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Exploring Conformal Symmetry in Anti-De Sitter Space: Quantum Chromodynamics in AdS/CFT Correspondence

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ABSTRACT

The Gauge/Gravity duality links Anti-de Sitter space (AdS), a curved spacetime in general relativity, with Conformal Field Theory (CFT), a quantum field theory on the border of AdS space. String theory and quantum gravity advanced much from this link. In many aspects, black holes are essential to AdS/CFT: The AdS/CFT relationship indicates that a higher-dimensional AdS space's physics is dual to its border's lower-dimensional CFT. Holography implies that boundary theory may encode AdS space information. Dual CFT investigations of AdS space black holes' thermodynamics and quantum characteristics are intriguing. Flat spacetime thermodynamics affects AdS black holes. Their entropy is related to horizon area and temperature. Traditional quantum field theory makes studying black hole thermodynamics challenging, but researchers can analyze it in a densely connected area. Black hole information paradox, a longtime physics quandary, has been revealed by the AdS/CFT correspondence. Particles falling into a black hole seems to delete data. Particle correlations in the border CFT may encode information, according to AdS/CFT. AdS/CFT correspondence is used to study black hole stability and quantum behavior. Hawking radiation, black hole evaporation, and information loss are included. The connection allows two black hole descriptions. General relativity in AdS space or the boundary CFT may explain black hole properties. The two theories are equivalent but provide different black hole physics insights. Black holes in the AdS/CFT correspondence provide a unique and powerful framework for studying gravity, quantum field theory, and spacetime fundamental structure. Researchers are examining this rich relationship to understand black hole physics and the universe.

Keywords: Anti-de Sitter space, Conformal Field Theory, quantum field theory, black holes

Introduction

The AdS/CFT correspondence, also known as the AdS/CFT duality or gauge/gravity duality, is a theoretical framework in theoretical physics that relates two seemingly distinct theories: Anti-de Sitter space (AdS), a type of curved spacetime in the context of general relativity, and Conformal Field Theory (CFT), a quantum field theory living on the boundary of the AdS space. This correspondence has been a significant development in the study of theoretical physics, particularly in the field of string theory and quantum gravity. Black holes play a crucial role in the AdS/CFT correspondence in several ways: The AdS/CFT correspondence suggests that the physics of a higher-dimensional AdS space is dual to the physics of a lower-dimensional CFT on its boundary. This is often referred to as holography because it implies that the information within the AdS space can be encoded on the boundary theory. Black holes in AdS space are of particular interest because they provide a way to study the thermodynamics and quantum properties of black holes in terms of the dual CFT. Black holes in AdS space obey thermodynamic laws similar to those in flat spacetime. In particular, they have an entropy proportional to the horizon area and a temperature. This allows researchers to explore the thermodynamics of black holes in a strongly coupled regime, which is often challenging in standard quantum field theory. The AdS/CFT correspondence has led to insights into the black hole information paradox, which is a long-standing puzzle in the field of black hole physics. It relates to the apparent loss of information when particles fall into a black hole. AdS/CFT suggests that the information might not be lost but rather encoded in the correlations of particles in the boundary CFT. Researchers use the AdS/CFT correspondence to study the stability of black holes and their quantum behavior. This includes investigations into Hawking radiation, black hole evaporation, and the information loss problem. The correspondence allows for a dual description of black holes. One can describe black holes and their properties either using general relativity in AdS space or using the CFT on the boundary. These two descriptions are equivalent, providing different insights into black hole physics. Overall, black holes in the context of the AdS/CFT correspondence offer a unique and powerful framework for studying the interplay between gravity, quantum field theory, and the fundamental nature of spacetime. Researchers continue to explore this rich connection to gain a deeper understanding of black hole physics and the nature of the universe.

Literature Review

[1] We demonstrate that the Hilbert space of certain conformal field theories in arbitrary dimensions contains a sector representing supergravity on the product of Anti-deSitter spacetimes, spheres, and other compact manifolds in the high N limit. To demonstrate this, we isolate a subset of branes from

the complete M/string theory and study the regime of limiting energies at which the brane's field theory becomes independent of the bulk. The near horizon geometry for big N is confirmed to be reliable in this limit. The additional supersymmetry generators in the superconformal group (as opposed to only the super-Poincare group) are responsible for the increased supersymmetries of the near horizon geometry. At the conformal point, the 't Hooft limit of 4-dimensional N=4 super-Yang-Mills is demonstrated to include strings, and these strings are proved to be of type IIB. For a number of Anti-deSitter spacetimes, we propose that compactifications of M/string theory are dual to conformal field theories. As a result, a new definition of M-theory is proposed, one that allows for the inclusion of five more non-compact dimensions. The absence of knowledge of spacetime geometry is a central idea in theoretical physics, and especially in Albert Einstein's theory of general relativity. The existence of mass and energy affects the curvature and structure of this four-dimensional continuum, which blends the three spatial dimensions with the dimension of time.

