Dynamical Inflaton Coupled to Strongly Interacting Matter

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According to the inflationary theory of cosmology, most elementary particles in the current Universe were created during a period of reheating after inflation. In this Letter, we self-consistently couple the Einstein-inflaton equations to a strongly coupled quantum field theory as described by holography. We show that this leads to an inflating universe, a reheating phase, and finally a universe dominated by the quantum field theory in thermal equilibrium.

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Introduction.—Cosmological inflation is a paradigm of extended exponential expansion of our Universe at its earliest moments. Because of the rapid expansion, this leads to a quickly cooling Universe, which at the end reheats to the hot plasma that then forms the big bang. The exponential expansion provides a natural explanation why our Universe is to a good approximation homogeneous, even though different parts could not have been in causal contact since the big bang.

One of the main uncertainties in inflation is the so-called "exit" to the hot big bang scenario. Because of the many e-foldings of expansion, a natural end state of inflation would be an empty universe, so the question is how ordinary and possibly dark matter arise in inflation. "Standard inflation" posits a distinct reheating stage where the inflaton undergoes a damped oscillation in the inflaton potential while interacting with and heating up ordinary matter [1–5] (see Refs. [6–10] for reviews). A different scenario is called "warm inflation" [11–14]. In this case there is always a subdominant but significant part of the Universe made up of ordinary or dark matter. It is only when the inflaton rolls down the potential that subsequently ordinary matter becomes dominant, thereby making a smooth transition to the big bang.

Many microscopic models have been proposed for either scenario, all of which have advantages and disadvantages (see, e.g., [15]). In standard inflation there is often a "preheating" phase, where bosonic fields undergo an exponential increase in density due to resonant amplification. This, however, leads to a nonthermal state of which it is not *a priori* clear if it thermalizes in time for the big bang scenario. Recently there has been renewed interest in warm inflation, since it may avoid some of the conjectured constraints on consistent quantum gravity theories that arise from the swampland program [16,17].

In this Letter, we present a toy universe in which the inflaton is coupled to a strongly coupled quantum field theory (QFT) (see also [18] for an earlier attempt). A unique and important aspect of strongly coupled QFTs is that they approach hydrodynamics and thermalize as fast as possible [19,20]. At the relevant energy scales even the strong coupling constant of quantum chromodynamics is small due to asymptotic freedom, so this QFT can be thought of as a hidden sector that exists at some high energy scale. The strongly coupled QFT is described using holography, which is a remarkable duality arising from string theory that can describe strongly coupled QFTs in terms of a classical anti–de Sitter universe of one higher dimension. The extra dimension can be thought of as energy scale, whereby for a thermal state there exists a black hole horizon in the infrared.

While we present a general framework for reheating with a strongly coupled QFT, in this Letter we will present a simple model example to illustrate its dynamics. Quite strikingly we find that the model qualitatively reproduces many of the features of warm inflation (see Fig. 1 for a cartoon). This includes an extended period of cooling and exponential expansion, an inflaton rolling down the potential, heating up the QFT, and finally the transition to a universe dominated by QFT matter in a thermal state.

In this Letter, we use standard inflationary terminology in describing the evolution of the constructed universe, but

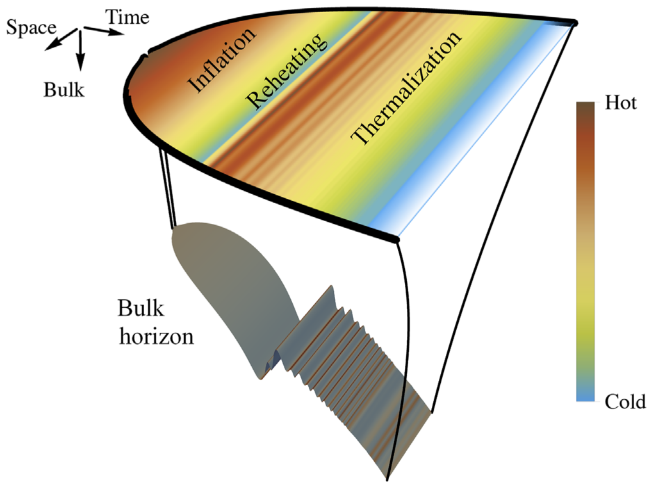

FIG. 1. Illustration of the bulk and boundary during holographic reheating.

