Explanatory Depth in Primordial Cosmology: A Comparative Study of Inflationary and Bouncing Paradigms

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Abstract. We develop and apply a multi-dimensional conception of explanatory depth towards a comparative analysis of inflationary and bouncing paradigms in primordial cosmology. Our analysis builds on earlier work due to Azhar and Loeb (2021) that establishes *initial condition fine-tuning* as a dimension of explanatory depth relevant to debates in contemporary cosmology. We propose *dynamical fine-tuning* and *autonomy* as two further dimensions of depth in the context of problems with instability and trans-Planckian modes that afflict bouncing and inflationary approaches respectively. In the context of the latter issue, we argue that the recently formulated trans-Planckian censorship conjecture leads to a trade-off for inflationary models between dynamical fine-tuning and autonomy. We conclude with the suggestion that explanatory preference with regard to the different dimensions of depth is best understood in terms of differing attitudes towards heuristics for future model building.

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1. Introduction

A heated debate has raged in contemporary cosmology regarding the scientific merits of the dominant inflationary paradigm. A small but influential minority of cosmologists have both questioned the justificatory basis for the predominate position of inflation and argued for an alternative framework based upon bouncing cosmological models. The primary axis of this debate relates to the comparison between the two approaches with regards to empirical support both in terms of *prediction* and *accommodation* of evidence. Most vividly, dispute along this axis has been played out in the exchanges between Ijjas et al. (2013, 2014) and Guth et al. (2014a, 2017). This aspect has recently received a detailed philosophical analysis from Dawid and McCoy (2021).

A secondary, but still significant, axis of debate concerns the relative *explanatory* merits of two approaches, taken both in comparison to each other and to the standard hot big bang framework. In this context, it is worth noting that even the seemingly straightforward explanatory comparison between inflationary explanations and the older hot model big bang proves controversial. Inflation was originally motivated by the observation that the hot big bang model involved *implausible coincidences* which cried out for explanation (Smeenk 2005; Azhar and Butterfield 2017). However, explication of the basis for the superiority of the inflationary explanation in comparison to the 'fine-tuned' hot big bang models is non-trivial. In particular, as persuasively argued by McCoy (2015), a simple probabilistic framing of the explanatory virtues of inflation in comparison to the fine-tuned hot big bang model falls foul of chronic ambiguities in the non-arbitrary definition of probabilistic structure in a modern cosmological context. A first step in a more satisfactory, non-probabilistic framing of the explanatory virtues of inflation over the hot big bang is to move away from a reliance on probabilistic notions and, following Maudlin (2007), focus on the fact that the inflationary explanation is a *dynamical* one. In this spirit, Azhar and Loeb (2021) have recently argued that finely-tuned dynamical models sacrifice *explanatory depth* and that on this basis the explanatory superiority of inflation in comparison to the hot big bang can be established.

We will seek to build on this earlier work through an analysis of the explanatory virtues of inflation in comparison to bouncing cosmologies. In particular, we aim to extend Azhar and Loeb's work by application of a multi-dimensional conception of explanatory depth. In addition to the dimension of explanatory depth in terms of initial condition fine-tuning that Azhar and Loeb identify, we will propose two further dimensions: dynamical fine-tuning and autonomy from higher energy scales. We will demonstrate the particular relevance of these dimensions to the inflation vs. bouncing cosmology comparison in the context of dynamical instabilities and the so-called trans-Planckian problem. Our analysis will not lead us to a verdict with regards to explanatory superiority of these two rival approaches to cosmology. Rather, we will seek to clarify terms of the relevant debate, and in doing so, better understand the basis upon which scientists are in fact disagreeing. Furthermore, we will suggest that the different choices with regards to explanatory strategy have direct implications for the heuristics of model building in contemporary cosmology. The nature of the dispute can thus in part be understood in terms of a disagreement over different strategies regarding how best to constrain theoretical practice. Given the heavily unconstrained empirical environment of modern cosmology, such methodological diversity is well justified.

2. Primordial Paradigms: Bangs, Bounces, and Inflation

2.1. **Hot Big Bang Model.** The Hot Big Bang (HBB) model is the standard paradigm for model building in cosmology.[1] In its modern ΛCDM incarnation it describes an expanding universe evolving according to the FLRW (Friedmann-Lemaître-Robertson-Walker) solution of General Relativity, that is composed of $\sim$ 5% baryonic matter, $\sim$ 26% non-baryonic cold dark matter, and $\sim$ 69% dark energy Λ. This universe is both extraordinarily flat and homogeneous, with departures in homogeneity restricted to tiny density fluctuations of order $\sim 10^{-5}$ and precisely characterized by a nearly scale invariant power spectrum.[2]

The dynamics of any FLRW universe are generically captured by the two Freidmann equations:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho - \frac{k^2}{a^2} + \frac{\Lambda}{3}, \tag{1}$$

$$\dot{H} + H^2 \equiv \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p), \tag{2}$$

where a is the scale factor, ρ is the matter energy density, p is the pressure, k refers to the spatial curvature of the universe, Λ is the cosmological constant, and H defines the Hubble parameter. The HBB model takes the observed conditions and material constituents of the universe, and projects the evolution of the universe forward through these equations, as well as backwards towards an initial cosmic singularity.

[1] For a more detailed overview of modern cosmology together with attendant philosophical issues see (Ellis 2014; Chamcham et al. 2017; Azhar and Butterfield 2017; Smeenk and Ellis 2017).

[2] These findings have been confirmed by main cosmology probes such as COBE, WMAP, and Planck Smoot (1999); Bennett et al. (2013); Aghanim et al. (2020), and received strong independent support from measurements of supernovae Perlmutter et al. (1997), baryonic acoustic oscillations (BAO) Aubourg et al. (2015), galaxy rotation curves Sofue and Rubin (2001), gravitational lensing Ellis (2010), Lyman-alpha forest Weinberg et al. (2003), galaxy clusters Allen et al. (2011).

2.2. **Inflating and Bouncing Models.** Despite its successes, physicists believe that the HBB model ought to be modified and the most popular proposals for doing so fall into two main categories: inflating models (the dominant paradigm) and bouncing models (a distant secondary option).[3] Such extensions primarily operate through the particular mass-energy content (i.e., the energy density and pressure) that these models place into the Friedmann equations, which then determines the subsequent evolution of the universe in terms of the velocity and acceleration of the scale factor.

Inflation is a paradigm for building models within which the universe underwent a period of very rapid expansion at early times. There are, however, an extraordinary number of ways of implementing this paradigm. Physicists have cataloged and categorized *at least* 74 different models of single-field inflation, not to mention more complicated multi-field models (Martin et al. 2014). Here we will restrict our attention to single-field models as these represent the most common way of realizing the paradigm. Similarly, bouncing cosmologies are not so much a single theory, but rather a paradigm of related models that implements the idea that the universe can transition from expansion to contraction and vice-versa from contraction to expansion. There are likewise many ways of mathematically describing contracting and expanding scenarios, but we will restrict our attention to models that pair ultra-slow contraction ('ekpyrotic contraction') with a non-singular bounce as these models are of current interest as well as distinguish themselves from inflation by avoiding singularities (Ijjas and Steinhardt 2018).[4]

Inflation and bouncing models are primarily driven by a dynamical scalar field with an associated potential, that is coupled to gravity and dominates the mass-energy content of the universe during particular stages of evolution.

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] \tag{3}$$

The dynamics of these models can be schematically understood by tracking the equation of state that results from the particular scalar fields and potentials that describe such scenarios. Generically the equation of state for a scalar field is given by,

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}, \tag{4}$$

where $\dot{\phi}^2$ represents the kinetic energy of the scalar field and $V(\phi)$ represents the potential of the scalar field.

