45 YEARS OF THEORY AT ICIMAF: FROM FIELDS TO STRINGS

45 AÑOS DE TEORÍA EN EL ICIMAF: DE CAMPOS A CUERDAS

N. Cabo-Bizet[a†]

División de Ciencias e Ingenierías, Universidad de Guanajuato, Loma del Bosque 103, 37160, León, Guanajuato, Mexico; nana@fisica.ugto.mx[†]
† corresponding author

Recibido 22/3/2021; Aceptado 20/6/2024

With this work, we celebrate the 45th anniversary of the Theoretical Physics Group (GFT) of ICIMAF in two aspects: historical and scientific. The article is based in the talk given at the conference FT-45. Anecdotes of the group's influence on the author's development are presented, and the impact the group has had on the Cuban community is described. A research direction, inheriting the group's work, is presented by reviewing recent advances in the study of the landscape of effective theories derived from string theory. The exploration of string theory vacua in extra toroidal dimensions and with fluxes, using Machine Learning is described [1]. This method consists of a neural network coupled with a genetic algorithm. Additionally, the constraints on quantum gravity theories in this model are explored. In particular, the well-studied conjecture that stable de Sitter (dS) vacua do not appear in effective theories consistent with gravity is addressed. We conclude by mentioning an avenue for exploring the landscape, related to the GFT's tradition.

Con este trabajo celebramos los 45 años del Grupo de Física Teórica (GFT) del ICIMAF en dos aristas: histórica y científica. Este artìculo se basa en la charla impartida en el evento FT-45 por la autora. Se presentan anécdotas de la influencia del grupo en la formación de la autora y se describe el impacto del GFT en la comunidad cubana trabajando en temas relacionados a la teoría cuántica de campos y a la gravitación. Se presenta una dirección de investigación, heredera de la labor del grupo, revisando recientes avances en el estudio del paisaje de teorías efectivas provenientes de la teoría de cuerdas. Se describe la exploración de vacíos de la teoría de cuerdas en dimensiones extras toroidales y con flujos, empleando Aprendizaje de Máquina. Este método consiste en una red neuronal acoplada a un algoritmo genético [1]. Además, se exploran las restricciones a las teorías de gravedad cuántica en este modelo. En particular, se aborda aquella, muy estudiada, que implica que no aparecen vacíos de Sitter (dS) estables en teorías efectivas consistentes con gravedad. Concluimos mencionando una vía futura de exploración del paisaje, relacionada a la tradición del GFT.

PACS: Quantum Gravity (Gravedad Cuántica), 04.60.m; Supersymmetry (Supersimetría), 11.30.Pb; Field Theories in dimensions other than four (Teorías de campo en dimensiones superiores a 4), 11.10.Kk.

I. 45 YEARS OF HIGH ENERGY PHYSICS AND GRAVITATION IN HAVANA

My scientific work and personal development owe a deep gratitude to the Theoretical Physics Group of the Institute of Cybernetics, Mathematics, and Physics (ICIMAF) of the Cuban Science Ministry. My earliest memories of the group include hearing about the discussions my father had and the articles he was working on during the afternoons when my mother, brother, and I waited for him in the car outside the ICIMAF building. This building, an old construction, was one block away from the Malecón, the wall that separates us from the sea of Havana. We could feel the wind and the quieter activity of the streets in the Vedado neighborhood before sunset. Sometimes, we spent our time queuing to order pizzas at the restaurant "La Piragua" (The Canoe), in front of ICIMAF, situated in the park that separated the building from Malecón Avenue. Other times, we all went together to have dinner at "Pio Pio," the Cuban fried chicken chain.

The concepts of articles and discussions then sounded like a sacred enterprise occurring within the Theory Group walls, brought to life by its members, and of the utmost importance in my childhood memories. It was serious work because they were understanding nature and pursuing knowledge. The word "theory" back then also sounded crucial, its meaning perceived as imagining and understanding the intrinsic workings of the Universe's phenomena, such as quarks in the atomic nucleus or distant, massive black holes.