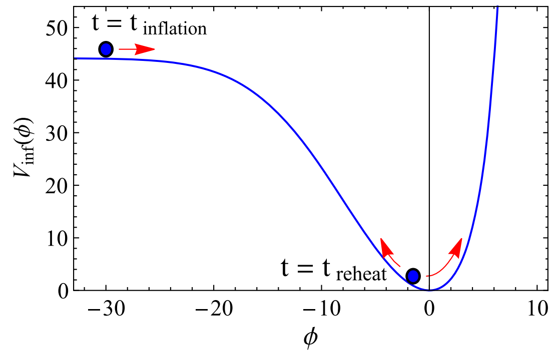

FIG. 2. The inflaton starts at $\phi = -30$ and then slowly rolls down the inflaton potential as shown. At the bottom of the potential the inflaton oscillates and reheats the universe due to its coupling to the QFT.

we stress that in this work we do not attempt to construct a realistic model for our Universe. Rather, we focus on a qualitative general description of an inflaton interacting with a strongly coupled QFT with a specific evolution as an explicit example.

Model.—In order to model the energy transfer of the inflaton field to matter on a dynamical spacetime, we evolve self-consistently the Einstein-inflaton equations together with the energy-momentum tensor for strongly coupled matter described by holography. The total action of this model consists of two different sectors and an interaction part:

$$S = S_{\rm EH+inf} + S_{\rm hol} + S_{\rm int}. \tag{1}$$

The first sector $S_{\rm EH+inf}$ consists of four-dimensional Einstein gravity with a dynamical inflaton field, $S_{\rm hol}$ models the dynamics of a strongly coupled QFT via the gauge/gravity duality in terms of a five-dimensional gravity dual, and $S_{\rm int}$ accounts for the direct coupling between these two sectors.

The first term in Eq. (1) is the standard Einstein-Hilbert plus Klein-Gordon action with a nontrivial scalar field potential $V_{\rm inf}(\phi)$, which together describe the dynamics of the spacetime and the inflaton ϕ in the four boundary dimensions:

$$S_{\rm EH+inf} = \int d^4x\sqrt{-\gamma}\left[\frac{R}{2\kappa_4} - \frac{1}{2}\gamma^{ij}\partial_i\phi\partial_j\phi - V_{\rm inf}(\phi)\right]. \tag{2}$$

Here, κ_4 parametrizes the strength of the gravitational interaction and R is the Ricci scalar of the spacetime metric γ_{ij}. We define this metric to be of Friedmann-Lemaître-Robertson-Walker type

$$ds^2 = \gamma_{ij}dx^i dx^j = -dt^2 + a(t)^2 d\vec{x}^2, \tag{3}$$

where $a(t)$ is the scale factor that determines the expansion of the spacetime via the Einstein field equations. We consider an inflaton potential as shown in Fig. 2, which is given by

$$V_{\rm inf}(\phi) = v_0 + \frac{9}{8}e^{\frac{2}{3}(\phi-\phi_m)} - 45e^{-\frac{1}{50}(\phi-\phi_m)^2}, \tag{4}$$

where ϕ_m and v_0 are fixed by demanding that the potential and the inflaton vanish at the global minimum $V_{\rm inf}(0) = V'_{\rm inf}(0) = 0$.