We recap the string theoretic justification for the AdS/CFT correspondence and talk about how it may be extended to gauge/gravity duality[2]. Noting that the Fisher information metric of a Gaussian probability distribution is an Anti-de Sitter space, we emphasize the connection to quantum information theory. We provide a holographic Kondo model as a practical illustration of the gauge/gravity duality. In condensed matter physics, the Kondo model explains the interaction of a spin impurity with a free electron gas: Low-energy screening removes the impurity and causes the resistivity to increase logarithmically. This corresponds to a negative beta function for the impurity coupling in quantum field theory, which causes the theory to converge to a non-trivial IR fixed point. We investigate a large N variant of this model in which the ambient electrons are tightly linked prior to turning on the interaction with the impurity as a starting point for the construction of a gravity counterpart. We describe the brane architecture that leads to the development of the gravity dual Kondo model and use this model to determine the power-law resistivity and the entanglement entropy of the impurities. In addition, we investigate quantum quenches and talk about how they connect to the Sachdev-Ye-Kitaev model. Lack of a metric on spacetime.

An overall solution to the Einstein equations that includes a temporal singularity is investigated in this section[3]. All three-dimensional vectors and tensors are broken down into components along the frame vectors, as is customary when working with homogeneous spaces. The model's development towards the singularity is characterized by the alternating of Kasner epochs according to a given rule of the replacement of the Kasner exponents. Unlike in homogeneous models, where the rotation of the Kasner axis only arises when matter is present, the inhomogeneous solution is present even in the vacuum situation. The terms resulting from spatial in homogeneity mimic the function of the matter energy-momentum tensor in the Einstein equations. The text lacks spacetime geometry.

We summarize the current state of thermodynamics in black holes[4]. Classical black hole thermodynamics, Hawking radiation from black holes, the extended second law, and the entropy boundaries problem are all included in our review. In addition, methods for determining black hole entropy are briefly discussed. We wrap off by talking about some remaining questions. Inadequate knowledge of spacetime geometry.

A relatively simple generalization of classical laboratory thermodynamics seems to be true for black holes[5]. We take a close look at this overarching idea and provide some practical applications of it. Hawking's application of quantum theory to black holes provides the basis for the thermodynamic relationship, and the quantum features are presented in depth from a variety of heuristic and other perspectives. The exact nature and origin of the thermal radiation emitted by the black hole, as well as the energetics of back-reaction on the hole, are discussed. The theory of thermal Green functions is also applied to the thermal states of quantum holes, and it is demonstrated that the entropy of the hole is connected to the loss of information about the quantum states beyond the event horizon. We also touch on some related subjects, including the thermodynamics of universal self-gravitating systems, super-radiance from spinning holes, and accelerated mirrors and observers in Minkowski space. There is a total lack of spacetime geometry details.

In this talk, I'll give you a high-level summary of how string theory and supersymmetry[8] came to be. It explains how the S-matrix theory program developed into superstring theory, a possible framework for building a quantum theory of all forces, including gravity. Beginning in the middle of the 1960s with S-matrix theory, the era concludes in the middle of the 1980s with the general adoption of superstring theory. Schwarz (2007) provides further information along with a list of sources. There is a total lack of spacetime geometry details. In contrast to bosonic string theory, it is the form of string theory that accounts for both fermions and bosons and integrates supersymmetry[9] to represent gravity, the term "superstring theory" is a shorthand for the more accurate term "supersymmetric string theory." There is no knowledge regarding the geometry of spacetime.

Existing System

Anti-de Sitter space is a concept in the field of theoretical physics and mathematics, particularly in the context of string theory and general relativity. It is a specific solution to Einstein's field equations of general relativity, characterized by a negative cosmological constant (Λ). Now, to understand the "system" before AdS space, we need to clarify what you mean by "system" in this context. AdS space itself is a mathematical and physical concept rather than a "system" in the traditional sense. It's a spacetime geometry that can be described mathematically. If you're asking about the cosmological context before the emergence of AdS space as a solution to Einstein's field equations, it's important to note that the concept of AdS space didn't exist before the development of the theories it is associated with. AdS space, as a mathematical solution to these equations, was discovered in the course of the development of general relativity and later became particularly relevant in the context of string theory and certain areas of theoretical physics. In a broader cosmological context, the universe's history is described by various cosmological models, including the Big Bang model, which is widely accepted as the current description of our universe's evolution. The universe is thought to have started with the Big Bang, and its early moments are described by models like cosmic inflation and the hot Big Bang theory, which are characterized by different spacetime geometries and physical conditions. AdS space becomes relevant in specific theoretical contexts, often involving high-energy physics and the study of black holes.

