 10^{-3}$ for oscillations to be detectable in the CMB. If H/M is at the one percent level, one would expect to see oscillations with an estimated period around $\Delta l \sim 100$.

Gratifyingly, it is also for values of $H/M \gtrsim 10^{-3}$ that the amplitude of the signal is at the same order of or larger than the inherent cosmic variance ambiguity in the CMB. For a period of order $\Delta l \sim 10$ the larger part of the observable CMB spectrum ($l_H < l \leq l_{max}$) is well approximated by (10). From the theoretical and detectability constraints discussed above, one finds that the amplitude $A(k) = \mathcal{A}k$, with $k_H \leq k \leq k_{max}$, runs between

$$\beta \left(\frac{H}{M} \right) \leq \mathcal{A}k \leq \beta. \quad (13)$$

This is easily beyond the 1% cosmic variance level around $k \sim k_{max}$, unless β is fine-tuned and unnaturally small. Here we should also point out that the observed near scale invariance of the CMB spectrum could a priori significantly constrain β as k approaches k_{max} . However, as it turns out, and mainly due to the oscillatory nature of the correction, this does not lead to a severe constraint on β . By dividing the observable parameters of the oscillations one would probe

the scale of new physics directly

$$\frac{\Delta l_{obs}}{\mathcal{A}_{obs}} = \beta \left(\frac{H}{M} \right). \quad (14)$$

Under the assumption of naturalness ($\beta \approx 1$) this fixes the interesting ratio of scales H/M . Moreover, if tensor modes are observed, the Hubble scale H will be known independently. The presence of CMB oscillations with a constant period in k or l would then allow a determination of the scale of new physics M through the boundary EFT formalism (again assuming naturalness).

It is a qualitative difference in the periodicity of the oscillations that distinguishes the near-scale invariant New Physics Hypersurface proposal. Whereas the generic prediction from boundary EFT was a constant period in k , the NPH proposal yields oscillations with a constant period in $\ln(k/k_{pivot})$. Here k_{pivot} is the arbitrary pivot point in k space where the normalization of the observed power-spectrum is set and compared to which slow roll is measured (e.g. COBE used $k_{pivot} = 7.5 H_{present}$). Specifically the periodicity is given by

$$\Delta \ln \frac{k}{k_{pivot}} = \frac{\pi H_{pivot}}{M \epsilon_H}. \quad (15)$$

This allows us to deduce how many oscillations we expect in the spectrum. Current CMB measurements range from roughly $10^{-4} H_{present} \leq k \leq H_{present}$ or

$$-4 \ln 10 - \ln \frac{k_{pivot}}{H_{present}} \leq \ln k \leq -\ln \frac{k_{pivot}}{H_{present}}. \quad (16)$$

Therefore the number of full oscillatory periods present in the CMB ought to be

$$N = 4 \ln 10 \frac{M \epsilon_H}{\pi H} \simeq \frac{3 M \epsilon_H}{H}. \quad (17)$$

For the observed estimate of $\epsilon_H \leq 0.01$ and the optimistic scenario that $M/H \sim 10^2$ we expect to see 1-10 oscillations over the whole power spectrum (see e.g. figure 1 in [9]).

An advantage of the near-scale invariant NPH proposal is that it allows one to determine the ratio of scales directly from the period of these oscillations. This is provided that the slow roll parameter ϵ_H is known. No appeal to naturalness is needed. In fact with the knowledge of the ratio of scales we can test directly the deviation $\tilde{\beta}$ from the standard Bunch-Davies state. A significant difference from unity for this number could be interpreted as an element of fine tuning at work.

Another important distinction between the NPH and EFT scenarios is that the EFT corrections grow with increasing k , whereas the NPH modifications decrease with increasing k . The physics behind this is clear: in EFT the effects grow larger as you approach

the cut-off scale. In NPH the k -dependent corrections are proportional to the Hubble scale, which decreases in time; larger k modes exit the horizon later and are therefore affected by a smaller Hubble scale. This indeed confirms that the natural place to look for corrections in the NPH scenario is the CMB spectrum. At the same time however, it suggests that the more natural place to look for EFT corrections would instead be in large k power spectra that seed galaxy formation.

III. CONCLUSIONS

In table I, we have summarized our discussion of initial state effects in the CMB that arise within boundary Effective Field Theory at a fixed time and within the special class of near-scale invariant New Physics Hypersurface initial conditions. The qualitative difference between the two scenarios is clearly the behaviour of the periodicity in k -space: constant for generic initial conditions in boundary Effective Field Theory; logarithmic for near-scale invariant New Physics Hypersurface scenarios. A secondary and related aspect is a linearly growing amplitude for boundary Effective Field Theory but a constant amplitude for near-scale invariant New Physics Hypersurface proposals. Note that under the assumption of naturalness the boundary EFT formalism predicts a marginally bigger window of opportunity in H/M space as compared to the NPH scenarios.