[3] There are even more options than this, including string gas cosmology (Brandenberger 2008) and emergent universe models (Ellis and Maartens 2004). However, we will not address these in this paper.

[4] Alternative ways of constructing bouncing cosmologies include singular bouncing cosmologies and non-singular matter bounce cosmologies, amongst others (Brandenberger and Peter 2017; Battefeld and Peter 2015).

2.2.1. *Inflation models.*

(1) *Inflation*: Inflation is driven by a scalar field (often called the 'inflaton') with a *positive* potential and these potentials are usually constructed so that there is a range of values for which the potential is relatively flat. When the potential is flat, the kinetic term $\dot{\phi}^2$ will be small as the field ϕ rolls down the potential function ('slow-roll inflation'). Under these circumstances, the potential $V \gg \dot{\phi}^2$ and $w \approx -1$.

(2) *Dynamics from Inflation*: This corresponds to a period of accelerating expansion ($\ddot{a} \gg 0$) and ($\dot{a} \gg 0$) as long as the potential dominates the equation of state, leading to an exponential expansion of space $a(t) \propto e^{Ht}$ that mimics the current epoch of dark energy dominated expansion (Baumann 2009).

2.2.2. *Bouncing models.*

(1) *Bouncing models*: Bouncing models aim to construct a universe where periods of expansion are followed by periods of contraction, and subsequent expansion. For instance, we are currently in a period of dark energy dominated expansion, which very well could be driven by a scalar field in a flat, positive range of its potential function (i.e., $w \approx -1$). Consider what happens if a relatively flat, positive potential V transitions to a steep, *negative* exponential, as is what happens in the kinds of 'ekpyrotic' models we are considering. Here, ρ cannot be negative because it represents the energy density of the universe. The kinetic term $\dot{\phi}^2$ becomes large and is approximately equal to V, which leads to a small positive number in the denominator of w. Yet, for negative V, the pressure p is also positive, which leads to a large positive number in the numerator of w. The result is that $w \gg 1$. Consider what this does to the dynamics of a universe evolving under the influence of mass-energy content with this equation of state.

(2) *Dynamics from Bouncing models*: When the scalar field begins rolling down this kind of potential, this changes the sign of the acceleration equation from $\ddot{a} > 0$ to $\ddot{a} < 0$ because $\frac{\ddot{a}}{a} = -\frac{8\pi G}{3}\left(\dot{\phi}^2 - V(\phi)\right)$, where V is a negative exponential and $\dot{\phi}$ is positive, contrary to the inflationary case where V is positive and dominates the equation. This decelerates the universe and eventually reverses expansion entirely. We can see this from recalling the first Friedmann equation $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$ and recognizing that a large, negative V offsets $\dot{\phi}$. Eventually, the negative acceleration will flip the sign of H to negative, taking $\dot{a} > 0$ to $\dot{a} < 0$. Following this period of contraction, an appropriate modification of gravity (via the dynamics of the scalar field) leads to a non-singular bounce well before the Planck scale and the potential rolls back to a positive value, causing the universe to revert back to expansion (Andrei et al. 2022; Ijjas and Steinhardt 2018; Steinhardt and Turok 2002a,b).

3. Explanatory depth as a theoretician's virtue

An adequate account of the dominant theoretical standpoint regarding model building in primordial cosmology requires some degree of consideration of the concept of scientific explanation. At first sight this observation may appear somewhat surprising, but the HBB model provides a valid explanans for the relevant cosmological explananda under virtually any extant account of explanation (Earman and Mosterin 1999; McCoy 2015). If the strong theoretical preference for modifications of HBB model is to be understood in explanatory terms, we are thus required to take a more nuanced and fine-grained approach to the characterisation of explanation. The most obvious approach would be to understand the explanatory weakness of HBB model, and strength of its rivals, in probabilistic terms. The HBB model may explain flatness, but by contrast inflation both explains flatness *and makes it overwhelmingly likely*. The problems with such a style of arguments have been carefully discussed in both the scientific and philosophical literature (Schiffrin and Wald 2012; Smeenk 2014; Curiel 2015; McCoy 2015, 2017; Gryb 2021). The key conclusion is that there exist chronic ambiguities in the non-arbitrary definition of probabilistic structure in a modern cosmological context. Depending on a judicious choice of formalisation one can justify both the statement that inflation is overwhelmingly likely and its negation.

The failure of a probabilistic explanatory approach might plausibly be taken to point away from explanatory considerations altogether, or at the very least, downgrade their relevance (McCoy 2015) and from an experimentally driven 'empiricist standpoint', such a view is appears well-justified. An alternative 'theoretician's standpoint', by contrast is that the inflationary explanation is indeed superior on account of having greater 'depth'. The theoretician's search for an alternative explanation to that provided by HBB is then a search for *deeper explanation*. How might we characterise the notion of explanatory depth more precisely in this context? And what is it that motivates theoretical cosmologists to be interested in deeper explanations?

The first key observation, noted en passant by Maudlin (2007), is that what cosmologists are really looking for is a *dynamical explanation*; an explanation that shifts the explanatory burden of the relevant observed facts from the initial conditions to the dynamical laws. Following Baumann (2009), we can note that the big bang model is perfectly adequate if we assume initial conditions that are extraordinarily flat and homogeneous (with tiny inhomogeneities possessing just the right amplitude and features for structure formation), but "a theory that explains these initial conditions dynamically seems very attractive". Guth and Steinhardt (1984) voiced a similar motivation in the initial development of inflation, saying that the "dynamics that govern the period of inflation have a very attractive feature: from almost any set of initial conditions the universe evolves to precisely the situation that had to be postulated as the initial state in the standard model".

We can understand the deployment of the idea of explanatory depth in the context of modern cosmology as aiming to make more precise the intuition behind such statements. In this context much valuable work has already been done in a recent paper by Azhar and Loeb (2021) (c.f. McCoy (2020)). Azhar and Loeb provide an account of explanatory depth that focuses on explanatory generalisations that have a *nomic character*, including dynamical explanations in our terms, and is specifically fitted to the explanatory context of modern cosmology.[5] Under Azhar and Loeb's account, one explanation is deeper than another when, for a fixed number of parameters and a single observable, there is a greater range of parameters that do not yield significant changes to the observable. In other words, the greater effective invariance of the explanandum variable for counterfactual values of the explanans variables is a marker of a deeper explanation. For example, an equilibrium explanation provides a deep explanation in the sense of a lack of initial condition fine-tuning, precisely because the explanandum of a final equilibrium state is suitably invariant under counterfactual values of the initial conditions part of the explanans. Stated another way, the less sensitive the explanatory relationship between explanans and explanandum is to counterfactual values of parameters within the explanans, the deeper the explanation is.

Azhar and Loeb provide a means to make precise the highly intuitive idea that cosmological models with fine-tuned initial conditions, such as HBB, suffer from an explanatory deficiency. The explanations provided by HBB models are such that parameters within the explanans can only take on a relatively small range of values without dissolving the explanatory relationship with the relevant explananda. By contrast, the extensions of HBB are such that there is a greater range of parameters under which the relevant explanatory connections are invariant. Azhar and Loeb persuasively argue that towards both the general claim that finely-tuned explanations sacrifice explanatory depth and the specific claim that the key reason for cosmologists preferring inflation to HBB can be understood in these terms. We are in agreement with this anlaysis and will provide a review of the key qualitative details in the following section (the reader to the original paper for the quantitative framing of the inflation case). There are four key aspects which we take need to be added to the Azhar and Loeb account to allow for a comparative study of inflation and bouncing paradigms in terms of explanatory depth.