Proposed System

Given its scope, it's no surprise that the AdS/CFT duality has been so fruitful in clarifying both ends of the correspondence: on the one hand, we can use gravity to perform calculations within strongly-coupled quantum systems that would have been impossible without it, and on the other, we can use our understanding of quantum field theories to better understand (quantum) gravity. From the viewpoint of general relativity, either way is exciting; the former displays the remarkably large number of GR's applications, while the latter tells us something new about gravity itself.

On the topic of applications, one may, of course, raise the objection that super-Yang-Mills is a conformal field theory, which is quite different from the'real-world' systems that we are attempting to comprehend. The astonishing reality is that despite this, it serves as a priceless toy model for researching universal variables that are shared by more well-known systems as well as for investigating novel groups of phenomena that are highly connected.

Applying this idea to quantum chromodynamics has resulted in the successful synthesis of lattice QCD and heavy ion phenomenology with gauge/string duality through the AdS/QCD program; for a more condensed summary, see [114], and for more in-depth studies, see [115, 116]. Although the possibility of linkages between string theory and particle physics has been predicted in some form or another since the 1970s, it comes as somewhat of a surprise to see that this philosophy can also be applied to a variety of systems that include condensed matter. This software, which goes by the name AdS/CMT, has proved very effective in describing a wide variety of physical processes, ranging from superfluid transitions to the behavior of non-Fermi liquids; for further in-depth assessments, see, for example, [117–119]. In each of these programs, the AdS/CFT correspondence not only offered the greatest instrument (and frequently the only tool) to solve the physical issues of concern, but even more surprisingly, these computations actually propose values that coincide with empirically observed quantities50 in the real world! This is a remarkable achievement. These two initiatives have both developed into active and continuing study fields in recent years. In the following, we will simply focus on a single facet of each to illustrate how successful they are, and we will direct the reader to the exemplary evaluations that were discussed earlier in this paragraph for a more in-depth analysis of the topic.

AdS/QCD

Quantum chromodynamics, the theory of the strong interactions between quarks and gluons, is a gauge theory based on the gauge group SU(3) (i.e. quarks come in $N_c = 3$ colors). Unlike super-Yang-Mills, QCD is neither super symmetric, nor a conformal theory since the coupling runs: at large energy scales the coupling becomes weak (i.e. QCD is asymptotically free), whereas at low energies it is strong. Below a certain ‘confinement’ temperature, the physical degrees of freedom are confined into color singlet hadrons (so thermodynamic quantities scale as N_c^0), whereas for higher temperatures the quarks and gluons deconfine into a ‘quarkgluon plasma’ (with N_c^2 scaling). At temperatures slightly above the deconfinement transition, which are typically the relevant ones for the quark-qluon plasma created in heavy ion colliders, the quarks and gluons are still strongly coupled. This naturally provides an excellent window of opportunity for holographic techniques. More broadly, while at zero temperature, super-YangMills and QCD are very different, one would expect that since finite temperature breaks both super symmetry and conformal invariance, the two theories become more alike in that regime, as has indeed been observed experimentally. Understanding confinement remains one of the important problems in QCD, so it is inviting to study it in other theories which serve as toy models for the real world. Confinement indicates that quarks are connected by flux tubes, with energy proportional to length. In the bulk dual, this flux tube (the large-N version of the QCD string) stretching between the quarks is codified by a fundamental string, which ends on the boundary at the position of the quarks. Hence the thick QCD string in 4 dimensions gets described by an infinitesimally thin fundamental string in the 5-dimensional bulk. Since the fundamental string wants to minimize its world sheet area (which determines its energy), it ‘hangs’ form the boundary into the bulk. We have already seen an analogous effect manifested in Fig. 1 (green curves, which in this context would represent snapshots of the string at a given time, and whose endpoints would represent the quarks). While the SYM on R 4 does not exhibit confinement (there is no independent length scale in the problem), we have already seen in §3.4 that SYM on Einstein static universe does exhibit a confinement deconfinement transition. More realistic setup involves a geometry where a spatial circle smoothly caps off, such as the ‘AdS soliton’ constructed, where the string cannot extend beyond the bottom of the geometry. Such a geometry automatically enforces a regime with the confining condition of energy of quark - anti-quark pair growing linearly with their separation: if the string endpoints are much further separated than the scale determining where the geometry caps off, the string extends along the bottom and recovers the scaling (i.e. linear growth with quark separation) characteristic of confinement. In this way, the AdS/CFT correspondence offers a simple picture of quark confinement.