The strongly coupled matter sector is defined via the gauge/gravity duality by the five-dimensional bulk action

$$S_{\rm bulk} = \frac{2}{\kappa_5}\int d^5x\sqrt{-g}\left[\frac{1}{4}\mathcal{R} - \frac{1}{2}(\partial\Phi)^2 - V_{\rm bulk}(\Phi)\right], \tag{5}$$

where κ_5 denotes the bulk gravitational coupling, $\mathcal{R}$ is the Ricci scalar associated to the bulk metric $g_{\mu\nu}$, and Φ is a bulk scalar field with potential

$$V_{\rm bulk}(\Phi) = \frac{1}{L^2}\left(-3 - \frac{3\Phi^2}{2} - \frac{\Phi^4}{3} + \frac{11\Phi^6}{96} - \frac{\Phi^8}{192}\right), \tag{6}$$

where L denotes the length scale of the asymptotic anti–de Sitter metric $g_{\mu\nu}$, which we set to unity. The bare bulk action $S_{\rm bulk}$ needs to be renormalized by adding appropriate counter terms $S_{\rm bdry}$ that render the holographic action $S_{\rm hol} = S_{\rm bulk} + S_{\rm bdry}$ in Eq. (1) finite on-shell. The renormalized action $S_{\rm hol}$ then defines a holographic bottom-up model [21] for a strongly coupled QFT with regular renormalization group flow between its conformal ultraviolet and infrared fixed points and broken conformal symmetry in between. The mass of the bulk scalar field $m^2 = (\partial^2 V/\partial\Phi^2)|_{\Phi=0} = -\frac{3}{2}$ determines the conformal scaling dimension $\Delta = 3$ of the dual operator $\mathcal{O}$ via the relation $m = \sqrt{\Delta(\Delta - 4)}$. It is important to stress that bottom-up means this model does not originate from a full string theory and it is hence unclear if the model is or can be UV-completed. Instead, bottom-up models (see also holographic QCD [22,23]) have proven useful as effective theories for strongly coupled physics to learn general qualitative lessons. The model is furthermore nonconformal and hence we can study the effects of the bulk viscosity that would not be present in simpler conformal models.

Finally, there is an interaction term in the effective action that couples the inflaton via the vacuum expectation value (VEV) of the scalar operator $\langle\mathcal{O}\rangle = \mathcal{O}_{\mathrm{QFT}}/\kappa_5$ to the holographic sector:

$$S_{\mathrm{int}} = \int d^4x\sqrt{-\gamma}U(\phi)\mathcal{O}_{\mathrm{QFT}}, \tag{7}$$

where the free function $U(\phi)$ defines the coupling of the model. In the QFT the inflaton hence acts as a source for the scalar operator $\mathcal{O}$, where the source is given by the asymptotic boundary value of the bulk scalar $\Phi_{(0)} = U(\phi)$.

The total energy momentum tensor in the boundary theory consists of three parts:

$$T_{ij} = \mathrm{diag}(\mathcal{E},\mathcal{P},\mathcal{P},\mathcal{P}) = T^{\mathrm{inf}}_{ij} + \mathcal{T}^{\mathrm{QFT}}_{ij} + T^{\mathrm{int}}_{ij}, \tag{8}$$

where $\mathcal{E}$ and $\mathcal{P}$ denote energy density and pressure, respectively. The first part is the usual expression for the energy-momentum tensor of a scalar field:

$$T^{\mathrm{inf}}_{ij} = \partial_i\phi\partial_j\phi - \gamma_{ij}\left(\frac{1}{2}\partial_k\phi\partial^k\phi + V_{\mathrm{inf}}\right). \tag{9}$$

The second term $\mathcal{T}^{\mathrm{QFT}}_{ij} = \mathrm{diag}(\mathcal{E}_{\mathrm{QFT}},\mathcal{P}_{\mathrm{QFT}},\mathcal{P}_{\mathrm{QFT}},\mathcal{P}_{\mathrm{QFT}})$ is the VEV of the holographic energy momentum tensor, where $\mathcal{E}_{\mathrm{QFT}}$ and $\mathcal{P}_{\mathrm{QFT}}$ denote the corresponding energy density and pressure. The third term results in an energy-momentum contribution due to the direct coupling between the inflaton and the holographic sector:

$$T^{\mathrm{int}}_{ij} = -\frac{2}{\sqrt{-\gamma}}\frac{\delta S_{\mathrm{int}}}{\delta\gamma^{ij}} = U(\phi)\mathcal{O}_{\mathrm{QFT}}\gamma_{ij}. \tag{10}$$

The total energy momentum tensor is covariantly conserved when using the on-shell condition for the scalar field $\nabla^i T^{\mathrm{inf}}_{ij} = -U(\phi)\partial_j\mathcal{O}_{\mathrm{QFT}}$ together with the Ward identity for the holographic energy-momentum tensor $\nabla^i\mathcal{T}^{\mathrm{QFT}}_{ij} = -\partial_j U(\phi)\mathcal{O}_{\mathrm{QFT}}$, where ∇^i is the Levi-Civita connection associated to γ_{ij}.