The first is advocation of a multi-dimensional model of depth as suitable to the cosmological context. Following from the discussion of Ylikoski and Kuorikoski (2010) and Weslake (2010) (c.f. Jackson and Pettit (1992)) we take explanatory depth to be a non-unitary concept with different dimensions relevant to different domains. We further take cosmology to be a domain in which there are at least

[5] Azhar and Loeb explicitly acknowledge that their account extends earlier work on depth in explanatory generalisations due to Hitchcock and Woodward (2003). They note, however, that the specific structure of the two schemes, and in particular the dimension of depth, are markedly different, although plausibly complimentary. There are also connections to the work of Weslake (2010) and Ylikoski and Kuorikoski (2010) which we will comment on shortly.

three relevant dimensions. We will return to the implications that this has for the comparison between explanations in the final section.

The second aspect of our positive proposal is the suggestion that in the cosmological context a specific dimension of depth that is relevant is the absence of *dynamical* fine-tuning. This involves only a minor modification of Azhar and Loeb's notion of depth via the absence of *initial conditions* fine-tuning. Rather than one explanation being deeper than another when, for a fixed number of parameters and a single observable, there is a greater range of parameters that do not yield significant changes of the observable, we would now have that one explanation is deeper than another when, for a fixed number of parameters and a single observable, there is a greater range of appropriately similar dynamical maps that do not yield significant changes of the observable. For example, a renormalization group explanation provides a deep explanation in the sense of a lack of dynamical fine-tuning, precisely because the explanandum of critical behaviour is suitably invariant under a variety of counterfactual forms of the fundamental Hamiltonian that enters into the explanans.[6] In what follows we will argue that the key explanatory weakness of bouncing models is lack of depth along the dimension of dynamical fine-tuning.

The third aspect of our proposal involves characterisation of a further dimension of depth, this time a more significant departure from Azhar and Loeb's framework. Here we are drawing partial inspiration from the idea of Weslake (2010) that *autonomy* is a significant dimension of explanatory depth. In our characterisation, one dynamical explanation is deeper than another when the domain of applicability of the relevant dynamical laws and the physical scale of the explanans and explanandum are more closely matched.[7] The paradigmatic example of a dynamical explanation that is deeper in this autonomy sense are the explanations provided in continuum fluid mechanics. They are successful precisely because neither the explanans nor the explanandum require reference to the molecular scales, which are outside the validity of the relevant continuous fluid dynamical laws (Batterman 2018).

Explanations that lack depth along the dimension of autonomy typically will do so by having explanans that pertain to many orders of magnitude lower than the explanandum and are thus vulnerable to breakdowns in the reliability of our models at scales far removed from the phenomena to be explained. By contrast, explanations which are deep in the sense of autonomy may be compatible with a

[6] This is a greatly simplified illustrative example. For more on renormalization group explanations see Batterman (2000, 2002); Reutlinger (2014); Franklin (2018).

[7] For Westlake autonomy is the view that it is possible for non-fundamental sciences to provide deeper explanations than fundamental science on the basis of a greater degree of abstraction, where abstraction is applicability to a greater range of types of physical systems. Our conceptualisation of autonomy, by contrast, focuses upon applicability to a greater range of realisations of the mico-physical structure underlying one type of physical system. The distinction is thus broadly equivalent to that between universality and robustness (Batterman 2000, 2002; Gryb et al. 2020).

wide variety of scenarios for modelling scales far removed from the phenomena to be explained, and are thus in a precise sense 'modally safer'.[8]

In the cosmological context, the explananda are tied to the scale of the CMB and the domain of validity of the relevant physical laws is that in which we can trust a description of the universe in terms of the perturbed Friedman equations together with quantum field theory. Fascinatingly, not only do inflationary models generically lose out to bouncing models in the autonomy dimension of explanatory depth, but we find that the subset of inflationary models that are autonomous, those that satisfy the so-called trans-Planckian censorship conjecture (TCC), are found to sacrifice explanatory depth along the dimension of dynamical fine-tuning.

The fourth aspect of our positive account is drawn from the problem of comparing rival explanations that excel along different dimensions of explanatory depth. On our view, the choice problem for theoretical cosmologists implied by such comparisons can be understood in terms of differing attitudes with regard to heuristics for future model building. That is, a choice between explanations with different forms of *heuristic fecundity*. Most straightforwardly, the reason why explanations that lack depth qua initial condition fine-tuning are so unsatisfactory is, at least in part, due to the heuristic sterility of explanations of phenomena that appeal to special initial conditions. A more complex choice, that we will argue to be relevant to our particular context, is between explanations that are deeper along the dimensions of autonomy and dynamical fine-tuning. The heuristic value of an autonomous but dynamically fine-tuned explanation can be understood in terms of the positive heuristics provided for theoretical model building in a constrained space within limitations on both the realm of relevant empirical phenomena and the possible dynamical structures that can be implements. By contrast, the value of an explanatory approach that is deep in virtue of not being dynamically fine-tuned, but shallower in virtue of lack of autonomy, might be understood in broadly empiricist terms. We will return to these issues in the final section.

4. Initial conditions and explanatory depth

4.1. **Flatness Problem.** The *flatness problem* can be characterized as the realization that, for the universe to possess its observed flatness today, the initial value of the density ρ had to be extraordinarily close to what is known as its critical value.[9] The critical value for density ρ_c is simply the unique value for which $k = 0$ according to the first Friedmann equation and can be written as the ratio $\Omega = \rho/\rho_c$. This allows one to write the so-called curvature parameter Ω_k in the following suggestive

[8]It is worth noting here that our approach does not make reductive explanations necessarily shallow in the sense of autonomy, but rather cautions against a form of reductive explanation that proceeds solely by connecting models at one scale to phenomena at a very different scale.
[9]For a detailed discussion of the flatness problem see Holman (2018).

way:

(5)
$$\Omega_k = 1 - \Omega = \frac{k}{a^2 H^2}$$

One can then interpret the curvature parameter as follows. The scale factor, a, is proportional to the actual size of the universe and the Hubble horizon, H, is inversely proportional to how far an observer can actually see (i.e., in units where $c = 1$, the Hubble horizon is simply H^{-1}). Thus, the parameter Ω can be understood to represent the ratio of the apparent size of the universe to its actual size. If $\Omega = 1$, $\Omega_k = 0$ and $k = 0$, which corresponds to a flat universe. However, this is what is known as an unstable fixed point as the scale factor a and Hubble parameter H evolve over time. Thus, the curvature parameter Ω_k will diverge over time *regardless* of what its initial value was. A universe that is observed to be essentially spatially flat today requires a density that was extraordinarily close to the critical value.

The preceding discussion on inflationary dynamics immediately equips us to see how an inflationary epoch will offer a significant increase in explanatory depth when compared to the HBB model. Recall that $H = \dot{a}/a$ and that during inflation, $a(t) \propto e^{Ht}$. Thus, H is approximately constant while a grows exponentially, and consequently, Ω_k is driven towards zero. This is analogous to how curved spaces can appear flat when the space we are considering is sufficiently small compared to the actual radius of curvature. Inflationary dynamics completely turn the tables. Rather than requiring a finely-tuned, specially chosen density value to explain why the universe we see today is flat, seemingly any density value (that still lends itself to being described by an FLRW universe) will correspond to a flat universe. The HBB drives the universe away from flatness while inflation drives the universe towards flatness. $\Omega = 1$ becomes what is known as an attractor solution, where a huge variety of initial states naturally evolve towards it. When compared to the HBB model, inflation offers a deeper explanation because it allows for significantly more variation in parameter values without dissolving the explanatory relationship with the explanandum.

