Cosmology as a holographic wormhole

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Abstract: In this paper, we suggest a framework for cosmology based on gravitational effective field theories with a negative fundamental cosmological constant, which may exhibit accelerated expansion due to the positive potential energy of rolling scalar fields. The framework postulates an exact time-reversal symmetry of the quantum state (with a time-symmetric big bang / big crunch background cosmology) and an analyticity property that relates cosmological observables to observables in a Euclidean gravitational theory defined with a pair of asymptotically Anti-de Sitter (AdS) planar boundaries. We propose a microscopic definition for this Euclidean theory using holography, so the model is UV complete. While it is not yet clear whether the framework can give realistic predictions, it has the potential to resolve various naturalness puzzles without the need for inflation. This is a shorter version of [1] (arXiv:2203.11220), emphasizing the effective field theory point of view.
Introduction  Cosmological observations establish that our universe is currently experiencing a period of accelerated expansion \cite{2, 3}. This is perhaps most simply explained by a positive cosmological constant in the gravitational equations, but an alternative possibility also consistent with data is that the acceleration is driven by the potential energy of scalar fields that are changing with time \cite{4–9}. From a theoretical perspective, it is very natural to consider this latter possibility, since the most general background consistent with the symmetries of a Friedmann-Robertson-Walker (FRW) cosmological spacetime also has time-varying scalars.

The evolution of time-dependent scalar fields with potential $V(\vec{\phi})$ in a flat cosmological spacetime with scale factor $a(t)$ is equivalent to the damped motion of a particle with coordinates $\vec{\phi}$ in the potential $V(\vec{\phi})$ with damping constant $3H \equiv 3\dot{a}/a$. Thus, while the universe is expanding, this particle will lose energy, and the scalar potential typically will reach smaller values. There is no particular reason why the potential should remain positive, so a natural possibility in this scenario is that the fundamental cosmological constant (defined as an extremal value of the scalar potential that the scalars are approaching) is negative.\footnote{Also, from the point of view of string theory, acceleration caused by a positive scalar potential in the vicinity of a negative extremum would seem to be much more generic than acceleration due to a positive extremum \cite{1}.} In this case, the sign of dark energy will reverse at some time in the future, leading to a deceleration and eventual recollapse of the universe.

A large class of such recollapse models have time-reversal symmetry at the level of background cosmology and have a geometry that is related by analytic continuation to a Euclidean geometry with a pair of asymptotically AdS regions (at imaginary proper time $\tau = \pm \infty$) \cite{1, 10–12}.

In this paper, following \cite{1, 10–15}, we explain how such cosmological models with time-dependent scalars, a negative cosmological constant, and an associated Euclidean asymptotically AdS geometry might be given a complete microscopic description using the tools of holography (the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence) in string theory. A more detailed account appears in \cite{1}.

While it is not yet clear that this framework includes models consistent with our detailed observations, there are number of attractive features. The cosmology has a preferred quantum state determined by the choice of effective field theory alone. This state exhibits time-reversal symmetry and observables that are related by analytic continuation to vacuum observables in a static, weakly-curved asymptotically AdS spacetime. Exploiting this relation, the computation of cosmological observables can be carried out without any detailed knowledge of
the UV completion or of the physics near the big bang, though the underlying string theory description provides useful constraints on the effective theory. The framework potentially resolves various naturalness puzzles without the need for inflation. It also provides candidate explanations for dark energy and its smallness, the cosmological coincidence problem, and the emergence of the standard model from an underlying supersymmetric theory.

**The wavefunction of the universe** In order to determine the evolution of the universe given some effective field theory, it is necessary to specify the state at some time. In standard discussions of cosmology, this is taken to be a time in the early universe (e.g. at the beginning of inflation). However, from the point of view of quantum evolution, the state of the universe can be specified at any time.