In the standard holographic dictionary the QFT lives on a fixed (curved) background spacetime γ_{ij} and also the scalar source $\Phi_{(0)}$ acts as a free parameter that can be specified arbitrarily. Here, however, we require them to satisfy the equations of motion that follow from the boundary action [Eq. (1)]. For the Friedmann-Lemaître-Robertson-Walker line element [Eq. (3)], one obtains the standard Friedmann equations together with a scalar field equation for the inflaton that is coupled to $\mathcal{O}_{\mathrm{QFT}}$:

$$H(t)^2 = \frac{\kappa_4}{3}\mathcal{E}(t), \tag{11}$$

$$\frac{a''(t)}{a(t)} = -\frac{1}{2}(\kappa_4\mathcal{P}(t) + H(t)^2), \tag{12}$$

$$\phi''(t) = \partial_\phi U(\phi(t))\mathcal{O}_{\mathrm{QFT}}(t) - 3H(t)\phi'(t) - \partial_\phi V_{\mathrm{inf}}[\phi(t)], \tag{13}$$

where $H(t) = a'(t)/a(t)$ is the Hubble rate and the total energy density and pressure are given by

$$\mathcal{E} = \mathcal{E}_{\mathrm{QFT}} + V_{\mathrm{inf}}(\phi) + U(\phi)\mathcal{O}_{\mathrm{QFT}} + \frac{1}{2}\phi'^2, \tag{14}$$

$$\mathcal{P} = \mathcal{P}_{\mathrm{QFT}} - V_{\mathrm{inf}}(\phi) - U(\phi)\mathcal{O}_{\mathrm{QFT}} + \frac{1}{2}\phi'^2. \tag{15}$$

The $-3H(t)\phi'(t)$ in Eq. (13) is the standard friction term that brings the inflaton to rest, but we note that with the holographic coupling the scalar VEV $\mathcal{O}_{\mathrm{QFT}}$ also contributes. Importantly, both $\mathcal{E}_{\mathrm{QFT}}$ and $\mathcal{O}_{\mathrm{QFT}}$ depend on the full bulk geometry, including explicit dependencies on $\phi(t)$, $\phi'(t)$, $a(t)$, and $a'(t)$. In addition, $\mathcal{O}_{\mathrm{QFT}}$, $\mathcal{E}_{\mathrm{QFT}}$, and $\mathcal{P}_{\mathrm{QFT}}$ are not independent, but related via the trace Ward identity

$$\gamma^{ij}\mathcal{T}^{\mathrm{QFT}}_{ij} = \mathcal{E}_{\mathrm{QFT}} - 3\mathcal{P}_{\mathrm{QFT}} = -U(\phi)\mathcal{O}_{\mathrm{QFT}} + \mathcal{A}, \tag{16}$$

where $\mathcal{A}$ is the conformal anomaly [24,25]. The variational principle in holography with dynamical boundary conditions, the holographic renormalization of S_{hol}, together with the resulting expressions for $\mathcal{E}_{\mathrm{QFT}}$, $\mathcal{P}_{\mathrm{QFT}}$, $\mathcal{O}_{\mathrm{QFT}}$ and the corresponding anomaly corrected Ward identities as well as the thermodynamic properties of the holographic QFT are given in the Supplemental Material [26].

Solution method.—Computing the time evolution of the scale factor $a(t)$, the inflaton $\phi(t)$, and the energy-momentum tensor $T_{ij}(t)$ for a given set of initial conditions requires one to solve the corresponding initial value problem for Eqs. (11) to (13) together with the dual bulk initial-boundary value problem in a self-consistent way. For this we follow essentially the same procedure as in [35], but promote $\Phi_{(0)}(t) = U(\phi(t))$ to a dynamical field that satisfies Eq. (13).