Does this analysis carry over to bouncing models? At first glance, it might seem surprising that it does. After all, a contracting universe is seemingly the opposite of an expanding universe. If exponential expansion flattens the universe, how could slow contraction accomplish the same? Furthermore, as a gets smaller during contraction shouldn't that amplify the curvature parameter rather than suppress it? The key insight is that during a slow contraction the behavior of H changes as well. A simple manipulation of the Friedmann equations shows that, when the equation of state $w \neq -1$, $H^{-1} \propto a^{\epsilon}$, where $\epsilon = \frac{3}{2}(1+w)$. For a contracting universe with an equation of state $w >> 1$, this means that the curvature parameter can be written as $\Omega_k \propto a^{2\epsilon}/a^2$. While a^2 decreasing in the denominator would seemingly blow up the curvature parameter, Ω_k is actually suppressed because the numerator $a^{2\epsilon}$ decreases faster. That is, the universe visible to an observer shrinks faster than the universe itself. Thus, a period of slow contraction mimics the effects of an inflationary period and likewise drives the universe towards flatness. Furthermore, this mechanism's effectiveness as an attractor is well established theoretically and has also been confirmed with detailed numerical simulations (Ijjas et al. 2020). This demonstrates that bouncing models that use this contraction mechanism offer an account of explanatory depth that is similarly compelling to their inflationary competitors.

4.2. **Horizon Problem.** The universe is also remarkably homogeneous, with departures from homogeneity showing up only at the level of 1 part in 100,000. Homogeneity itself is not by itself a problem as it would not be surprising for a system of particles in causal contact to attain conditions and properties that are nearly homogeneous, but the fact that the vast majority of the universe exists in causally disconnected patches makes observing such homogeneity a genuinely striking puzzle. This is known as the *horizon problem*. We have already encountered the Hubble horizon. This horizon forms a causal past light cone for each observer, and it is apparent that many of the points in the universe that we see today lie outside outside each other's present Hubble horizons, while displaying the same remarkable homogeneity. It has been estimated that at the time of recombination when the CMB photons first started streaming, the universe consisted of $\sim 10^5$ causally disconnected regions (Baumann 2009).

Inflating and bouncing cosmologies both approach this problem similarly. Rather than simply asserting that the initial conditions of the universe were such that causally disconnected regions happen to be homogeneous, they provide a mechanism such that these regions of the universe share a causal past, before then explaining why these regions *appear* to be causally disconnected to us now.

Prior to an inflationary phase, distant points in the universe share a causal past. During inflation, the rapid exponential expansion of space shrinks the so-called co-moving Hubble horizon $(aH)^{-1}$. Intuitively the co-moving Hubble horizon represents the fraction of the universe that is observable. Following exponential expansion, this co-moving Hubble horizon shrinks significantly, meaning that regions that were in prior causal contact now appear to be outside each other's past light cones. Inflation needs approximately 60 e-folds (i.e., the time interval in which the exponentially growing scale factor grows by a factor of e) to solve the horizon problem (Baumann 2009).

Coming to bouncing models, we find again that inducing a period of slow contraction manages to accomplish the same thing. Slow contraction causes this co-moving Hubble radius to shrink. Rather than shrinking via the exponential expansion of a as in inflation, the co-moving Hubble radius shrinks because a^{ϵ} declines faster than a. This is again due to the very different behavior of H given matter-energy content with an equation of state $w >> 1$. Upon transitioning to a subsequent expanding phase, the co-moving Hubble horizon proceeds to grow again, which results in regions that were previously in causal contact re-entering the horizon while appearing as if they were never in causal contact (Ijjas and Steinhardt 2018).

Both of these accounts allow the universe we observe today to share a common causal past, yet as Ijjas and Steinhardt (2018) explain, "removing the causal impediment is necessary but not sufficient to explain why the energy density distribution was so smooth at the time of last scattering". The aforementioned dynamical mechanisms responsible for resolving the horizon problem manage to explain this as well. Rather than postulating what would need to be very finely-tuned initial conditions within causally disconnected regions of the universe, both paradigms allow for a far larger variance in initial parameter values that eventually leads to the same observable state of interest. This is because even if there were larger inhomogeneities in these causally connected regions, the dynamics of inflation models dramatically stretch them out (Carroll 2014), whereas conversely the dynamics of bouncing models dramatically shrink them (Ijjas and Steinhardt 2018), with the end result being that the universe is homogenized. Here again, dynamics drive the explanatory power and depth of the respective models, and there is a significant reduction in the fine-tuning of initial conditions needed to account for the observed state of the universe.

4.3. **Scale-invariant density perturbations.** The previously alluded to inhomogeneities in the CMB are extremely important to cosmology because it is these density perturbations that ultimately seed the large-scale structure in the universe. It had long been argued that primordial density perturbations should be scale-invariant ($n_s = 1$) (Harrison 1970; Peebles and Yu 1970; Zeldovich 1972). The exact justifications differed, including theoretical and empirical arguments that a spectrum $n_s >> 1$ would produce too many black holes and that $n_s << 1$ would mean that the perturbations would not be large enough to properly seed cosmic structure (Smeenk 2018).[10] However, within the HBB model it is not at all clear where these density perturbations come from. Of course, you can put these highly tuned inhomogeneities in the initial conditions, but this would add yet another implausible degree of fine-tuning.

The prediction of scale-invariant density perturbations is counted as one of the most important successes of the inflationary paradigm. Within a few years of the theory first appearing, it became clear that inflation could source these perturbations and several researchers had independently derived a nearly scale invariant spectrum of fluctuations (Mukhanov and Chibisov 1981; Press 1980; Guth and Pi 1982; Hawking 1982; Bardeen et al. 1983). Intuitively, these perturbations represent tiny quantum mechanical variations in the field values of the inflaton itself. We can use standard quantum field theory to quantize these perturbations and compute their quantum statistics. Computing the power spectrum of these fluctuations gives

[10]This property has been measured and is frequently discussed as the scalar-spectral index n_s. Planck has measured this to be $n_s = 0.9649 \pm 0.0042$, with perfect scale-invariance corresponding to $n_s = 1$ (Aghanim et al. 2020).

(Baumann 2009):

$$\Delta^2_{\mathcal{R}}(k) = A_{\rm s}\,(k/k_*)^{n_{\rm s}-1}\,, \tag{6}$$

where $\Delta^2_{\mathcal{R}}$ is the power spectrum of density fluctuations $\mathcal{R}$, A_s is the amplitude, k is the fluctuation mode, k_* is a reference length scale usually taken to be the horizon crossing, and n_s is the scalar spectral index. $n_{\rm s}-1$ can be computed for any inflation model from analyzing its dynamics and $n_s \approx 1$ is a generic feature of single-field inflation models that satisfy the typical constraints in the inflationary paradigm such as having a relatively flat potential with a valid slow-roll approximation. This is normally computed directly from the from of the scalar field's potential $V(\phi)$.

Bouncing paradigms predict a nearly scale-invariant spectrum as well through a similar procedure (with some important differences, as we shall see later). Similar to the flatness and horizon problems, both inflating and bouncing paradigms invoke dynamics that drive the values of important features of the universe towards those that are actually observed, and both offer similar increases in explanatory depth over the standard HBB model by shifting the burden of explanation from finely-tuned initial conditions to dynamics.

