Bootstrapping Cosmological Correlations

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ABSTRACT

Cosmology is famously an observational rather than an experimental science. No experimentalists were present in the early Universe, and the birth and subsequent evolution of the Universe cannot be repeated. Instead, we can only measure the spatial correlations between cosmological structures at late times. A central challenge of modern cosmology is to construct a consistent "history" of the Universe that explains these correlations. In the last few years, a new bootstrap approach was developed to understand this history using only physical consistency conditions. In this article, we will describe the basic idea behind this "cosmological bootstrap" and explain why it promises new insights into the physics of the very early Universe.

INTRODUCTION

A remarkable fact about our Universe is that the structures we see around us are not distributed randomly but rather display interesting spatial correlations. By tracing these correlations across cosmic time, we can infer the contents and evolutionary history of the Universe. The earliest measurement of the cosmological correlations comes from observations of the temperature anisotropies in the cosmic microwave background (CMB), the afterglow of the hot Big Bang. A striking feature of the observed correlations is that they are present over distances that exceed the maximal distance traveled by light since the Big Bang. These superhorizon correlations, therefore, require that our cosmological history extends to earlier times, before the Universe reached a state of thermal equilibrium. A key goal of modern cosmology is to discover what really happened in this period and to understand how this physics generated the seeds for the formation of structure in the Universe.

An important clue lies in the fact that the observed fluctuations are scale-invariant, meaning that they have equal power on all scales. This suggests that the dynamics that created the fluctuations were nearly time-translation invariant. In particular, the energy density was nearly constant, sourcing an exponential expansion of the spacetime that we call inflation [1]. If inflation really occurred, it was a rather dramatic event in the history of the Universe. In just 10^{-33} seconds, the Universe doubled in size about 80 times. A region of space the size of a mosquito was stretched to the size of a galaxy, allowing the entire observable Universe to originate from a microscopic, causally connected region of space. The correlations observed in the afterglow of the Big Bang were then inherited from correlations in the quantum-mechanical fluctuations during inflation.

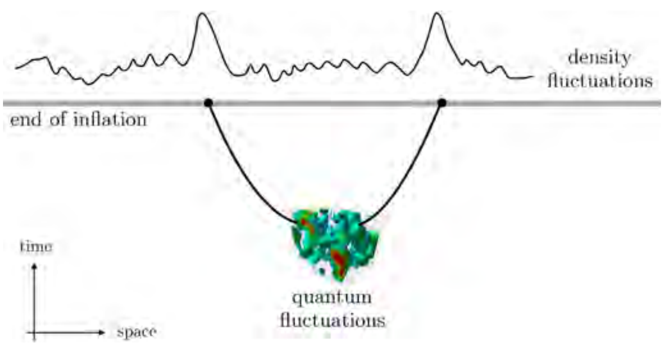


Fig. 1: A pair of inflaton particles is created by quantum fluctuations and the particles are then stretched apart by the rapid expansion of the spacetime. Since these particles have a common origin, the density fluctuations associated to them are correlated.

While this picture provides an elegant explanation for the initial conditions of the primordial Universe, it must be emphasized that inflation is not yet a fact at the same level that, for example, the formation of the light elements in Big Bang nucleosynthesis is a fact. Further tests of inflation will come from more precise measurements of the cosmological correlations, which we hope will provide new clues about the physics of the primordial Universe.

Inflationary correlations

The mechanism by which inflation created the initial correlations is rather beautiful. A way to think about it is illustrated in Figure 1. We believe that the inflationary expansion was sourced by the nearly constant energy density of the so-called inflaton field. Quantum mechanics then allows pairs of inflaton particles to be spontaneously produced out of the vacuum. This increases the energy density in that region of space, so that the inflationary period lasts for a slightly longer time, resulting in fluctuations in the density after inflation. The reason that these density fluctuations are correlated can also be seen from the illustration in Figure 1. As soon as a particle pair is created, the particles are stretched apart by the rapid expansion of the spacetime, creating density perturbations at separated points. Because the particles originated from a common source, pairs of points in the density after inflation are correlated, with the details of the correlations depending on the dynamics during inflation. Inflation has turned microscopic quantum fluctuations into the macroscopic cosmological correlations that we observe in the sky.