At the initial time $t = t_{\mathrm{ini}}$ we need to specify initial conditions for the energy density $\mathcal{E}_{\mathrm{QFT}}(t_{\mathrm{ini}}) = \mathcal{E}^{\mathrm{ini}}_{\mathrm{QFT}}$, the inflaton $\phi(t_{\mathrm{ini}}) = \phi_{\mathrm{ini}}$ and its time derivative $\partial_t\phi(t_{\mathrm{ini}}) = \phi'_{\mathrm{ini}}$, as well as a profile for the bulk scalar $\Phi(r, t_{\mathrm{ini}}) = \Phi_{\mathrm{ini}}(r)$, along the holographic coordinate r and whose asymptotic value is consistent with the inflaton $\lim_{r\to\infty} r\Phi_{\mathrm{ini}}(r) = U(\phi_{\mathrm{ini}})$. Equations (11) to (13) then determine ϕ''_{ini} as well as the Hubble rate H and its time derivative H'. It is

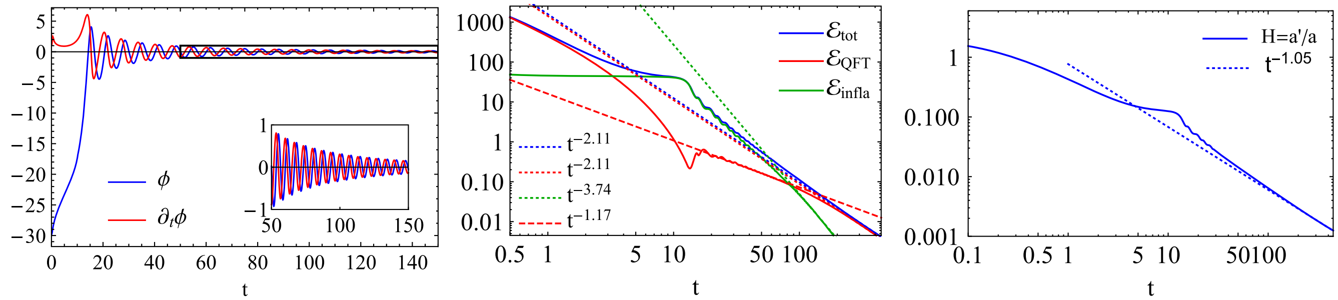

FIG. 3. Left: After an initial stage where the QFT cools down (until about $t = 3$), the inflaton ϕ slow-rolls down until it starts oscillating in the potential well. Middle: Initially the dynamics is dominated by the QFT energy until about $t = 3$. After this the universe inflates until the inflaton reaches the bottom of the potential at $t = 14.3$. The inflaton oscillations then reheat the QFT universe. Right: Initially the Hubble rate decreases due to the dilution of the QFT energy until $t \approx 5$. After this, the universe inflates at a constant exponential rate until about $t = 14.3$ when the inflaton is at the bottom of the potential.

important to note that $\mathcal{O}_{\rm QFT}$ depends on H' and also that $\mathcal{E}_{\rm QFT}$ depends on $\partial_t^2\phi$. The equations are hence coupled and lead to a sixth-order polynomial equation that we solve numerically [36]. After the initialization we evolve H and $\partial_t\phi$ using Eqs. (12) and (13). As in [35] for the boundary metric we replace $\partial_t^3\phi$ and $\partial_t^4\phi$ derivatives that appear in the regularized bulk equations by their solutions in terms of the near-boundary expansion.

For the evolution presented in this work, we set $\kappa_5 = 1/9$, $\kappa_4 = (2\pi/5625)$, $U(\phi) = \lambda\phi$ with $\lambda = 1/30$, and use $\mathcal{E}_{\rm QFT}^{\rm ini} = 13275$, $\phi_{\rm ini} = -30$, $\phi'_{\rm ini} = 3/10$, and $\tilde{\Phi}(r) = -6 + 120/r - 300/r^3$ as initial conditions, where $\tilde{\Phi}(r)$ is defined by $\Phi(r) \equiv \Phi_{\rm NB}(r) + r^{-3}\tilde{\Phi}(r)$ and $\Phi_{\rm NB}(r)$ contains near-boundary terms up to $\mathcal{O}(r^{-2})$ and $\mathcal{O}[r^{-4}\log(r)]$. These parameters are tuned to get an evolution that shows both an inflationary and a reheating phase.