In a time-symmetric cosmology, there is a special time slice with $\dot{a} = 0$ where the universe stops expanding and starts recollapsing. Rather than choosing the big bang (or big crunch) as the natural time at which initial conditions are specified, we propose to define the state of the universe at this recollapse point, which we define as $t = 0$. To define the state at this time, we need to specify initial conditions for the classical fields that determine the background cosmology, and the quantum state of the fields that describe fluctuations about this background. We will assume that the background is homogeneous, isotropic, and flat, with the standard FRW form

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2. \tag{1}$$

As natural “initial” conditions for the scalars at this point, we will assume that the time derivatives vanish as they do for the scale factor. This can be motivated by symmetry: with this choice, the background solution will have an additional symmetry under time-reversal. It also provides a special feature that we need in order to define a preferred state of the quantum fields: with this extra symmetry, the background can be analytically continued to a real reflection-symmetric Euclidean spacetime \[1, 10–12\]

$$ds^2 = d\tau^2 + a_E^2(\tau)d\vec{x}^2. \tag{2}$$

where $a_E(\tau) = a(i\tau)$. The geometry and scalar fields at the reflection-invariant slice $\tau = 0$ are the same as those at the time-symmetric slice $t = 0$ in the cosmology. The Euclidean scale factor $a_E(\tau)$ increases away from this point, and has asymptotically AdS behavior for $\tau \to \pm\infty$ provided that the scalar fields do not diverge here and the scalar potential remains negative \[1\]. The metric (2) therefore describes a Euclidean AdS wormhole connecting two distinct asymptotic boundaries.
A natural state of the quantum fields at the time-reflection invariant slice in the cosmology can be specified by defining its wave functional via a Euclidean path integral

\[ \Psi[\phi^0_\alpha] = \int_{\tau<0}^{\phi_\alpha(0) = \phi^0_\alpha} [d\phi(\tau)] e^{-S_{\text{Euc}}}, \]  

(3)

where we integrate over field configurations on half of the background geometry (2). To fully define this gravitational path integral, we need to provide some UV completion. The asymptotically AdS behavior suggests that this can be accomplished via holography, making use of an underlying three-dimensional CFT associated with the asymptotically AdS boundary [17–19]. Such holographic models are discussed in detail in [1, 12], however, the only input we will need from this underlying description are the four-dimensional effective gravitational theory that it provides and the boundary physics of the fields in the effective theory at the asymptotically AdS boundaries.

Thus, we propose the following steps to define the physics of a cosmology:

- Start with a 4D gravitational effective field theory. The choice here is constrained by requiring some consistent dual CFT. In particular, the requirement of asymptotically AdS solutions requires that the scalar potential should have an extremum with a negative value.

- Specify some boundary conditions for the fields in the Euclidean version of this theory at a pair of asymptotically AdS boundaries. This is a crucial step that we discuss further below.

- Find a reflection-symmetric solution for the background geometry that connects the two asymptotically AdS regions. This gives the background geometry (2).

- Analytically continue this to find the Euclidean background cosmology (1).  

- Use the effective field theory on the Euclidean background to define a state of the quantum fields in the cosmology via (3).

\footnote{This is similar to the Hartle-Hawking proposal for the wavefunction of the universe [16], but we have asymptotically AdS boundary conditions in the Euclidean past instead of the no-boundary condition of Hartle and Hawking.}

\footnote{For the full geometry with two asymptotically AdS boundaries, the proposal is to make use of a pair of 3D Euclidean CFTs coupled together by an auxiliary higher-dimensional field theory.}

\footnote{Equivalently, use the metric and fields on the reflection-invariant slice to define initial data for the background fields in the cosmology.
Extracting cosmological observables  By our construction, the background cosmological spacetime and the correlation functions in the cosmology (which encode structure, the CMB, etc...) are related by analytic continuation of the time coordinate $t$ to observables in the Euclidean theory. Via a simpler analytic continuation (replacing $x \rightarrow ix$ for one of the translation-invariant $\vec{x}$ coordinates), they are also related to the vacuum physics of the Lorentzian theory on a third spacetime,

$$ds^2 = d\tau^2 + a^2(\tau)dx_\mu dx^\mu,$$

which is a static spacetime with a pair of asymptotically AdS regions at $\tau = \pm \infty$. We will refer to this as the Lorentzian wormhole geometry since it has two asymptotically AdS regions connected through the interior.

In practice, the simplest way to extract predictions for the cosmological physics is to compute observables in either the Euclidean or Lorentzian asymptotically AdS geometries and then analytically continue these back to the cosmological spacetime. In these other descriptions, the background geometries are weakly curved everywhere, so it is not necessary to know about the details of physics near the big bang (including the details of the UV completion of gravity) to compute observables. Further, in the Lorentzian wormhole picture, we only need to understand observables in the vacuum state of the theory; remarkably, these should contain everything we wish to know about the cosmological physics.