5. Dynamics and explanatory depth

In the context of explanations within primordial cosmology, dynamics, like initial conditions, is something that can be varied within the explanans. This may seem strange since we are used to working with fixed dynamical laws while varying parameters like initial conditions or the number of relevant forces, but the important idea in this context is that inflation and bouncing cosmologies are not themselves specific theories with fixed dynamical laws, but rather paradigms with many different dynamical realizations. In other words, we are interested in how effective these research programmes are at providing a greater range of dynamical maps appropriately suited to describing the observable universe, for a given set of parameters and observables. In this context, we can examine the space of dynamical realizations of the paradigms, vary the relevant dynamical structure, and evaluate these competing paradigms on the sensitivity of their explanatory relationships to dynamical variations. In this section, we will show that this is one manner in which these paradigms start to diverge in their explanatory depth, with inflation emerging as the deeper explanation in terms of this dimension of dynamical fine-tuning.

5.1. **Primordial gravitational waves.** A positive detection of primordial gravitational waves, or tensor perturbations is a major goal in observational cosmology. Two of the primary reasons these perturbations are so significant are as follows: (i) they produce a distinctive B-mode polarization that cannot be mimicked by the types of scalar perturbations we have already detected (Zaldarriaga and Seljak 1997) and (ii) such a distinctive signature would be seen by many cosmologists as strong evidence for inflation because inflation generally predicts significant production of primordial gravitational waves (Baumann and Zaldarriaga 2009). It is important to note that such a detection does not uniquely single out inflation. As Brandenberger (2019) emphasizes, primordial gravitational waves can be produced both by topological defects in standard HBB cosmology or in particular realizations of other competing early universe paradigms. Thus, if tensor perturbations were detected, one would have to carefully look at additional data points such as the tensor spectral tilt to differentiate competing theories.

Such tensor perturbations can be directly related to the energy scale of an inflating or contracting mechanism because the ratio between tensor and scalar perturbations r can be manipulated to directly constrain V and the energy scale of such a mechanism (Baumann 2009). The exponential expansion that inflation generates is expected to occur at near GUT-scale energies, leading to a relatively high production of tensor perturbations and tensor-scalar ratio r. On the other hand, the slow contraction mechanism employed by the kinds of ekpyrotic bouncing models we are considering[11] occurs at lower energies that are much further away from the Planck scale, leading to significantly lower expectations for tensor perturbations and r (Ijjas and Steinhardt 2019).

The most recent Planck constraints indicate that $r < .10$ (Aghanim et al. 2020). This is not a problem in the slightest for bouncing models considering that r is expected to be unobservably small. However, these recent constraints actually rule out many of the simplest and most studied inflation models that broadly fall under the a category known as 'power-law inflation'. Following the Planck results detailed assessments of the paradigm have found that 'plateau inflation' models are now strongly favoured by the data (Chowdhury et al. 2019; Martin 2016; Akrami et al. 2020). While these models are not prima facie unreasonable[12], this episode illustrates that the inflation paradigm has had to invoke some non-trivial degree of dynamical fine-tuning to account for present observational constraints on the tensor-scalar ratio. On the contrary, bouncing models face no such constraints given that on any dynamical realization of this particular bouncing paradigm the tensor-scalar ratio r should not be observable.

5.2. **Scale-invariant density perturbations.** While generically predicting unobservable tensor perturbations and a low r value is certainly a point for the bouncing paradigm, things get a little more complicated when coming back to the scalar perturbations. While both inflation and bouncing paradigms can produce results consistent with the scale-invariant spectrum of density perturbations seen in cosmological probes, inflation does so in a more natural way.

[11]It should be noted that some other kinds of bouncing models that, such as a pure matter bounce scenario, can lead to significant production of primordial gravitational waves (Brandenberger 2019).

[12]Although, they have been criticised as requiring more parameters and fine-tuning than power-law models in order to achieve the same desired outcomes Ijjas et al. (2013).

In an expanding, inflating universe the growing scalar modes that are understood to be the all-important seeds of structure formation are actually decaying modes in the corresponding time-reversed, contracting universe. Similarly, the growing modes in a contracting universe map onto the decaying modes in the corresponding expanding universe that necessarily follows once contraction transitions into expansion (Lehners et al. 2007; Creminelli et al. 2005). The dynamics responsible for inflation naturally source scale-invariant density perturbations through these growing modes. However, a bouncing cosmology needs to reckon with the fact that the growing modes during the contraction phase become decaying modes during subsequent expansion, but the decaying modes that would naturally grow in the subsequent expansion have already decayed away.

One way to solve this problem is to introduce an additional, 'spectator' scalar field that couples to the ekpyrotic scalar field (Lehners et al. 2007; Levy et al. 2015). While the details are beyond the scope of this paper, the coupling of the spectator and ekpyrotic fields can generate a scale-invariant spectrum of density fluctuations. Other solutions include choosing particular matching conditions to match growing modes in the contracting phase to growing modes in the expanding phase, but this is arguably less desirable as it requires very specific choices of matching conditions (Brandenberger and Peter 2017).

There is thus is a sense in which the bouncing cosmology paradigm requires dynamical fine-tuning in a way that the inflation paradigm does not. Inflation and its many dynamical realizations generically predict density perturbations with the features we observe, whereas the basic dynamical realizations of bouncing cosmologies require supplementation in the form of additional dynamical variables to generically produce the same results.

5.3. **Avoiding instabilities.** Perhaps the biggest hurdle that bouncing models have had to overcome is the existence of instabilities. Within physics, 'instability' can have a few different meanings. It could refer to an unstable fixed point, such as we saw in the example of the flatness problem. This is not in and of itself disqualifying, it just means that we don't expect the system to remain in such a state for very long. Instabilities can manifest in far more concerning ways though, in the form of an unbounded Hamiltonian. These instabilities are frequently called 'ghost' or 'gradient' instabilities and are considered to be so problematic because they are both perturbatively ill-defined and can lead to the infinite production of non-physical, negative energy states (Rubakov 2014; Wolf and Lagos 2019). These frequently manifest themselves in the form of 'wrong-signed' terms in a theory's Lagrangian, such as a minus sign in front of the kinetic term. Theories with such instabilities are not generally considered to be physically viable.

This pathological behavior can be traced to the fact that bouncing cosmologies violate the *null energy condition* (NEC). The NEC holds that for any form of material content, $p + \rho \geq 0$. Inflation does not violate this constraint as this condition holds during an expansion phase with $w \approx -1$; however, bouncing cosmologies necessarily violate this condition when they transition from contraction to expansion. That is, $\dot{H} \propto -(p+\rho) \leq 0$ during contraction, and flipping $\dot{H}$ from $\dot{H} < 0$ to $\dot{H} > 0$ when contraction reverses to expansion requires violating this energy condition (Ijjas and Steinhardt 2018).

Ijjas and Steinhardt (2016, 2017, 2019) solved this problem by introducing modifications to gravity during the bounce phase. They took inspiration from Horndeski gravity, which is the most general form of scalar-tensor theory of gravity leading to second order equations of motion (Horndeski 1974). In particular, they make use of the so-called $\mathcal{L}_4$ interaction, which includes a non-minimal coupling between the scalar field and the Ricci scalar as well as non-standard kinetic terms. In doing so, they proved that implementing this particular variant of modified gravity within non-singular bouncing models allows for a stable violation of the NEC before, during, and after the bounce phase, free of pathologies.

This reflects an interesting way in which the dynamical realizations of the bouncing paradigm need to be dynamically fine-tuned (i.e., introduce highly specific modified gravity dynamics). Not all dynamical fine-tuning is bad. When examining the space of dynamical realizations of these paradigms, it is not at all problematic for some degree of dynamical fine-tuning to enter the picture as new observations further constrain models. Indeed, this can actually be desirable as it narrows the space of acceptable theories and helps theorists and experimentalists focus on those models which are more likely to be successful. However, dynamical realizations of the bouncing paradigm need not only be fine-tuned to accord with some observations (as does inflation), but they must also be dynamically fine-tuned to be viable in principle. There is a precise sense in which bouncing models need to thread the needle dynamically in order to be physically viable, whereas dynamical realizations of the inflation paradigm face no such hurdles. Inflation possesses more explanatory depth in this dimension of dynamical fine-tuning because the paradigm itself can sustain the explanatory relationship with the observable universe in a way that is far less sensitive to variations of its dynamical variables. Bouncing models and their relevant dynamical variables, on the other hand, necessarily need to be wedded to very specific modified gravity dynamics, along with any associated baggage, to maintain their physical and explanatory viability.

