Research Statement

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Recent research activity: Braneworlds from the Swamp

Understanding the microscopic nature of dark energy remains one of the most difficult challenges at the intersection of cosmology and string theory. Lately, it has become increasingly clear that building even the most basic models of cosmology through flux compactification mechanism poses a highly non-trivial task, where obstructions like scale separation, moduli stabilisation and supersymmetry breaking must be overcome. [1] Furthermore, the swampland program restricts even more the requirements that any lower-dimensional EFT has to satisfy in order to be consistently embedded within quantum gravity. These difficulties seem to force us to venture into unexplore regions of the landscape, where our current understanding of string theory is put to the test. [2]

A promising avenue is to explore alternative constructions in the context of braneworld cosmology, a direction I have pursued through my doctoral studies at Uppsala University and postdoctoral research at Kyoto University. While early braneworld models–as Randall-Sundrum-II (RS-II), Karch-Randall (KR) or asymmetric braneworlds–seemed to offer elegant mechanisms to reproduce induced four-dimensional cosmologies on a brane, they were later found to suffer from anomalous gravitational behaviour, unnatural fine-tuned tension and a lack of reliable UV-embeddings into string theory. However, swampland conjectures–non-susy AdS decay and cobordism to nothing conjectures–have renewed interest in braneworld cosmology by transforming quantum gravity constraints into constructive design principles. Making virtue of necessity, these conjectures provide a novel laboratory for testing fundamentally new braneworlds: the Dark Bubble (DB) and End-of-the-World (ETW) brane models, both capable of reproducing viable accelerated four-dimensional cosmologies with rich phenomenological implications. [3, 4]

The **Dark Bubble** model, motivated by the non-susy AdS decay conjecture, envisions an accelerated expanding four-dimensional cosmology riding the boundary of a decaying non-supersymmetric AdS$_5$ vacuum, colloquially called the bubble. The region of AdS$_5$ enclosed by the boundary, i.e. a subcritical D$_3$-brane, nucleates with finite size and expands towards the AdS boundary via a Brown-Teitelboim instanton. The critical-subcritical tension difference is interpreted as a small positive dark energy density on the induced cosmology. Through systematic analysis of its gravitational perturbations and consistency checks that I have substantially contributed with during my research career, this model crucially reproduces the normal behaviour of four-dimensional gravity [5], can be decorated with dust matter and both gravitational and electromagnetic waves. [6, 7] Moreover, its string theory embeddings yield a novel hierarchy of scales where *scale separation* is implemented via the tension-to-charge ratio of the expanding brane, rather than small extra dimensions. [8–10]

A recent complementary yet conceptually distinct construction is that of the **End-of-the-World** (ETW) braneworld cosmology. This model proposes that our observable universe rides on a boundary separating a finite five-dimensional AdS$_5$ spacetime from a "nothing" region, à la Brown and Dahlen formulation (i.e. $L_{\text{AdS}} \to 0$). [4] However, this picture may naïvely lead to the conclusion that the brane has infinite negative tension. This is no longer true when holographic renormalisation is applied, rendering a brane with finite positive tension acting as boundary of spacetime itself. My ongoing collaboration with Padilla and Muntz, authors of the original work, focus on constructing a concrete UV-realisation of ETW branes, by exploring candidate configurations of Ads$_d \times \mathcal{M}_{D-d}$, where internal cycles are stabilised with the addition of topological fluxes. Early results indicate that its fundamental tension (and associated moduli) may be constrained by the presence of these topological contributions. This points to promising pathways toward understanding ETW brane's nature, offering complementary phenomenological descriptions to the ongoing rigorous mathematical approach by the swampland community.

Future research

The following research trajectory is a natural continuation of my previous work, aiming to advance the rigorous theoretical and phenomenological development of new braneworld models. These can be categorised in three interconnected research axes:

- A rigorous development of an universal junction-condition formalism applicable to arbitrary-codimension hypersurfaces in higher-dimensional geometries with arbitrary normal vector orientation. Such mathematical machinery remains essential for clarifying the microscopic consistency of the Dark Bubble's UV-embedding as well as understanding the fundamental features of braneworld's UV-embedding with co-dimension > 1 when compact dimensions are accounted for.
- As previously commented, early results of ETW braneworld's UV-embedding suggest a research continuation exploring the comparison of ETW branes to regular spacetime boundaries given arising constraints in its fundamental moduli behaviour. It would be enlightening to further explore how the critical exponent behaviour changes when the ETW-brane is present before the compactification process. [11] Furthermore, this string theory embedding provides a rich induced structure with scalars living on the boundary, providing an interesting playground to test inflation predictions on the induced cosmology in this higher-dimensional model.
- The dark bubble construction cannot only provide a higher-dimensional interpretation of dark energy's nature, but it also derives the four-dimensional GW spectrum and the EFT of electromagnetism from the bulk field dynamics and their interactions with the expanding brane. This suggests that other sectors of the Standard Model can find a higher-dimensional interpretation through this construction. Specifically, neutrino masses could be interpreted as Kaluza-Klein (KK) modes of bulk right-handed neutrinos coupling to brane-localized left-handed neutrinos. Computing how this coupling is affected by the internal dimensions' warping, one could formulate a lepton interaction action and extract the exact masses for left-handed neutrinos from the resulting KK tower. These computed neutrino masses can then be directly compared against future experimental cosmological and high-energy physics bounds, providing a falsifiable test for the Dark Bubble construction.

Beyond these main objectives, I remain interested in exploring how these novel braneworld constructions can serve as valuable theoretical laboratory where swampland conjectures can be tested and refined. These settings may provide controlled frameworks to probe (new) fundamental quantum gravity constraints. Moreover, and tangentially related to previous proposal, my curiosity is leaning toward the exploration of non-perturbative decay hierarchies and moduli physics within broken SUSY backgrounds. Specifically, on how WGC constrains brane decay rates in realistic string compactifications with broken SUSY backgrounds. To have a better understanding of these constraints, with emphasis on their interplay with moduli stabilisation, could reveal interesting connections between quantum gravity consistency conditions and observable phenomenology.

References

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