As an example, equal time correlation functions $\langle T_{tt}(x_1, t) \cdots T_{tt}(x_n, t) \rangle$ of the energy density in the cosmology are obtained by analytic continuation $\tau \rightarrow it$ from vacuum correlation functions $\langle T_{\tau\tau}(x_1, \tau) \cdots T_{\tau\tau}(x_n, \tau) \rangle$ of the stress tensor component $T_{\tau\tau}$ for the same effective field theory in the geometry (4). The cosmological correlators obtained in this way correspond to quantum correlators in the full wavefunction. These can be understood as an average over the ensemble of possible classical cosmologies described by the wavefunction. We can equivalently understand the correlators as telling us about a spatial average of correlators in a typical cosmology in the ensemble (see e.g. [20]); in this way we can try to connect with observations in our own universe.

The effective field theory  To make specific predictions, we need to specify the 4D gravitational effective field theory for the model, including the boundary physics at the two asymptotically AdS boundaries. A significant constraint is that the effective field theory must have a Lorentzian wormhole geometry as a vacuum solution. As explained in [1], this requires a large amount of negative null energy in the vacuum stress-energy tensor for the fields, and this can arise only with a special choice of boundary physics for the fields in the

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5Here, operators are chosen to lie in the 2D plane that remains spatial in all three pictures.
Figure 1. Left: time-symmetric $\Lambda < 0$ cosmology. Right: replacing $t = i\tau$ gives a Euclidean wormhole with two asymptotically AdS regions. The effective field theory description of such a wormhole may require coupling the fields in the two asymptotic regions via an auxiliary non-gravitational field theory (green).

two asymptotically AdS regions. Specifically, we have argued in [1, 12] that the two boundaries should be coupled via an auxiliary non-gravitational quantum field theory, as shown in Figure 1. A specific example showing how such a coupling between quantum field theories can lead to the required type of enhanced negative energies was given in [12, 21]. In that case, a crucial step was tuning a parameter associated with the interface towards a critical value. The physics of interfaces between four-dimensional quantum field theories is poorly understood in general; understanding this better will be a key step towards realizing explicit examples of our proposed framework.

If this framework can describe realistic cosmology, the underlying gravitational effective field theory should be some extension of the Standard Model. The existence of a holographic description suggests that this extension should be some 4D supergravity theory with a gauge group $G$ that will ultimately be broken to give $SU(3) \times SU(2) \times U(1)$. The asymptotically AdS regions correspond to a solution of this effective theory where supersymmetry and gauge symmetry are preserved and the scalar fields lie at some extremum of the potential with negative value; away from the boundaries (and in the cosmological solution) the scalars have varying expectation values that contribute to gauge and supersymmetry breaking as described below.

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6This coupling arises from a similar coupling of the 3D CFTs in the underlying holographic description. As explained in [1, 12], the auxiliary system also appears in the effective description of the cosmology picture as a non-gravitational auxiliary system that the fields in the cosmology are entangled with.

7In the example, the two field theories were taken to be holographic CFTs. The resulting cosmology was standard $\Lambda < 0$ plus radiation flat cosmology [1, 12]. Evidence that such large negative energy states appear also for free field theories will be presented in [22].
**The cosmological constant**  The extremum of the scalar potential sets the fundamental cosmological constant for the theory. This is directly related to the number of degrees of freedom in the dual CFT. Thus, the smallness of the cosmological constant (and the largeness of the universe relative to the Planck scale) is ultimately related to having an underlying CFT with a very large number of degrees of freedom. As discussed further in [1], it is likely important that the underlying CFT is chosen to be supersymmetric so that the bulk cosmological constant does not receive large quantum corrections. In this case, the underlying bulk effective theory has unbroken supersymmetry, but (as we now describe) the relevant effective theory describing the cosmological physics can appear non-supersymmetric because of the time-varying scalar. For supersymmetric effective gravitational theories arising from string theory, it is also important to ensure that the scale of the compact extra dimensions is small. Examples of supersymmetric AdS string vacua with acceptably small cosmological constant and small extra dimensions have been described recently in [23, 24].

**The scalar potential**  To get a realistic $\Lambda < 0$ cosmology with late-time acceleration, we need to have time-varying scalar fields, and these must have a potential that is sufficiently flat in order to satisfy observational constraints on the time-variation of dark energy. Remarkably, time-varying scalars with a very flat potential are generic in this holographic setup. Effective gravitational theories dual to holographic 3D superconformal theories typically have some scalars with negative mass squared; these are in one-to-one correspondence with relevant scalar operators in the dual CFT. In generic asymptotically AdS solutions to the effective theory, such negative mass scalars develop expectation values as we move away from the asymptotically AdS boundary [25, 26].