An important feature of the observed correlations is their "Gaussianity." This refers to the fact that the size of the correlations between two points in the sky is larger than the size of the correlations between three or more points. Such Gaussianity arises because the physics during inflation was very "weakly coupled," so that the probability to create pairs of particles was larger than the probability to produce three or more particles. Nevertheless, there can be subtle imprints in higher-order correlations (non-Gaussianity), which would contain vital information about the detailed physics of the inflationary period, and there is an active experimental effort to measure these correlations.

Cosmological collider physics

Any particles with masses below the energy scale set by the inflationary expansion rate—which may be as high as 10^{14} GeV—will experience the same quantum fluctuations as the inflaton. Such particles would then also be pair-produced during inflation (see Fig. 2). However, because these particles are massive, they are unstable and can decay into pairs of inflaton particles. This produces higher-order correlations in the density after inflation, which later get imprinted in the large-scale structure of the Universe. What makes these particular correlations so interesting is that they are tracers of the underlying inflationary dynamics (they depend sensitively on the evolution during inflation) and are key signatures of the high-energy completion of inflation (which requires the existence of these massive particles).

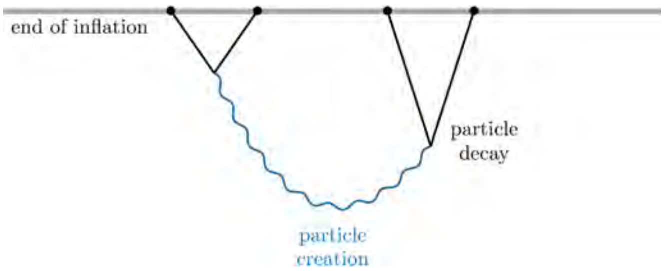


Fig. 2: Massive particles can be produced by inflationary expansion. These particles then decay into inflaton particles, which leads to density fluctuations that can be measured. The imprint of these massive particles can be seen in subtle correlations between the resulting density fluctuations.

The fact that all sufficiently light particles are produced during inflation provides the opportunity to perform a kind of "cosmological collider physics" [2]. Like in ordinary collider physics, the presence of the new particles can reveal itself through resonances. In the cosmological case, instead of an excess of events at the energy corresponding to the mass of the particle, one finds that the higher-order correlations oscillate when the distance between correlated points varies, and they do so with a frequency given by the mass of the new particle. Moreover, the dependence of the signal on the relative orientation of the correlated points gives information about the spin of the new particle; this is akin to a particle collider, where the spin of the new particle is encoded in the angular distribution of the outcoming particles.

While the cosmological collider provides the tantalizing prospect of probing physics at energies far exceeding those accessible to any terrestrial experiment, the signals are small and can only be extracted from the data if they can be predicted very precisely. Unfortunately, the standard way of computing the signals is rather complicated

[3]. The coupled fluctuations in the fields and the spacetime geometry have to be evolved in time, giving rise to convoluted time integrals that usually involve non-elementary functions. Moreover, local evolution requires keeping track of additional (gauge) degrees of freedom whose effects must cancel out of the final answers. The complexity of the calculations motivates a fresh look at the problem of inflationary correlators, through a new approach that avoids explicitly computing the time evolution and instead focuses directly on the physical observations at the end of inflation.

Back to the future

All cosmological correlations that we observe in the late Universe can be traced back to the origin of the hot Big Bang, where they reside on the spatial "boundary" at the end of an inflationary spacetime, also known as the reheating surface (see Figure 3). Although we have accumulated a substantial amount of evidence for the preceding inflationary period, it is important to stress that we don't have direct observational access to this epoch. Instead, we infer its existence and its properties from the detailed structure of the spatial correlations measured on the reheating surface. These "boundary correlators" serve as the final observable output of inflation, and are usually computed by following the production and decay of particles as a function of time.