Throughout our discussion, we have taken a decidedly phenomenological perspective on transplanckian physics, emphasizing — as in table I — the generic signatures one would hope to find if high energy physics does in fact yield an observational imprint on the CMB. For completeness, we briefly note one important theoretical issue. Part of the growing literature on transplanckian physics has involved a debate about the expected magnitude of transplanckian corrections. In [2, 3] it was argued that — as in the approaches we have reviewed above — we should expect order H/M_{cutoff} corrections, a conclusion borne out by many explicit studies [1, 4]. However, in [5] it was argued that corrections could at most be of order $(H/M_{cutoff})^2$. Due to cosmic variance limitations, this constitutes a qualitative difference as to whether the corrections can, even in principle, ever be seen. The disparity between these two claims arose because [2, 3] explicitly — and [1, 4] implicitly — allowed for modified boundary conditions and modified dynamics whereas [5] only allowed for modified dynamics (coming from higher order operators in the *bulk* effective field theory). The second paper of [5] went further and argued that it was physically inconsistent, or at the very least technically unnatural due to large backreaction, to have any but the standard BD boundary conditions. The advantage of working

	Boundary EFT	Minimal NPH
Power Spectrum	$P = P_{BD} \left(1 + \mathcal{A}k \sin \left(\frac{2\pi k}{C} \right) \right)$	$P = P_{BD} \left(1 + A \sin \left(\frac{2\pi}{C} \ln \frac{k}{k_{pivot}} \right) \right)$
Amplitude	$\mathcal{A} = \beta \frac{1}{a_0 M}$	$A = \tilde{\beta} \frac{H_{pivot}}{M}$
Period	$\Delta k = C = \pi a_0 H$	$\Delta \ln \frac{k}{k_{pivot}} = C = \frac{\pi H_{pivot}}{M \epsilon_H}$
Number of Osc.	$N \lesssim \frac{M}{\pi H}$	$N \simeq \epsilon_H \frac{M}{\pi H} \ln \frac{k_{max}}{k_{min}}$
Ratio of Scales	$\mathcal{A} \cdot \Delta k = \beta \frac{H}{M}$	$A = \tilde{\beta} \frac{H}{M}, \frac{\epsilon_H C}{\pi} = \frac{H_{pivot}}{M}$

TABLE I: Phenomenological signatures of initial state effects on the primordial CMB power spectrum. P_{BD} is the Power Spectrum computed w.r.t. Bunch-Davies initial conditions and an arbitrary constant phase has been dropped.

in a boundary EFT formalism, as in [7], is that backreaction can be systematically analysed. And as shown in [7] and [10], large backreaction within the context of effective field theory can be avoided, giving us a self-consistent framework that predicts order H/M_{cutoff} corrections.[22]

Thus, the most important observation is that with minimal assumptions, i.e. that H/M be large enough compared to errors due to cosmic variance, the *generic oscillatory* characteristics of initial state effects should be visible in future if not current CMB experiments [14]. Nature could of course have arranged itself such that the controlling coefficients β or $\tilde{\beta}$ in the Effective Field Theory or New Physics Hypersurface scenarios — describing the particulars of new physics at the cut-off scale M — are small. This would be yet another fine-tuning to bewilder us theorists. Absent that, with guarded optimism we can imagine that in the not too distant future we might catch the very first experimental glimpse of near-Planck scale physics.

Note added:

As indicated at the end of section 2, a more natural place to look for EFT effects might be the power spec-

trum of density perturbations deduced from galaxy surveys (like for instance the Sloan Digital Sky Survey [15]). We would like to thank G. Holder, W. Kinney, R. Easther and L. Hui for pointing out to us that over a large range of length scales the galaxy survey power spectrum is still governed by linear physics. This potentially allows for new physics signatures according to the EFT formalism. However, assuming the co-moving cut off scale k_M is high enough to cover the galaxy survey scales does exacerbate the conundrum mentioned in footnote (III).

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 - [16] For a recent theoretical review of CMB physics, also covering some of the issues raised here, see [13].
 - [17] One can show that the Bunch-Davies state is special from the boundary effective action point of view as well; see [7].
 - [18] Nearly all known examples of Planck scale modifications to the CMB fall into the two classes of modifications we have discussed. We will therefore limit our attention to them.
 - [19] One needs the exponential factor to avoid non-localities at order H [7]. Any subleading prefactor will be unobservable.
 - [20] For very high comoving momentum modes this can directly be extrapolated to an amplitude and period in the observed multipole moments C_l to reasonable approximation; although in truth a full deconvolution is called for [12].
 - [21] This dimensional relation between k_H and k_M does yield a conundrum. Since the boundary action should preferentially be introduced before the time the lowest modes in the CMB were formed, we expect $k_H \lesssim k_{min}$. In other words the scale k_H is expected to be at the least the horizon size of the lowest mode in the CMB at $t = t_0$. This simple observation creates an unexpected tension between 1) the physical idea that modes become non-dynamical when they exit the horizon, 2) the wish to describe the full four-orders of magnitude range of CMB modes with one boundary EFT with fixed time initial conditions and 3) the expectation that H/M is of order 10^{-2} . Because the power spectrum follows from linear analysis where modes do not interact 1) can be sacrificed without losing its inherent idea. For an interacting field theory it remains an open question, however, how to resolve the tension between 1), 2) and 3).
 - [22] Backreaction in the context of the NPH proposal was discussed in [11], with qualitatively the same conclusion that a clear window of opportunity to detect new physics in the CMB remains.