The action for gravitational and scalar fields can be written as

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{g} (R - g^{ab}\partial_a\phi\partial_b\phi - \frac{6}{L^2} V(\phi)) + S_{\text{matter}}$$

(5)

Here, the scalar field and its potential $V(\phi)$ are dimensionless, and the cosmological constant $\Lambda = -\frac{3}{L^2}$ has been included in the scalar potential, which we can write as

$$V(\phi) = -1 + \frac{1}{2} \hat{m}^2 \phi^2 + V_{\text{int}}(\phi)$$

(6)

For effective actions dual to CFTs, it is natural that the parameters in this potential (including $\hat{m}$) are dimensionless numbers of order one. In particular, we have that

$$-\frac{9}{4} \leq \hat{m}^2 < 0$$

(7)

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8There are also solutions where theses scalars remain constant, but these are measure zero in the space of asymptotically AdS solutions of the effective theory.
for scalars associated with relevant CFT operators (this also follows from requiring stability of asymptotically AdS gravitational solutions). Since the Planck scale appears only in front of the action, the natural length/time scales for variations of the scalar fields in the geometry is the same as the cosmological constant scale.\(^9\) The cosmological constant scale sets the age of the universe in the cosmology picture, so the conclusion is that the time scale for variation of dark energy produced by these scalar fields is the same as the age of the universe; at a qualitative level, this is what we need to satisfy observational constraints.

**Accelerating cosmology from scalars** The scalar field expectation values vary with radial position in the wormhole solutions, and with time in the cosmology. The potential energy from these scalars has the interpretation of a time-dependent dark energy. A typical potential in one of these negative mass squared directions is shown in Figure 2. The evolution of the scalar from the middle of the wormhole to the asymptotically AdS boundary is the same as a damped motion of a particle with coordinate \(\phi\) in a potential \(-V(\phi)\), so typically descends from some value \(\phi_0\) with negative \(V\) to the asymptotic value \(\phi = 0\) with a smaller magnitude negative \(V\). The evolution of the scalar in the expanding phase of the cosmology is the same as a damped motion of a particle with coordinate \(\phi\) in a potential \(V(\phi)\). Thus starting from the early universe, the scalar potential may decrease from positive values before becoming negative and reaching \(\phi_0\) at the time when \(\dot{a} = 0\). In some cases, these positive values of the scalar field give rise to a phase of accelerated expansion before the collapse; in

\(^9\)In a time-symmetric cosmology, the Friedmann equation at the time-symmetric point requires that the energy density from matter and radiation has the same magnitude as the dark energy, so this does not introduce an additional scale.
a realistic example, this could be the present accelerating phase of the universe.

**Symmetry breaking** The scalar field expectation values will typically break supersymmetry and some of the gauge symmetry. To understand this in detail, it is useful to rescale the scalar field in the action (5) as $\phi = \sqrt{8\pi G} \phi_p$ to give standard particle physics normalizations. This gives

$$S_\phi = \int d^4x \sqrt{g} \left( -\frac{1}{2} g^{ab} \partial_a \phi \partial_b \phi - \frac{m^2}{L^2} \phi^2 - \frac{1}{8\pi G L^2} V_{\text{int}}(\sqrt{8\pi G} \phi_p) \right). \tag{8}$$

Here, the quadratic term is set by the cosmological constant scale, and the dimensionless quartic coupling is naturally of order $G/L^2$. With this action, the potential varies over values of order the extremum of the potential (the negative cosmological constant associated with the AdS vacuum) for Planck scale variation of the field expectation values. Thus, we can have gauge symmetry and supersymmetry breaking at a high scale (set by the value of the scalar field) while the vacuum energy remains small. Fermions that couple directly to such a varying scalar via $\phi \bar{\psi} \psi$ terms will have large time-dependent masses induced by the background value of $\phi$. The light fermions of the Standard Model will be some subset of the remaining fermions that do not get large masses in this way. The fluctuations $\delta \phi$ of the scalar about its time-dependent classical solution will correspond to a light scalar particle (whose mass is given by $V''(\phi)$), but we will only have simple $\delta \phi \bar{\psi} \psi$ interactions for the fermions that also get a large mass from the background value of the scalar, so long range forces mediated by $\delta \phi$ on Standard Model matter might be avoided. Quanta of the $\delta \phi$ field will presumably contribute to the dark matter.\(^\text{10}\)

**Generic predictions and naturalness** The details of the cosmological physics for the framework that we discuss will depend on the effective field theory, which in turn is determined by the underlying holographic field theory. However, there are a number of generic predictions that we can make.