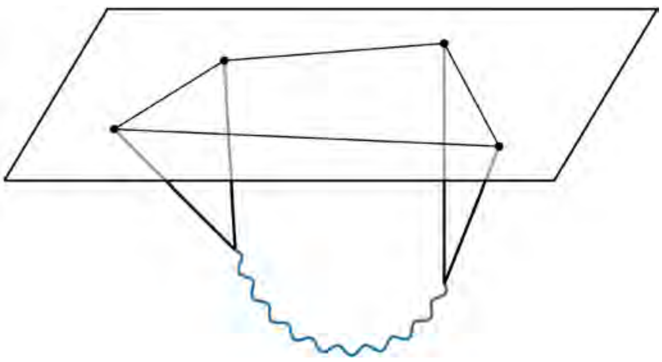


Fig. 3: The dynamics of particles in the inflationary spacetime are encoded on the future boundary of the spacetime (the reheating surface). These correlations provide the initial conditions for the subsequent evolution of the Universe. By measuring these correlations, we hope to infer the physics of the inflationary epoch.

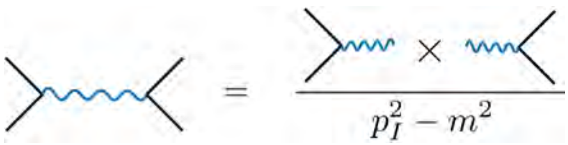
Given that only the spatial correlations on the final boundary of the inflationary spacetime are important for the subsequent dynamics of the Universe, it is natural to ask whether we can understand these boundary correlators directly, without having to follow the detailed time evolution during inflation. There are two reasons to be optimistic that this might be possible: first, the final answers obtained from explicit time evolution are often simpler than the complexity of the calculations would suggest. Secondly, the final boundary observables must be consistent with cherished principles of modern physics such as unitarity, locality, and causality, which will impose strong constraints on the allowed correlators. In the usual computations these properties arise as outputs, guaranteed by the way the calculations are performed. The goal is to reverse the logic and view these principles as the fundamental input. The allure of this approach is that it focuses directly on the observable output of the inflationary process—boundary correlators—without getting mired in complex intermediate technicalities that do not have a physical interpretation. The hope is that the final answers are so constrained by physical consistency requirements that they can be reconstructed—or "bootstrapped"—from these inputs alone.

S-matrix bootstrap

A success story of the bootstrap philosophy—and an inspiration for the application to cosmology— comes from the study of scattering amplitudes in flat space. Scattering amplitudes are the fundamental observables associated with the interactions of particles in quantum field theory. Much like boundary correlators in cosmology, scattering amplitudes can be thought of as "asymptotic" observables, residing on the boundary of flat Minkowski space.

Much of the apparatus of quantum field theory was developed to compute scattering amplitudes in a way that makes locality manifest. However, this comes at a cost, as the calculations can become fearsomely complicated, especially for gravity and gauge theories. The number of Feynman diagrams contributing to a given physical process can grow factorially: for example, to compute the simplest (tree-level) scattering process involving 10 gluons would already require over 10 million diagrams [4]. Even more importantly, none of the individual terms in this expansion is by itself meaningful, and they must all be added up with precise relative coefficients to obtain the physical final answer. Needless to say, computing 10 gluon scattering using standard techniques is far out of reach. Nevertheless, heroic computations of gluon and graviton scattering were done with fewer particles [5, 6] and, shockingly, the final answers are far simpler than any of the intermediate steps. The sharpest example is the so-called Parke–Taylor formula, which describes the scattering of an arbitrary number of gluons, with particular polarizations, in a single term [7]. This unexpected simplicity, first guessed and then later proven, was the first hint of hidden structures in scattering amplitudes that would enable more complicated computations to be done using totally new techniques.

The modern amplitudes program fully embraces the bootstrap philosophy. By focusing on the final scattering output, remarkable techniques have been developed to bypass Feynman diagram calculations. An important fact enabling this progress is that our understanding of how physical properties are encoded in scattering amplitudes is substantially more mature than in the cosmological context. In particular, we have an ever-improving understanding of how locality and unitarity of particle scattering are reflected in the analytic properties of the observables. For example, at tree level, scattering amplitudes have singularities when an intermediate particle go "on-shell," meaning that its momentum p_I satisfies $p_I^2 = m^2$, with m the mass of the particle. Since the particle then propagates a long distance in spacetime before decaying, the coefficient of this singularity becomes a product of simpler lower-point amplitudes:



In many cases, these factorization constraints are enough to uniquely reconstruct tree-level amplitudes [8–10] and rule out many inconsistent theories [11].