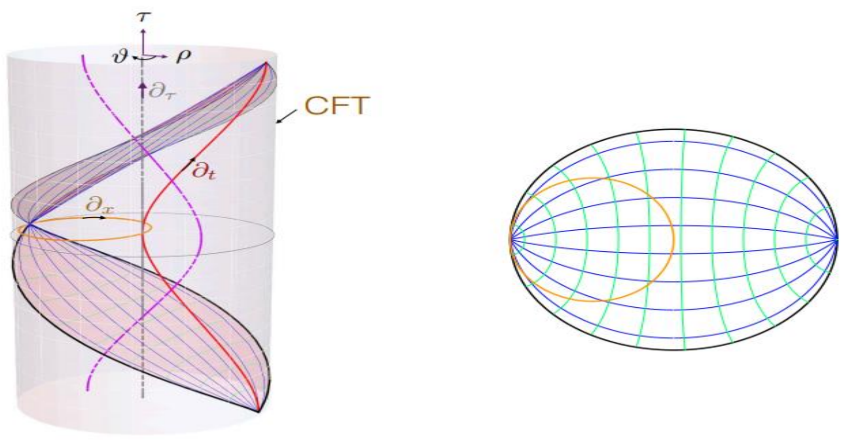

Fig. 1 L: Schematic plot of global AdS[5], showing the Poincar´e patch. The vertical coordinate is τ, the horizontal radial coordinate is $\tan^{-1}\rho$ (so that the spacetime is drawn compactified and radial null geodesics are at 45 degree angle), and the angular coordinate ϑ is one of the S^3 directions of the AdS. Poincare horizon is a null surface [red] (generated by null geodesics [blue]) whose constant-τ slices are spacelike extremal surfaces anchored on spherical regions or (on equatorial slices of S^3) spacelike geodesics [green]. For orientation we have also plotted two z = l (equivalently r = l) curves, one at constant $x^i = 0$ which describes orbit of $\left(\frac{\partial}{\partial t}\right)^a$ [red ∂t], and one at constant t = 0 which describes or bit of $\left(\frac{\partial}{\partial t}\right)^a$[orange ∂x] willing fields. Also shown are two time like geodesics are static at 'center' of global AdS following $\left(\frac{\partial}{\partial \tau}\right)^a$ [grey $\partial\tau$] and one [purple] reaching to p = l, to illustrate the confining nature of AdS. R: Poincare disk of AdS, which is a spatial (constant τ) slice of AdS. Spacelike geodesics and projections of null geodesics, as well as the z = l, t = 0 curve, are drawn [with the same color scheme as in the left panel].

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Instead of considering a meson, one could also consider just a single quark. The bulk dual is again a fundamental string ending on the quark. As the quark moves and accelerates, the bulk string trails behind accordingly. One can compute its back reaction on the bulk spacetime, and from this read off the boundary stress tensor $T^{\mu\nu}$, which in turn indicates the energy-momentum distribution in the strongly-coupled plasma through which the quark propagates. This then allows us to study interesting features such as the drag the quark experiences in moving through the plasma, its radiation due to acceleration, the propagation and dispersion of this radiation through the plasma, and so on. It is rather intriguing that the bulk string codifies both the quark (and its surrounding gluonic cloud) as well as the radiation it produces. In fact, cutting off the same bulk configuration at different radial distances allows us to extract the physics of a 'dressed quark', including radiation damping and effects of acceleration on the surrounding gluonic cloud, in very simple way. While from the field theory perspective these are rather complicated and sometimes puzzling effects (such as the well-known pre-acceleration effect), the bulk dual naturally provides neatly-packaged and automatically self-consistent description.

Conclusion

Gravity/Gauge duality linkages AdS space, a curved spacetime in general relativity, and CFT, a quantum field theory on its boundary. String theory and quantum gravity progressed much from this relationship. Many features of AdS/CFT depend on black holes: The AdS/CFT connection shows that a higher-dimensional AdS space's physics is dual to its border's lower-dimensional CFT. Holography suggests boundary theory encodes AdS space information. Dual CFT studies of AdS space black holes' thermodynamics and quantum properties are fascinating. Flat spacetime thermodynamics influences AdS black holes. Their entropy depends on temperature and horizon area. Researchers can examine black hole thermodynamics in a highly linked region, but traditional quantum field theory makes it difficult. The black hole information paradox, a longstanding physics puzzle, was revealed through AdS/CFT correspondence. Black hole particles destroy data. According to AdS/CFT, border CFT particle correlations may encode information. Black hole stability and quantum behaviour are studied using AdS/CFT correspondence. Information loss, black hole evaporation, and Hawking radiation are covered. The link enables two black hole descriptions. General relativity in AdS space or border CFT may explain black hole features. The two ideas are identical but provide distinct black hole physics insights. Black holes in the AdS/CFT correspondence provide a unique and powerful framework for understanding gravity, quantum field theory, and spacetime basic structure. This rich interaction is studied to understand black hole physics and the cosmos.

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