5.4. **The entropy problem.** As was first pointed out by Penrose (1980, 1989), a universe that emerges from a gravitational singularity would naturally be expected to be maximally entropic as all degrees of freedom should be excited (matter, radiation, gravitational, etc.). Here gravitational entropy should be significant and is understood to be associated with the Weyl curvature tensor, which contains tidal effects and gravitational waves. Furthermore, it is not clear that inflation could begin from a state that is expected to be dominated by gravitational tidal effects and inhomgeneities. Yet, the universe we observe in the CMB is nearly maximal in its thermal entropy and negligible in its gravitational entropy, which already corresponds to a very low initial entropy state. This implies that there must have been an extraordinarily special initial state for inflation to occur at all. A non-singular bouncing model seemingly avoids these entropy puzzles because its dynamics naturally protect it from the singularities that lead to such large expectations for the initial entropy of the universe.

While researchers within the bouncing paradigm consider resolving this problem to be a major advantage over inflation, the explanatory comparison is difficult to frame in the terms we have introduced. In part, this is because the aforementioned issues regarding probability measures mean that arguments based upon appeal to relative typicality are not well defined (Schiffrin and Wald 2012). Furthermore, the inflation community has also pointed out that a full resolution of questions surrounding singularities will likely only come with a theory of quantum gravity that describes Planck scale physics (Guth et al. 2014b). If one has every expectation that we can develop a theory that will provide a window of exploration into these questions, combined with the understanding that these various cosmological paradigms are effective field theories, we can see why inflation theorists are less concerned by the entropy problem and singularity avoidance.

This explanatory consideration illustrates a further aspect of explanatory virtue which relates to the relationship of a cosmological paradigm with the wider explanatory background. Competing early universe paradigms are developed with different physical and theoretical motivations in mind, so it is not surprising that one paradigm may engage more closely with the explanatory problems most relevant to the theoretical background it emerges from, while another paradigm may be useful for resolving specific conceptual issues that are judged to be important by those pursuing the paradigm. These considerations are relevant to a more general discussion of explanation, but do not directly map onto our particular notions of explanatory depth.

6. Autonomy and explanatory depth

Recall that one dynamical explanation is deeper than another along the dimension of autonomy when the domain of applicability of the relevant dynamical laws and the physical scale of the explanans and explanandum are more closely matched. The trans-Planckian problem in cosmology can be understood as a threat to the autonomy of the explanations for key cosmic phenomena, such as the scale-invariance of the density fluctuations, based upon a breakdown in separation of scales. In this section we will consider the particular relevance of the problem to our explanatory comparison between inflationary and bouncing models. We will find that the problem gives us give reason to believe that the explanations offered by inflationary models are in general terms less deep than those offered by bouncing cosmology along the dimension of autonomy. We will also find that in the context of the so-called Trans-Planckian Censorship Conjecture (TCC), the sub-set of compatible inflationary models are such that they have greater depth in the dimension of autonomy, however this comes at a cost with regard to their depth in the dimension of dynamical fine-tuning.

6.1. **Inflation and the Planck-scale physics.** The trans-Planckian problem for inflationary cosmology can be stated as follows. First, we observe that scalar perturbations result from tiny fluctuations in the fields driving cosmological dynamics. For an inflating space-time, the exponential expansion present in any such scenario stretches these fluctuations exponentially. Second, we note that inflation needs to last for a minimum length of time in order to solve the horizon and flatness problems. Third, when inflation lasts for a sufficient duration of time, fluctuation modes that originated as trans-Planckian modes (i.e., modes that are smaller than the Planck length) can be stretched such that they exit the Hubble radius and 'freeze'. These frozen modes undergo a quantum to classical transition, re-enter the horizon, and are understood to seed the scale-invariant density perturbations that form large scale structure, a cosmological explanandum of considerable importance that has already been featured prominently in this analysis. Thus, at least some of these *classical* fluctuations originated as *quantum* fluctuations smaller than the Planck length. In other words, this means that these trans-Planckian modes are described by the cosmological framework comprised of the perturbed Friedmann equations and quantum field theory, when it is clear that this lies well outside this framework's domain of validity. The problem can then be stated qualitatively in terms of a *sensitive dependence* between the prediction of a scale-invariant spectrum in inflationary cosmology and *hidden assumptions* about super-Planck scale physics (Martin and Brandenberger 2001).

Before providing a more detailed description of the problem in terms of a concrete cosmological model, let us briefly set out the implications of the problem for the explanatory depth of inflation. First, and most obviously, the trans-Planckian problem implies that for the inflationary explanation of the scale-invariant spectrum to obtain, one needs to add supplementary conditions relating to the relevant hidden assumptions regarding the super-Planck scale physics. Most prominently, as we shall discuss shortly, this seemingly requires some assumption regarding the adiabaticity within the Planck scale initial conditions or dynamics. This explicitly sacrifices at least some degree of explanatory depth along either the initial condition or dynamical fine tuning dimensions. Even more problematically, such a modification to the explanation has dire consequences for the explanatory depth along the dimension of autonomy. The physical scale of the explanans makes reference to physics at the Planck scale, which is well beyond the domain of applicability for the explanans' dynamical laws. The mismatch with the physical scale of the explanandum is then around thirty orders magnitude (using a comparison between the Planck temperature and the CMB temperature). We can thus see why the trans-Planckian problem means that the inflationary explanation for the scale-invariant spectrum is rendered shallow along the dimension of autonomy and at least somewhat shallower along the dimensions of fine-tuning (either initial condition or dynamical depending on the formulation of the problem).

To give a more concrete explanation of the problem we can build upon the analogy with a the trans-Planckian problem in black hole thermodynamics.[13] Soon after Hawking's famous prediction that black holes produce thermal radiation (Hawking 1975) it was noted that the derivation of Hawking radiation makes essential use of a breakdown in the separation between micro- and macro-scales (Gibbons 1977). Following the formulation of Helfer (2003), it can be demonstrated that modes measured as cis-Planckian by stationary observers near future time-like infinity must have originated as trans-Planckian modes from the point of view of free-falling observers less than a Planck unit of proper time before falling through the horizon. The Hawking radiation incident on a finite, stationary detector far away from the black hole can therefore be traced back to what are, for free-falling observers, trans-Planckian energies at the horizon.[14]

Various responses to the black hole trans-Plackian problem have been represented within the literature.[15] Most relevant for our purposes are approaches that appeal to modified dispersion relations (Unruh and Schützhold 2005; Himemoto and Tanaka 2000; Barcelo et al. 2009). Here the idea is that quantum gravity corrections to the Hawking spectrum can be modelled in terms modifications to the dispersion relation of the high-energy Hawking modes. The late-time flux of Hawking modes is explicitly computed with the modified dispersion relations using a straightforward generalisation of Hawking's original derivation. Provided the modifications to the dispersion relation satisfy a number of plausible criteria, the Hawking spectrum can be shown to be insensitive to the modifications. The thermal spectrum of radiation is thus robust against a wide variety of potential modifications to the dispersion relation and even if the modes responsible for black hole radiation do originate from the trans-Planckian regime, the thermal properties of such radiation will very likely be insensitive to such Planck scale physics.