Results.—Figure 3 shows the resulting evolution of the inflaton (left), energy density (middle), and Hubble rate (right) of the model. The early phase is dominated by the high initial energy density of the QFT, but at $t = 3.27$ the inflaton energy density becomes dominant and the universe enters a phase of relatively constant exponential expansion. Later at $t = 14.3$ the inflaton reaches the bottom of the potential and starts oscillating rapidly. These oscillations form sources for the QFT energy, which then increases from a minimum of $\mathcal{E}_{\rm QFT} = 0.21$ at $t = 13.5$ to a subsequent maximum of $\mathcal{E}_{\rm QFT} = 0.64$ at $t = 17.3$. Crucially this reheating continues, which is apparent from the relatively slow scaling $\mathcal{E}_{\rm QFT} \propto t^{-1.17}$ of the QFT energy density. The universe then keeps expanding at increasingly slower rates, thereby cooling down both the inflaton and the QFT energy density. At late times the QFT energy density is dominant.

In Fig. 4 we show the evolution of the pressure of the QFT (left), the inflaton (middle), as well as the total pressure (right). After a very short far-from-equilibrium stage, we see that the QFT pressure is well described by the equations as given by viscous hydrodynamics, much like what was found in [35]. After the inflaton rolls down, however, we see that the reheating pushes the QFT significantly out of equilibrium. After this the system settles down to equilibrium rather quickly. At late times the evolution is completely dominated by the QFT, which is now close to its conformal IR fixed point where $\mathcal{P}_{\rm QFT} = \mathcal{E}_{\rm QFT}/3$ (Fig. 4, right). It is important that this fast approach to hydrodynamics

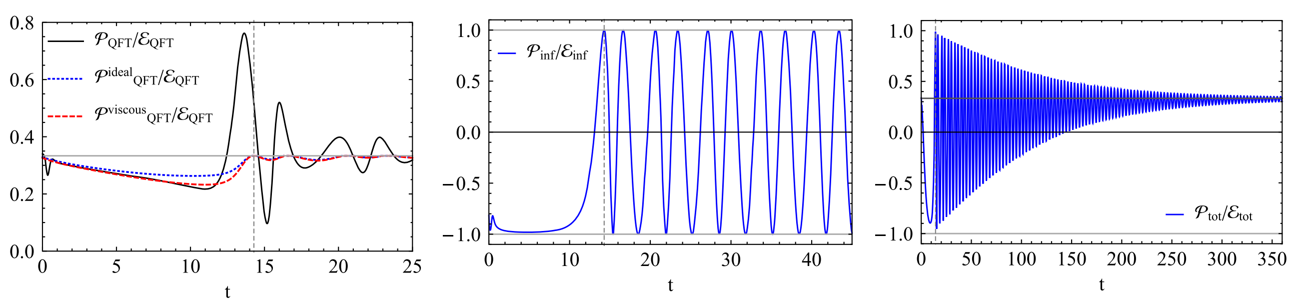

FIG. 4. Left: The pressure over energy density of the QFT together with the predictions from ideal and viscous hydrodynamics. After a brief initial hydrodynamization period, the QFT is well described by viscous hydrodynamics until the inflaton sources the QFT out of equilibrium. Middle: The equivalent figure for the inflaton. Initially it is dominated by the potential having $\mathcal{P} = -\mathcal{E}$ after which it oscillates around the minimum. Right: We show the total pressure over energy density, which is initially dominated by the QFT, then by the inflaton and at late times again by the reheated QFT.

