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# Initial conditions for inflation

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ABSTRACT

Within the $\alpha$-attractors framework we investigate scalar potentials with the same pole as the one featured in the kinetic term. We show that, in field space, this leads to directions without a plateau. Using this, we present a proposal, which manages to overcome the initial conditions problem of inflation with a plateau. An earlier period of proto-inflation, beginning at Planck scale, accounts for the Universe expansion and arranges the required initial conditions for inflation on the plateau to commence. We show that, if proto-inflation is power-law, it does not suffer from a sub-Planckian eternal inflationary stage, which would otherwise be a problem. A simple model realisation is constructed in the context of $\alpha$-attractors, which can both generate the inflationary plateau and the exponential slopes around it, necessary for the two inflation stages. Our mechanism allows to assume chaotic initial conditions at the Planck scale for proto-inflation, it is generic and it is shown to work without fine-tuning.



## 1. Introduction

Cosmic inflation [1,2] accounts for the fine-tuning problems of hot big bang cosmology (horizon and flatness), explains the origin of structure (primordial curvature perturbation) and it is fully consistent with observational data [3]. Recent observations are setting stronger bounds on tensor-to-scalar ratio $r$, limiting the maximal scale of inflation and favour flatter inflationary potentials, featuring an inflationary plateau, which may be motivated by modifications of gravity [2], quantum field theory [4,5] or both [6].

Inflation models with a plateau are characterised by a scalar potential limited from above by the energy scale of inflation, which due to the constrains from observations cannot be bigger than the scale of a grand unified theory (GUT) $m_{\rm GUT} \sim 10^{16}\,$GeV. This gives the rise to the problem of initial conditions, described in e.g. Ref. [7]. The issue is the following: Let us assume that the Planck scale $M_P \sim 10^{19}\,$GeV is a natural scale for setting initial conditions for the pre-inflationary Universe. Assuming an expanding Universe, since the density scale of the inflationary plateau is at least $(\frac{M_P}{m_{\rm GUT}})^4 \sim 10^{12}$ times smaller, there may be a long period of a decelerated expansion of the pre-inflationary Universe, during which the cosmological horizon is dominated by inhomogeneities. To avoid this, one needs to assume that the Universe is homogeneous over exponentially many horizons at the Planck scale, which leads to massive fine-tuning of initial conditions. This is because for a long time it has been considered that inflation needs a homogeneous patch of at least a Hubble volume to begin with.

However, recently, it has been argued that, even inhomogeneous (and anisotropic) initial conditions for the large field inflation may still allow inflation to take hold [8–10]. Nevertheless, the analysed scenarios assume an initially non-contracting space, which in the case of exponentially many causally disconnected regions seems to be another source of massive fine-tuning.[1]

In fact, the problem can be more acute because the Planck-scale Universe lacks the initial boost towards the expansion of space, so an initially expanding space without inflation is non-trivial to postulate. Refs. [8,9] considering inhomogeneous initial conditions, assume expansion (at least on average) such that they stay clear from the quantum complications of spacetime foam at the Planck scale. However, one can argue that, because in spacetime foam the extrinsic curvature can change by quantum fluctuations, one could not have sustained expansion, so no net expansion, i.e. on average $\dot{a} = 0$. Now, to get from no expansion to expansion you need $\ddot{a} > 0$, that is inflation. Thus, it is inflation that produces the Universe expansion. Without it, the Universe remains at the Planck scale.

[1] In fact, a varying extrinsic curvature (which determines whether space is expanding or contracting) has been partially considered only in Ref. [9] and only under special initial conditions (e.g. constant initial velocity of the inflaton). Space was assumed to be predominantly expanding, while the authors acknowledge that "In general, we should expect the local expansion rate to be a function of spatial position that can be both initially expanding or collapsing. ...We reserve the general case for future work."

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Indeed, this is supported by some early work of Brout, Englert and Gunzug [11], and Zel'dovich and Vilenkin [12] (see also Ref. [13]). More recently, results from the theory of Causal Dynamical Triangulations [14] also indicate the crucial role of high energy cosmological constant (which in the realistic case should be replaced by the flat inflationary potential) in the process of creating a classical Universe from the quantum foam. Therefore, we see that we need to start inflation at the Planck scale at density much larger than the inflationary plateau.

To solve or ameliorate the problem of initial conditions one can include the internal curvature of the FRW metric [15,16], assume compact topology [17], consider the Jordan frame Planck scale as a physical one [18] (for modified gravity inflation) or include a proto-inflationary phase, which would homogenise the Universe at the Planck scale [19–21].

In the latter case case of multi-phase inflation, the scenario suffers from the problem of extensive eternal proto-inflation; when quantum corrections overwhelm the classical evolution of the proto-inflaton field and, in many horizons, the inflaton cannot reach its minimum. This issue is especially dangerous when the degree of freedom that is responsible for proto-inflation is eternally inflating at sub-Planckian density. While undergoing eternal inflation, the proto-inflaton cannot stop inflating, while the plateau inflaton may keep rolling towards its minimum, leaving no space for a GUT-scale accelerated expansion.

In this paper we propose another idea, namely a two field inflationary scenario with an initial power-law inflation[2] and a subsequent plateau inflation as proto-inflation and GUT-scale plateau-inflation respectively. We show that, even though starting at the Planck scale, power-law proto-inflation evades the sub-Planckian eternal inflation problem and lasts only a limited number of e-folds, such that the system safely lands on the plateau of the slow-roll GUT-scale plateau-inflation. A similar proto-inflation model is presented in Ref. [20]. In contrast to that proposal, our model is generic, in that any plateau model of inflation can be accommodated, while our proto-inflaton and plateau-inflaton fields are unrelated and may correspond to degrees of freedom of different sectors of the theory. Our proposal can be naturally realised in the context of the $\alpha$-attractors [4,5], in a different way than in Ref. [20].