The contrast with the cosmological trans-Planckian problem can then be explicitly made by applying a similar modified dispersion relation approach in the context of inflationary models. The key idea is to consider non-trivial relation between the physical frequency and comoving momentum of fluctuation modes (Martin and

[13]This problem is subject to a detailed philosophical treatment in (Gryb et al. 2020) and in what follows we build on that discussion, in particular §2.3 and §4.3

[14]For more on the trans-Planckian problem for Hawking raidation see (Unruh 1981; Jacobson 1991, 1993; Unruh 1995; Brout et al. 1995). Accessible introductions are (Jacobson 2005, §7) and (Harlow 2016, pp.36-8).

[15]Of particular interest are arguments based upon respectively: i) the Unruh effect and equivalence principle (Agullo et al. 2009); ii) horizon symmetries (Birmingham et al. 2001; Banerjee and Kulkarni 2008; Iso et al. 2006); iii) the adiabatic theorem and particular 'nice slice' representation Polchinski (1995); and iv) connections between non-thermal vacuum states and violation of the semi-classical Einstein equations (Candelas 1980; Sciama et al. 1981). See Harlow (2016); Wallace (2018); Gryb et al. (2020) for further discussion.

Brandenberger 2001, 2003; Brandenberger and Martin 2013). Most straightforwardly, we can consider scalar metric fluctuations and modify the standard linear dispersion relation such that:

$$\omega^2 = k^2, \rightarrow \omega = F(k)$$

where $k \equiv \frac{n^2}{a^2}$, n and k are the comoving and physical wave-numbers respectively, and F is assumed to be a non-linear function.

The modifications to the dispersion relation can then be fed into the dynamics of simple inflationary models and the quantitative effects on the resulting power-spectrum studied. What can be shown is that the scale invariance of the power spectrum depends sensitively on the form of modification. In particular, it can be shown that it is only if the modified dispersion relation satisfies an adiabaticity constraint in the UV sector that we can avoid the spectrum of cosmological perturbations acquiring a blue tilt whose spectral slope can well exceed current limits. This amounts to a specific choice of quantum gravity dynamics that is compatible with adiabaticity. The modified dispersion relation approach thus directly implies that inflationary explanations for the scale-invariant spectrum are required to sacrifice explanatory depth in terms of both autonomy and the dynamical fine-tuning dimensions.[16]

An alternative approach is to *not* evolve the fluctuation modes during the time period in which their wavelength is smaller than the length scale of new physics. This corresponds to introducing a time-like 'new physics hypersurface' on which special initial conditions are imposed. As noted by Brandenberger and Martin (2013), under such an approach the trans-Planckian problem has simply been shifted to the problem of choosing initial conditions on the new physics hypersurface. Furthermore, one version of this approach consists in explicitly starting modes off in their local adiabatic vacuum. In essence, this converts the dynamical fine-tuning at the trans-Planckian scales needed in the modified dispersion relation approach to a form of initial condition fine-tuning. Moreover, once more, such an approach will inevitably involve scarifies of explanatory depth along the dimension of autonomy.

6.2. **Bouncing cosmology and Planck-scale physics.** The relationship between various proposals for bouncing cosmology and the physics of the Planck scale is a key factor in evaluating the models. As mentioned before, one of the primary motivations for the introduction of a bounce is avoidance of the initial singularity. A generic feature of bouncing cosmologies is that an initially contracting phase connects us to the currently expanding one via a bounce that takes place at some minimal value of the scale factor hence avoiding the blow up in scalar curvature invariants generically associated with the cosmic big bang singularity (Hawking and

[16]We should note here that the modified dispersion relation based arguments towards this conclusion are not entirely without controversy See discussions of Kaloper et al. (2002, 2003) and Brandenberger and Martin (2002); Burgess et al. (2003).

Penrose 1970; Ellis and Schmidt 1977; Thorpe 1977).[17] On one hand, the physical realisation of such a bounce in many cases involves explicit reference to the Planck scale in terms of some form of quantum gravitational mechanism. On the other hand, a general feature of bouncing models is that the bounce time can be expected to be order of magnitude above the Planck time. There is thus a quite general sense in which the bouncing cosmology paradigm can be expected to provide explanations which are autonomous from the Planck scale.

At a more specific level, in the context of the trans-Planckian problem, we can find good reasons to expect that explanatory depth along the dimension of autonomy will obtain for explananda such as the scale invariance of the spectrum of density fluctuations. In particular, while fluctuations will shrink somewhat during a contraction phase, as long as the bounce remains far from the Planck regime, the fluctuations of interest never come close to approaching the trans-Planckian regime (Cai 2014; Brandenberger 2021). According to Brandenberger and Peter (2017), if the energy scale of the bounce corresponds to the same energy scale as in typical inflation models, then the wavelengths of scales corresponding to observed cosmic microwave background anisotropies were always larger than 1 mm. This means that the relevant explanations can be provided in a manner such that they are autonomous from the Planck scale without requiring further dynamical or initial condition fine-tuning.[18]

6.3. **Inflation and the trans-Planckian censorship conjecture.** Let us now return our discussion to inflationary models and consider a third potential response to inflation's trans-Planckian problem: the recently formulated *Trans-Planckian Censorship Conjecture (TCC)* (Brandenberger 2021; Bedroya and Vafa 2020; Bedroya et al. 2020). The TCC holds that observers such as us are necessarily screened from trans-Planckian modes, in analogy with the Cosmic Censorship Conjecture (CCC), which, in its weak form, can be plausibly interpreted to assert that for 'physically reasonable' spacetimes, there can be no singularities visible for observers at 'late' times (i.e. near future null infinity) (Penrose 1969, 1973). In both cases the idea is that there is a physical constraint that prevents observers being exposed to radiative modes which have in their past probed arbitrarily high frequencies.

In qualitative terms, the TCC amounts to assertion that the trans-Planckian problem can be circumvented *by fiat* such that structure formation in the early universe is autonomous with regards to the physics of the Planck regime (Schneider

[17]It is worth noting here the contrast with inflation where it has been shown that the Penrose-Hawking singularity theorems can be extended to show that a broad range of 'physically reasonable' eternal inflationary universes are necessarily inextenable and geodesically past incomplete, and therefore singular in the relevant sense (Borde et al. 2003).

[18]A similar argument can run for the autonomy of the bouncing cosmological explanation of the smoothness of the universe from potential destabilisation effects of chaotic evolution in the asymptotic BKL regime. See Ijjas and Steinhardt (2018) and Battefeld and Peter (2015) for detailed dicussion.

2021). In more quantitative terms, the TCC consists in the specification of a condition which enforces the autonomy of inflationary models from the Planckian scale. This condition can be expressed explicitly via the relation (Brandenberger 2021):

$$\frac{a_f}{a_i}\ell_p < \frac{1}{H_f}, \tag{7}$$

where inflation begins at scale factor a_i and ends at scale factor a_f. This equation implies that a fluctuation the size of the Planck length ℓ_p cannot be amplified such that it is greater than the Hubble radius at end of inflation. In other words, such trans-Planckian modes are not allowed to exit the horizon and 'freeze', only to re-enter the horizon as classical modes later. As long as this inequality holds, observers are protected from trans-Planckian modes.[19]

Assuming the truth of the TCC, an inflation model will necessarily be autonomous from Planck-scale physics: the explanations offered for the relevant cosmic explananda are stipulated to be such that the relevant physical scales are closely matched. We do not need to speculate about initial conditions on trans-Planckian scales in order to offer an explanation for classical large scale structure formation. Inflationary explanations with the TCC in hand are deep in the explanatory dimension of autonomy since the explanans, explananda, and domain of applicability of the relevant dynamical laws are all within the same broad order of magnitude.