The last few decades have seen enormous progress in our understanding of scattering amplitudes in gauge theory and gravity through the S-matrix bootstrap (for an overview, see [12, 13]). One of the advantages of this formalism is that only physical degrees of freedom appear in computations, so there is no need for them to decouple at the end. These on-shell techniques have revealed hidden symmetries and mathematical structures that are completely invisible in the standard approach of Lagrangians and Feynman diagrams. Indeed, we have come to realize that the Lagrangian approach obscures important physics. The bootstrap method has enabled a wealth of new calculations (including powerful recursive formulas for scattering [14]), has revealed relations between seemingly distinct theories (like QCD and gravity [15]), and has led to a steadily improving understanding of loop processes [16]. Moreover, aside from their utility in making predictions for collider experiments, these calculations have generated an ocean of new "theoretical data" from which the outlines of more radical theories can be seen, replacing locality and unitarity with new mathematical and physical structures [17].

Cosmological bootstrap

Implementing a bootstrap approach in cosmology requires a bit of detective work, since we don't yet know the precise rules that the cosmological correlators have to satisfy, and how these rules are enforced on the boundary. However, even studying a subset of the possible consistency conditions has already led to interesting simplifications and new insights into the structure of boundary correlations [18] (see also [19–23]).

As we have seen above, the production and decay of massive particles naturally leads to four-point correlations in the inflaton fluctuations. Connecting the four points on the boundary forms a quadrilateral and the strength of the correlations changes as we vary the shape of this quadrilateral (see Fig. 4). This is how the history of the inflationary dynamics is imprinted in the boundary correlations. It turns out to be simpler to Fourier transform the coordinates on the spatial slice and consider cosmological correlators in momentum space, where the energies of the particles in the inflationary spacetime get represented as the lengths of the sides of the quadrilateral on the boundary.

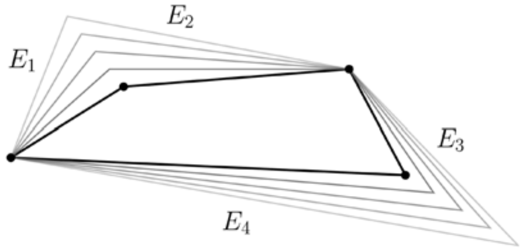
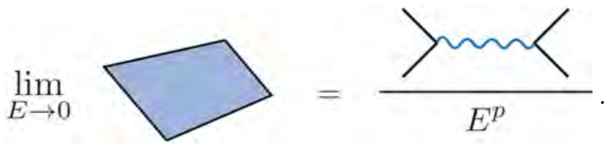


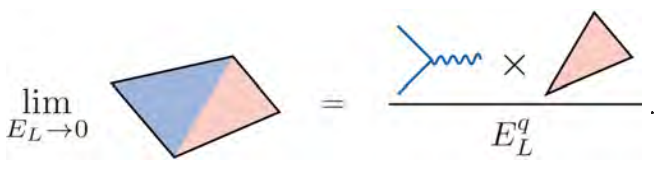
Fig. 4: The strength of the correlations varies as the shape of the quadrilateral is changed. This dependence encodes time-dependent physics during inflation, which on the boundary becomes a differential equation in the side lengths.

An important insight from the S-matrix bootstrap is that the behavior of asymptotic observables is largely controlled by their singularities. As a first step, we would therefore like to understand the possible singularities of the boundary correlators—particular configurations where the strength of the correlations formally becomes infinite. An important fact about correlation functions in cosmology is that, while they depend on the energies of the particles involved, the energy of a process does not need to be conserved, due to the time dependence of the cosmological background. This also means that the total energy of a boundary correlator—corresponding to the total length of the perimeter of the quadrilateral, $E \equiv E_1 + E_2 + E_3 + E_4$ and E_I does not have to add up to zero. Nevertheless, we can ask what happens if the total energy does happen to sum to zero. Importantly, this cannot occur in any physically realizable process (as some of the energies would have to be negative), but if we allow ourselves the freedom to think of the correlator as an abstract function, we can reach this point by analytic continuation. As we approach this limit, the correlator diverges, and, remarkably, the coefficient of this singularity is the scattering amplitude associated to the particular process in the bulk spacetime [24, 25]. Pictorially, we have



The fact that amplitudes are contained inside correlators provides a beautiful bridge to the scattering amplitudes program.

