LOI: Warped Extra-Dimensional Geometry and Localized Gravity

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Extra dimensions have been a part of physics since the early 20th century when Kaluza first proposed them as a means of unifying forces. The idea had a renaissance in the late 1990s when the potential phenomenological applications were recognized (and the notorious chirality problem was solved with branes and string constructions). As an outgrowth of that effort, new solutions to Einstein's equations—in particular warped extra-dimensional geometry with localized gravity -- motivated in part by string theoretical constructions with branes were discovered [1] whose implications have had far-reaching consequences well beyond the initial phenomenological domain but including those as well. An important connection and reason for this is the relation to AdS spacetime, where many new and exact results have been found. Because of the diverse phenomenological and cosmological applications, the discovery of a truly novel model building element, and the potential to exploit dualities to better understand strong interactions and conceptual aspects of the gravitational theory, warped extra dimensional geometries have had a sustained and consequential impact and are likely to do so in the future.

We propose a part of the Snowmass report which reflects on warped extra-dimensional geometry and its tentacles in phenomenology, cosmology, gravity wave physics, string constructions of de Sitter space, and black hole information. The first few topics were an immediate outgrowth of the initial study of the hierarchy problem and warped extra dimensions. The latter topics grew out of the work in string theory trying to find tractable realizations of de Sitter space and the search for tractable models to study black hole entropy and evaporation (see https://arxiv.org/abs/2006.06872 for a review) , particularly in more than two dimensions. In this brief LOI we very briefly enumerate some of the ways the geometry appears in a variety of contexts that can feature in the theory initiative—particularly in its attempt to unify the cohort of activities currently underway.

Model Building, Phenomenology, and Cosmology

The realization in the late 90s that the existence of extra spatial directions can be compatible with observations has generated a long and fruitful body of work in particle physics phenomenology. Warped extra dimensions provide a natural framework in which to address the hierarchy problem for the Higgs boson, as well as the fermion mass hierarchy(the flavor problem). This is important because the true challenge of addressing the hierarchy problem is to explain both the weak gauge boson mass scale and the structure of the fermion mass spectrum we observe. For warped

[1] Strictly speaking solutions were known but not widely recognized or applied.

geometries these hierarchies have a natural (dual) interpretation in terms of partial compositeness. Furthermore, the distinction between the quark and lepton hierarchy has a compelling explanation in this scenario.

The phenomenology of this framework beautifully fits the dual description of new physics models based on strongly coupled dynamics, using AdS/CFT correspondence suitably modified for the purpose. The generic predictions of the existence of higher mass partners of the 4D graviton, and of various SM fields in well-motivated extensions, generically called KK modes, has and continues to drive activities in collider experiments such as LHC. The arena provides distinct, feasible but challenging possibilities at colliders and has led to the development of several ideas for novel signatures to look for in collider phenomenology. The warped extra-dimensional framework has also led to new perspectives on gravity-- that a 4D massless graviton can be compatible with a higher dimensional world without compactification, that a massive bound state can play the role of a graviton, and that solutions to the cosmological constant problem in toy models can be addressed.

Using the duality, warped extra-dimensions have the potential to provide a way to calculate observables in strongly coupled theories.Model builders can explore and simulate nonperturbative particle dynamics that were previously intractable. For example, the radiation patterns of collisions are inherently distinct from QCD at the LHC, therefore these models could facilitate the development of anomaly-based new physics detection. This has also allowed theoretical computations relevant to the properties of the quark-gluon plasma, which can be performed in geometric language but are hard to perform directly due to strong coupling.