The problem is that this success along the autonomy dimension of explanatory depth comes with an attendant cost. The inequality (7) represents an upper bound on the amount of inflation that can occur without violating the TCC; however, there is also a lower bound if inflation's dynamical, causal explanations are to function properly. The lower bound is given by the following (Brandenberger 2021).

$$\frac{a_i}{a_0}\frac{1}{H_0} < \frac{1}{H_i}, \tag{8}$$

where a_0 denotes the current scale factor and H_0 denotes the current Hubble radius, while i denotes the beginning of inflation. The inequality (8) implies that modes that are within the horizon now must have been in causal contact (i.e., within the Hubble radius H_i) at the beginning of inflation. This is necessary for inflationary dynamics to offer a causal explanation of structure formation.

As Brandenberger shows, the two bounds given by (7) and (8) can be combined to constrain the energy scale of inflation, such that inflation would have had to occur at $\sim 10^8$GeV, or several orders of magnitude lower than the GUT scale ($\sim 10^{15}$GeV) that inflation has traditionally been believed to operate within. This has significant implications for inflationary dynamics. Among other things, it implies that the inflaton potential must be dynamically fine-tuned in order to match the observed amplitude of scalar fluctuations, while also operating within these constraints on the energy scale (Brandenberger 2021; Bedroya et al. 2020).

[19]In this context, there is a connection between the TCC and the Swampland Conjectures in string theory (Bedroya and Vafa 2020).

The implication, within our framework for evaluating depth of explanations, is that inflation with the TCC trades explanatory shallowness in terms of autonomy for explanatory shallowness in terms of dynamical fine-tuning. The problem of choosing between inflationary explanations with and without the TCC, like that of choosing between inflation and bouncing explanations, then becomes one of *weighting* dimensions of depth. We will consider this issue and its broader implications for both cosmology and the nature of scientific methodology in the final section.

7. Dimensions of depth and heuristics

In this paper we have understood explanatory depth as a non-unitary concept with different dimensions relevant to different domains. The domain of primordial cosmology is one in which the three most relevant dimensions can be understood as i) initial condition fine-tuning; ii) dynamical fine-tuning; and iii) autonomy. Following the insightful analysis of Azhar and Loeb (2021), we diagnosed the explanatory preference of contemporary cosmologists for the inflationary paradigm over the HBB paradigm as being based upon the greater explanatory depth along the dimension of initial condition fine-tuning. This observation encodes a primarily descriptive rational reconstruction of the preference of cosmologist for inflation over the HBB.

Where things become more complex, and our account starts to blend the normative and descriptive, is in the explanatory comparison between inflationary and bouncing paradigms. In that context, we have isolated what we take to be the principal factor motivating the explanatory preference of most, although not all, cosmologists for the inflationary approach. Both paradigms successfully provide explanations that avoid initial condition fine-tuning and offer far more depth than the HBB model that preceded them. However, the paradigms can be differentiated along the dimension of dynamical fine-tuning. Due to the need to avoid unphysical instabilities, models within the bouncing paradigm can be understood to display a form of dynamical fine-tuning which renders the relevant explanations lacking in depth along this dimension. That is, the explanatory relationship between explanans and explanandum is highly sensitive to variations in the dynamical structures *because* the physical viability of such models requires a significant degree of dynamical fine-tuning.

Taken on its own, dynamical fine-tuning allows us to appreciate why most theorists favour an inflationary account of the early universe. However, things become more controversial when we consider the explanatory dimension of autonomy. In this context, the trans-Planckian problem afflicts inflationary models, but not bouncing models, and represents a severe challenge to the autonomy of the relevant explanations, particularly with regard to the scale invariance of the power spectrum. This bifurcates the explanatory merits of inflation into two different routes.

One possibility is that we accept that inflation's explanatory merits are shallow along this dimension of autonomy. In this case, inflation could potentially provide invaluable access to trans-Planckian physics and quantum gravity. However,

Dimension of Depth	Hot Big Bang	Inflation (no TCC)	Inflation (with TCC)	Big Bounce
Initial condition fine-tuning	✗	✓/✗	✓	✓
Dynamical fine-tuning	✓	✗/✓	✗	✗
Autonomy	✓	✗	✓	✓

TABLE 1. Deeper explanations are marked by a ✓ and correspond to *less* fine-tuning. The ✗/✓ in Inflation (no TCC) reflects a choice with regard to how to avoid the trans-Planckian problem.

in this scenario, inflation ends up being a bridesmaid rather than *the* bride, in that it stands adjacent to the trans-Planckian physics that is actually responsible for the salient features of the observable universe, but is itself not the main actor. This is a trade-off that many physicists would be willing to make, but in this case we must acknowledge that inflation does not carry the same explanatory weight most often attributed to it as much of this explanatory burden would then be shifted to the relevant trans-Planckian details.

The other possibility is to make a move to restore the autonomy of inflation's explanatory power. The trans-Planckian problem can be ameliorated by appeal to the trans-Planckian Censorship Conjecture. Such a move, in turn, then requires inflationary models to be themselves dynamically fine-tuned in a non-trivial way so as to avoid violating the conjecture. The result of this move is that both inflationary and bouncing models display a lack of explanatory depth in terms of dynamical fine-tuning. The main source of the difference between the paradigms is then that bouncing models need to be dynamically fine-tuned to be viable in principle, whereas inflation models need to be dynamically fine-tuned in order for the desired explanatory relationships to hold. Descriptively, it does seem like the dynamical fine-tuning evident in the bouncing case is more harshly judged because it concerns the physical viability of the model, rather than the dynamical fine-tuning invoked to match observational constraints. The full situation can be concisely represented in Table 1.

Where does this leave us? One the one hand, our analysis provides a degree of clarity with regard to the reasons why cosmologists so strongly disagree with regard to the extra-empirical merits of the various paradigms: on our account they may simply be arguing at cross purposes by relying upon comparisons along incommensurable dimensions of depth. On the other hand, the result of this explanatory incommensurablity is to blunt the normative utility of our analysis so far as we would like to provide a means through which to recommend scientist towards the deepest explanation available. On our analysis, there is no fact of the matter with regards to whether the explanations provided by inflationary or bouncing paradigms are deeper because there are multiple relevant dimensions of depth without a common measure of comparison.

What we would like to propose, on a more constructive note, is that the explanatory preference with regard to the different dimensions of depth can be understood in terms of differing attitudes with regard to heuristics for future model building. In particular, the reason why explanations that lack depth qua initial condition fine-tuning are so unsatisfactory is, at least in part, due to the heuristic sterility of explanations of phenomena that appeal to special initial conditions.[20]

The choice between explanations that are deeper along the dimensions of autonomy and dynamical fine-tuning might be similarly framed in terms their respective forms of heuristic fecundity. The heuristic value of an autonomous but dynamically fine-tuned explanation can be understood in terms of the positive heuristics provided for theoretical model building in a constrained space within limitations on both the realm of relevant empirical phenomena and the possible dynamical structures that can be implements. By contrast, the value of an explanatory approach that is deep in virtue of not being dynamically fine-tuned, but shallower in virtue of lack of autonomy, might be understood in broadly empiricist terms: the failure of autonomy opens a window for plausible empirical constraints connecting vastly different energy scales (c.f. Schneider (2021)). In this sense, trade-offs between dimensions of explanatory depth might be interpreted as encoding differing methodological stances rather than a choice between strictly incommensurable alternatives.

[20]Here we would similarly categorise explanations for temporal asymmetry that rely on the so-called past hypothesis Earman (2006); Gryb (2021).

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