We can also ask what happens when only a subset of the energies adds up to zero. We can think of reaching this limit by triangulating the quadrilateral and then analytically continuing the side lengths so that the length of the perimeter of one of the triangles vanishes.



From the viewpoint of the bulk process shown in Figure 3, this limit corresponds to energy conservation on the left vertex so that $E_L \equiv E_1 + E_2 + E_I$ adds up to zero, where E_I is the energy of the intermediate particle. In this case, the correlator is again singular, but the coefficient is slightly different: it is a product of a three-point scattering amplitude associated to the particles whose energies add up to zero times the three-point correlation function associated to the other particles, corresponding to the triangle whose side lengths we did not make add up to zero. These "partial energy" singularities encode the particle production in the bulk spacetime. The fact that the coefficients of the partial energy singularities consist of lower-point objects is a hint that we can iteratively build up more complicated correlators from simpler processes. The singularities of the boundary correlator are special kinematic configurations, at which the structure of the correlator is completely fixed. However, to obtain the full correlator, we have to understand how to extend the solution away from these points. This extension captures the dynamics associated to bulk time evolution, precisely because changing the shape of the quadrilateral corresponds to evolving through time in the inflationary spacetime. In fact, this connection to time evolution implies that the boundary correlation functions satisfy a differential equation as a function of the energies (side lengths of the quadrilateral; see Fig. 4). The singularities then serve as boundary conditions for this differential equation, selecting the physical correlators as solutions [18].

For certain models of inflation, the dynamics of the inflaton and other particles are strongly constrained by symmetry and we can understand this differential equation as a consequence of these symmetries. In particular, if the inflaton energy density evolves sufficiently slowly, then the inflationary spacetime will be approximately de Sitter space—which is highly symmetric—and all of the interactions will respect the symmetries of this spacetime. On the late-time future boundary of de Sitter space,

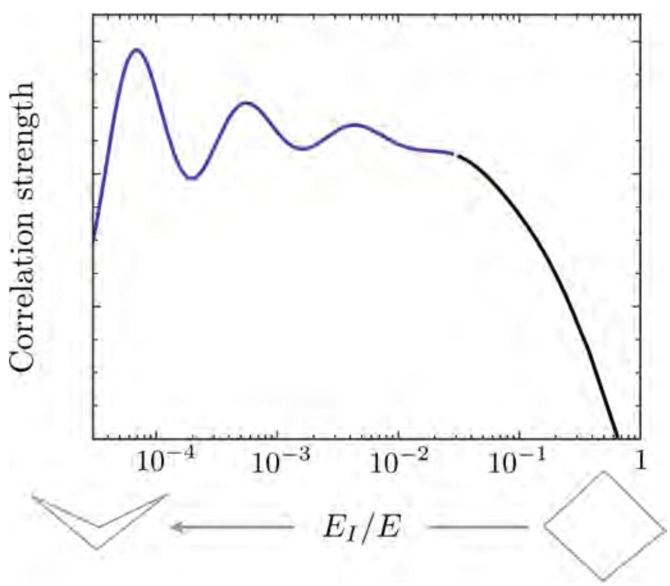


Fig. 5: In the limit where one of the diagonals of the quadrilateral shrinks to zero *($E_I \to 0$)*, correlations display a characteristic oscillatory feature, which is a signature of the production and decay of a massive particle.

these symmetries act as conformal transformations (transformations preserving angles but not distances). Boundary correlation functions must therefore be invariant under these conformal symmetries. The precise statement is that the boundary observables satisfy Ward identities, which are differential equations expressing the invariance of the dynamics under the conformal transformations.