The framework gives rise to cosmologies in which the background spacetime is flat, homogeneous, and isotropic; all of these are consequences of the underlying $\mathbb{R}^3$ symmetry of the model (though we could generalize to models with spatial curvature). The cosmologies eventually recollapse in a time-symmetric way; the time-reversal symmetry is also present in the full quantum state describing the ensemble of possible classical cosmologies, however this does not imply that the evolution of structure in the individual classical cosmologies is

\(^{10}\text{We emphasize that a much more careful analysis will be required to understand whether there are legitimate examples satisfying phenomenological constraints.}\)
time-reversal symmetric. Generically, the models have time-varying scalar fields which would give time-dependent dark energy.

The framework provides a potential resolution for a number of naturalness problems in cosmology. Typically, these problems (e.g. the horizon and flatness problems, and the cosmological coincidence problem) are observations that the state of the universe at early times appears to be finely tuned in various ways in order that it can evolve to something that agrees with present observations. For example, this initial state must be extremely flat and homogeneous and have correlations between regions of space that (according to a simple evolution from the big bang) were never in causal contact. Inflation proposes a resolution by postulating an earlier phase of evolution that naturally leads to a state with these special properties.

In our framework, the “initial state” naturally produced by the model is defined at the time-symmetric point where $\dot{a} = 0$. Thus, in addressing questions of naturalness, we should not ask if the state in the early universe is natural, but rather whether the state at the time-symmetric point (obtained by evolving forward from our present observed universe) is naturally produced by the Euclidean path integral in the model. The construction does give rise to a universe that is very flat and homogeneous because of the $\mathbb{R}^3$ symmetry of the model, and it leads to correlations on all scales, since the correlators are the same as vacuum correlators in the wormhole geometry in which there are massless fields. Thus, the framework may alleviate the need for inflation in resolving naturalness puzzles. However, it is important to understand whether the model can reproduce quantitative predictions of inflationary scenarios, namely the nearly scale-invariant spectrum of perturbations that gives rise to structure and CMB anisotropies that agree with observations.

Our framework also provides a possible explanation for the “cosmic coincidence” puzzle, that the vacuum energy and matter/radiation energy are of the same order of magnitude today despite evolving very differently under cosmological evolution (constant vs $1/a^3$ or $1/a^4$). In the flat recollapsing universes of our framework, the Friedmann equations imply that the total energy density must be exactly zero at the middle time when $\dot{a} = 0$, so the negative contribution of dark energy must have exactly the same magnitude as the remaining positive contributions from matter/radiation. The time scale for the variation of the ratio of densities is the scale of dark energy at this time-symmetric point, which also sets the age of the universe, so the dark energy density and matter energy density will typically be of the same order of magnitude for most of the age of the universe. Provided that the present era is at a typical time, we will observe a coincidence in the energy densities.
**Discussion**  We have presented a possible framework for cosmology that should give specific predictions for the evolution of the background cosmology and its perturbations based only on the choice of four-dimensional gravitational effective theory (including a choice of boundary physics in the Euclidean picture). This has a variety of attractive features that we have described, but it remains to be seen whether complete microscopic examples can be constructed and whether there are examples that produce realistic results for the scale factor evolution or for the cosmological perturbations and structures.\(^\text{11}\) Even if the models are not realistic, they may provide a useful theoretical laboratory for learning about quantum aspects of cosmology.

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\(^{11}\)Alongside searching for complete realizations of this framework, it may be fruitful to investigate models that only incorporate some of its features. Without assuming any analytic properties of the state, it is interesting to ask whether one can come up with realistic models of cosmology via time-dependent scalars in 4D supergravity theories dual to CFTs, since these theories are known to have UV completions. We might also have a situation where the Euclidean wormhole picture is well-defined and has a holographic description, but the Lorentzian wormhole isn’t physical (e.g. since the underlying 3D CFT isn’t unitary). Other approaches to cosmology that make use of some features of our framework include [27–33], as described in [1].
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