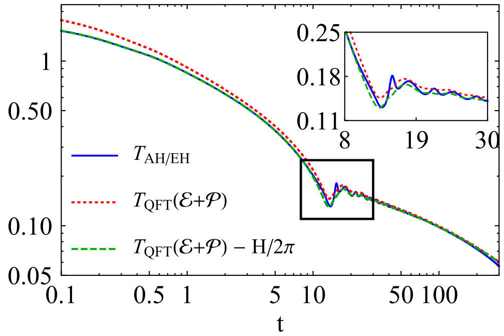

FIG. 5. We show in blue the temperature as measured by the surface gravity of the apparent horizon and the event horizon, which are numerically indistinguishable. The dotted red line is the temperature of the QFT as determined by the equation of state. The green dashed line shows that the horizon temperatures are lower than the QFT temperature by exactly the de Sitter temperature $T_{\rm ds} = H/2\pi$.

(also called "hydrodynamization" [19,37]) is a general feature for strongly coupled theories that contrasts with perturbative mechanisms and is hence expected to be a qualitative feature of reheating in holographic theories.

In Fig. 5 we show in blue the temperature obtained from the surface gravity of the apparent horizon $T_{\rm AH}$ (explicit formulas are given in the Supplemental Material [26]). We verified that the event horizon location is numerically indistinguishable from the apparent horizon throughout the evolution, which is expected for a theory in thermal equilibrium but unlike the vacuum de Sitter case of [38]. During the entire evolution the temperature is dominated by the QFT energy $\mathcal{E}$. Since $H^2 \propto \mathcal{E}$ and $T^4_{\rm QFT} \propto \mathcal{E}$ at late times, the temperature of the cosmological horizon $T_{\rm dS} = H/2\pi \propto T^2_{\rm QFT}$ is negligible if $T_{\rm QFT}$ is small. At early times we notice a significant difference between the apparent horizon temperature and the temperature obtained from the QFT equation of state. This can be fully explained by the fact that the universe is expanding. Indeed, subtracting $T_{\rm QFT} \to T_{\rm QFT} - H/2\pi$ accurately describes the complete evolution with the exception of a small off-equilibrium time window where the inflaton approaches the minimum of the potential for the first time. This is consistent with the analytical solution of a thermal plasma expanding in de Sitter space for a strongly coupled conformal theory (see, e.g., [39,40]). We verified that the exact same subtraction describes the evolution in Fig. 9 of [38] up to the point where $T_{\rm QFT} \approx T_{\rm dS}$.

Discussion.—For simplicity, our work is restricted to a specific model that assumes a holographic potential that realizes in the dual field theory a renormalization group flow between UV- and IR-fixed points and leads to the thermodynamics of a smooth cross over between two conformally symmetric phases.

Changing the potential would allow one to study QFTs with different equilibrium properties, like for example theories with phase transitions and confinement [23,41], or one may vary the dimension Δ of the scalar operator that couples to the inflaton. Choosing $\Delta < 3$, for example, makes the linear coupling to the inflaton relevant, as ϕ has a weak-coupling dimension near 1.

It would also be interesting to generalize the field content of our construction, for example by adding the dynamics of a gauge field in the bulk theory, which would allow one to model the dynamics of conserved charges [42] and gauge fields [43,44] in the boundary theory.

One may also change the function $U(\phi)$ that controls the coupling of the inflaton to the scalar QFT operator. Nonlinear options for this function may affect the evolution nontrivially, like, for example, a quadratic U affects the effective mass of the inflaton and may stop inflation if it becomes large enough.

The holographic reheating scenario has several relevant scales. There is the initial energy density in the QFT, there is the initial vacuum energy and the time it takes to roll down [both largely determined by our choice of inflaton potential in Eq. (4)], and finally our QFT is nonconformal due to the bulk potential [Eq. (6)] and its coupling to the inflaton U. One important aspect to consider regarding these scales is that the reheating temperature is largely unconstrained by cosmological observations, as long as it is at a sufficiently high temperature. As long as the universe then exits inflating and reheats into a radiation dominated universe at a sufficiently high temperature the actual scales present are not essential.

The most exciting avenue will be to make our model into a realistic inflationary scenario for our own Universe that satisfies all the constraints known from cosmology. For this several steps are required, including a realistic coupling of the QFT to fields of the standard model.

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