The cosmological evolution of a warped extra-dimensional world is another potential boon for observations. The high temperature phase can be thought of as an AdS-Schwarzschild black-brane geometry whereas the low temperature phase is dominated by the radion potential in the low temperature regime. The phase transition is likely to be first order, so it has the potential to be readily distinguishable from other electroweak scenarios. Robust features of this phase transition can allow a unique way to probe the scenario, for example in possible gravitational-wave signals, and modification of relic abundance of constituents of our universe (e.g. dark matter, baryons). The signatures of such a transition might be seen in the stochastic gravity wave background. The strength of the gravitational wave background increases with the duration of the phase transition, and this is naturally larger in warped models, structurally tied to generation of large particle physics hierarchies. Also, at extremely high scales, warped extra-dimensional structure can underlie orbifold grand unification. Associated Kaluza-Klein excitations, with masses orders of magnitude beyond collider reach, can nevertheless imprint themselves on primordial non-Gaussianities that can be probed in precision Large Scale Structure and 21-cm cosmology measurements.

Warped Geometry and Formal Applications/Implications

Warped geometries with branes have found important applications in addressing fundamental questions in quantum gravity and string theory. Crucial for this connection is the fact that these braneworlds naturally result in geometries that are locally AdS space and so can be interpreted with the AdS/CFT correspondence. The latter asserts that gravity on AdS is equivalent to a conformal field theory living on its boundary, providing a setting in which quantum gravity can be reliably studied. This connection to AdS/CFT allows an interpretation of warped compactifications with branes in a dual field theory language with interesting consequences (non-perturbative RG,compositeness). One application that was realized early on is that this connection provides a generalization of AdS/CFT to spaces with boundaries. As a direct offshoot of this investigation, the first example of a consistent theory of interacting massive gravity was uncovered which paved the way for many of the advances that followed in this arena.

More recently, the same tools have found interesting applications in addressing questions about black hole evaporation. Brane worlds naturally provide a setting in which AdS gravity can be coupled to an external bath, allowing the study of black hole evaporation in the well-controlled setting of AdS/CFT. The crowning achievement of this line of thinking was an exact determination of the so-called Page curve, the unitary evolution of the entanglement structure of the black hole and its Hawking radiation. While many of the important insights gained from this investigation are presumably valid much more broadly, examples in which this calculation is under control crucially rely on the physics of branes, which in this context are often referred to as end-of-the-world branes. Also recently, RS2 modeling has been invoked as a key feature in the construction of smooth traversable wormhole solutions.The subject of asymptotic symmetries has also enjoyed renewed interest in the last several years. In this context, novel infinite-dimensional asymptotic symmetries of gravitational theories in asymptotically AdS4 spacetime were discovered by exploiting an RS2-like substructure (in one lower dimension).

Another more formal application that has grown too out of phenomenological observations is the development of controlled models of de Sitter space, such as the one famously pioneered by Kachru, Kallosh, Linde, and Trivedi. The observation of a positive cosmological vacuum energy is a big challenge in string theory in that the only controlled models that resemble our world rely on spacetime supersymmetry that can never have a positive energy vacuum. Breaking supersymmetry in a controlled fashion when the associated energy is far less than that of electroweak physics introduces a big challenge. One way to address this is to generate a small parameter through warping—one that competes with a supersymmetry breaking energy that is suppressed by mass scales. This theory has introduced a good deal of interest and controversy and has in part catalyzed the swampland studies which are quite prevalent now.m and will continue to dominate some studies of string vacua.
Another recent application considered warped geometry ending on a brane, leading to an effective reduction of the dimensionality when certain conditions are met. This idea was useful in deriving the infinite-dimensional asymptotic symmetries present in 4-dimensional AdS space, previously thought to be absent. Using a weak gauging of a 3D CFT (dual to 4D AdS) and in a probe limit of the gauging, the correlators were seen to effectively become 2D CFT like, and seen to satisfy Virasoro and Kac-Moody ward identities.

Summary:

This is a brief sampling of some of the important implications of warped geometry and its underlying resurgence and persistence in recent years. Both theoretically and phenomenologically it yields tractable testable examples that can be rigorously studied in detail. We think this work has had sufficient impact to merit its own section in a Snowmass type study.

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