We consider natural units, where $c = \hbar = 1$ and Newton's gravitational constant is $8\pi G = m_P^{-2}$, with $m_P \equiv M_P/\sqrt{8\pi} = 2.43 \times 10^{18}$ GeV being the reduced Planck mass.

## 2. The model

Our proposal is that the inflationary scalar potential is of the form

$$V = V(\varphi) + V(\psi)\,, \tag{2.1}$$

where $V(\varphi)$ is featuring the inflationary plateau with $V(\varphi) \lesssim m_{\rm GUT}^4$ and is responsible for potentially long slow-roll, GUT-scale plateau-inflation, which generates the observed curvature perturbation, while $V(\psi)$ is responsible for the limited proto-inflation period which accounts only for the initial conditions and is negligible afterwards. Initially, we expect

$$V(\varphi) \lesssim m_{\rm GUT}^4 \ll V(\psi) \lesssim m_P^4\,. \tag{2.2}$$

We argue that proto-inflation can be power-law with the scale factor growing as $a \propto t^p$, where $p$ is a constant parameter (with $p > 1$ for inflation). Thus, during this period, $V(\psi) \propto \exp\left(\sqrt{\frac{2}{p}}\psi/m_P\right)$, where without loss of generality we have chosen $\psi > 0$ [23]. In that way, proto-inflation may last only a limited number of e-folds, while sub-Planckian eternal inflation can be altogether avoided.

[2] The model of power-law inflation has firs been studied in Ref. [22].

### 2.1. The danger of an extensive diffusion zone on the hill

We motivate considering power-law inflation by avoidance of an extensive diffusion zone, i.e. one which corresponds to sub-Planckian energies, on the hills of the plateau valley.

The expectation value of a scalar field $\phi$ during inflation changes due to its classical slow-roll evolution as[3] $|\dot\phi| \simeq |V'|/3H$ and due to its quantum fluctuations by $\delta\phi/\delta t = H^2/2\pi$, i.e. given by the Hawking temperature per Hubble time. Many inflation models have regions (called diffusion zones) where the quantum fluctuations overwhelm the classical evolution of the field(s). Inside the diffusion zone the scalar field is oblivious of the potential so it does not roll towards its minimum, while it may exit the diffusion zone only via chaotic quantum fluctuations. If, during inflation, the system finds itself inside a diffusion zone, then it undergoes eternal inflation [24]. This means that, even though the system may typically exit the diffusion zone eventually, there will always be locations in physical space where the system remains trapped in the diffusion zone so that inflation continues.

In our setup we consider two stages on inflation. The proto-inflaton field $\psi$ is driving the initial stage, taking the system from Planckian density down to GUT-scale density, where the second stage of inflation takes place, driven by the plateau-inflation field $\varphi$. Thus, the GUT-scale plateau direction (parametrised by $\varphi$) corresponds to a valley in field space, while its walls (the hills) correspond to the orthogonal proto-inflaton direction (parametrised by $\psi$), see Fig. 1.

The problem with an extensive diffusion zone on the hill is the following. During proto-inflation, the plateau-inflaton field $\varphi$, being light (the plateau is very flat), undergoes intense quantum fluctuations that send it to large values along the plateau. If proto-inflation is eternal then the build-up of the $\varphi$ condensate becomes very large and so the typical expectation value of $\varphi$ moves further down the plateau valley and away from minimum (taken at $\varphi = 0$). However, the plateau-inflaton is not light near the minimum, where the valley becomes steep and curved. When the plateau-inflaton finds itself in this region it no more undergoes eternal inflation but instead it does roll towards its minimum.[4] Now, this region is larger when $H$ is smaller, because the slope of the potential along the valley can overcome the "quantum kicks". Thus, if the diffusion zone on the hill is extended, then eternal inflation on the hill may occur even for $H$ much smaller than $m_P$, in which case the region of where the plateau-inflaton allows slow-roll towards the minimum (when $V'(\varphi) > H^3$) is enlarged.

This means that there is a preference against an extended diffusion zone on the hill, because, were there one, then the proto-inflaton $\psi$ could still be in it (so undergoing eternal inflation) for sub-Planckian density. However, the more $H$ decreases the more the diffusion zone in the valley for the plateau-inflaton $\varphi$ withdraws from the minimum, so the more likely it becomes that $\varphi$ finds itself outside its diffusion zone and begins to roll towards the minimum, while $\psi$ is still eternally inflating on the hill. In this case, there may be no plateau-inflation left, once the proto-inflation finishes.

As a simple choice, consider a proto-inflaton field with $V(\psi) = \frac{1}{2}m^2\psi^2$ potential such that the hills of the valley correspond to the quadratic rise of the potential. The eternal inflation regime corresponds to $\psi \gtrsim m_P\sqrt{m_P/m}$, which is well below the Planck density scale, for which $\psi \sim m_P^2/m$. Taking $m \sim m_P$ would push the eternal inflation limit towards the Planck scale but the potential would

[3] The prime and the dot denote derivative with respect to the inflaton field and the cosmic time respectively.

[4] Indeed, in Refs. [8,9] it is shown that, if the plateau inflaton, in a given region, finds itself in the potential minimum, this drags the field into the minimum in neighbouring areas too.