The natural next step is to solve the differential equation. An interesting feature of the solutions is that the boundary conditions enforced by the singularities in unphysical configurations of the quadrilateral require that certain features appear in physically realizable configurations. The most striking signature is a characteristic oscillation of the strength of correlations as one of the diagonals of the quadrilateral shrinks to zero (see Fig. 5). These oscillations are the characteristic signatures of particle production in the inflationary spacetime: indeed, the frequency is set by the mass of the produced particle. Remarkably, a time-dependent dynamical signature (the effect of particle production and decay) appears in this language as an inevitable consequence of singularities and symmetries of a completely time-independent, static object: the boundary correlator.

One of the key insights from the bootstrap approach is that there is a hidden unity amongst cosmological correlations. One might imagine that correlations due to particles of different masses or spins would be totally different and would have to be computed anew by solving the differential equation that governs them, with different boundary conditions. However, in reality there is an intricate web of relations between these solutions: they can be transmuted into each other by certain elementary operations, and all can be derived from simple "seed" correlations that capture the essence of particle production in the inflationary spacetime [19]. This unifying simplicity is invisible in the standard approach and is practically useful: it provides a natural basis of structures to search for in analyses of cosmological data.

OUTLOOK

The adventure of studying cosmological correlators from the boundary has just begun, and there are still many challenges to overcome. So far, the bootstrap has only been applied to the simplest situations with a large degree of symmetry [18–20]. While this makes the analysis very clean, it also suppresses the strength of the interactions and hence the size of the non-Gaussian signals. To describe larger signals, the bootstrap method needs to be extended to situations with less symmetry. It is in those situations that the bootstrap approach would have immediate observational relevance, producing signals that can be searched for with future galaxy surveys [26–28]. Some tools to study these less symmetric cases have already begun to be developed. For example, it was shown that singularities still control much of the structure of the correlations [20] and that constraints from unitarity may help to extend them away from these singularities [23]. Beyond this, the fact that boundary correlations obey a differential equation is a robust feature of time evolution in the inflationary spacetime, and there are indications that these differential equations are connected to some interesting mathematical structures.

Aside from these observationally relevant applications, the cosmological bootstrap could also lead to new conceptual insights into the structure of cosmological correlations. One of the major advances of the S-matrix bootstrap program was to go beyond the notion of Feynman diagrams. The standard approach involves a decomposition into individual diagrams—also called channels—that do not individually have a physical meaning, which then sum up to the physical answer. The S-matrix bootstrap bundles all of the information together and constructs the final answer directly, bypassing this (unphysical) intermediate step. This is an advance yet to be made in the cosmological context: the outputs arising from boundary consistency considerations, so far, still resemble the outputs of Feynman diagrams. An important goal is to understand how to construct the full correlators directly without a decomposition into channels. Said in another way, cosmological correlators have not yet had their "Parke–Taylor moment"—by which we mean the discovery of a radically simple formula for correlations that points to an underlying structure of extreme hidden simplicity. However, the insights already uncovered provide reason to be optimistic that such structures are there, waiting to be discovered.

A beautiful feature of inflation is that it provides a bridge between the very large and the very small. Since the large-scale structures that we see distributed throughout the Universe began as microscopic quantum fluctuations stretched to macroscopic size by the inflationary expansion, studying the largest scales today can give us insight into physics at very small distances. Making the connection between long-distance (IR) observables and shortdistance (UV) physics precise remains an important open problem. In the case of scattering amplitudes, the analytic structure is understood well enough to use complex analysis to relate the IR limit of the amplitude to its UV completion [29], leading to so-called dispersion relations that are similar to Kramers–Kronig relations, familiar from electromagnetism. These UV-IR relations provide interesting constraints on the parameters of low-energy effective field theories. Conversely, they relate measurements of the low-energy parameters to properties of the high-energy theory. A long-term goal of the cosmological bootstrap is to understand the analytic structure of cosmological correlators well enough to derive similar UV-IR relations. Such results would provide a direct link between observations of the largest structures in the Universe and their microscopic origin.

Although we are just uncovering the first threads, it is clear that there is a beautiful tapestry of interconnections between cosmological correlations, scattering amplitudes, and the physics of the early Universe. We are optimistic that understanding more of this underlying structure will provide new insights into the evolution of the Universe in its earliest moments.

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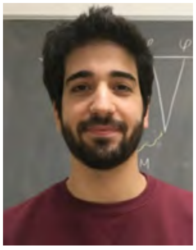

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