Maybe the longest we waited was one hour, but I felt that during that time, crucial things were happening among my father and his friends-colleagues. Before sunset, we would take the car and drive along the Malecón, to the end, over Port Avenue, passing Havana's old city, and then take the Vía Blanca to find the "Virgen del Camino" (Virgin of the Road) and enter our neighborhood, San Miguel del Padrón. It was a 15-kilometer journey that took a bit more than half an hour after everyone in the family had completed their day's mission.

The afternoons outside of ICIMAF gave me the accurate feeling that concentration and interactions with others were essential for thinking about scientific problems.

As a kid, teenager, and then adult, I recall the wisdom of Hugo Pérez Rojas, the group's founder. He always had interesting opinions on physics and society. I read his book on physics for the general public, and his iconic phrase: "The perfect is the enemy of the good", is an important lesson to follow. This sentence helps to finish projects, wrap up, and decide when to stop, whether in personal or professional endeavors.

The camaraderie among the group's members has always been dear to me as well. Among my fondest childhood memories was the day Anatoli Shabad surprised us by arriving from Moscow at our door with a bag of chocolates in hand. He was my father's PhD advisor, a researcher at the distinguished Lebedev Institute in Moscow, and a great leader for the ICIMAF Theoretical Physics Group. Shabad supported the group with guidance and information during the pre-digital and pre-internet era. In every visit, he brought the latest scientific news and publications. Many times when he visited the group, he stayed in the Academy of Science Guest Houses, sometimes in Cojimar, far from Havana's center, but he gladly did it as his personal mission.

In our childhood, the son of Augusto González, Augustico, had a cousin who attended the same school as my brother Alito and I. Augustico's cousin was also Alito's "cousin", and he defended him at school accordingly. I have always cherished the conversations I had with group members and the scientific culture they fostered in me. Within the group, there was a tradition of many students attending the Diploma program at the International Centre for Theoretical Physics (ICTP). There were many ICTP diploma students preceding us, which opened the possibility for me to take part in that program. This path helped me pursue research in String Theory.

There were also other members, not officially working at ICIMAF, but part of the scientific work carried out. Over the years, there was a sense of belonging and mutual support. In my case, Alain Delgado, who did his PhD in the group under the supervision of Augusto González, helped me join the Physics Department of the Center of Technological Applications and Nuclear Development (CEADEN). This helped me start collaborating with the group and allowed me to conduct research in High Energy Theory by securing a junior research position.

From my father's passion for science and his approach to problem-solving, I knew I wanted to understand nature myself. As a kid, the activities I did with my dad were mostly artistic; we would paint landscapes together, often featuring Chinese pagodas. Later, when I started attending Physics Olympiads, he gave me problems to solve and sometimes explained concepts to me. I also studied his famous problem from the 1991 Cuban International Physics Olympiad (IPhO), which involved a rotating sphere falling to the ground. When I studied physics, I completed my bachelor's and master's degrees in condensed matter theory with the group at the University of Havana, and I was co-advised by him. This was our first research interaction, from which others followed, initiating my research in quantum field theory. My favorite works in collaboration with him are in Quantum Chromodynamics (QCD) [2], the only paper that my father, my brother, and I share. I am also fond of a collaboration work on Statistical Physics for metastable states [3], which involves statistics similar to Tsallis statistics in a certain class of physical systems [4]. I am very happy with our latest collaboration, together with colleagues from GFT and the University of Guanajuato, based on an idea proposed in [3]. I will mention this work at the end of this article. It explores quantum corrections in effective field theories arising from string theory, which could lead to modifications of the cosmological constant.

The theory group tradition has led to numerous investigations in high energy theory at the international level over the last three decades, particularly in string theory and physics beyond the standard model. There are many Cuban researchers linked to the group who have been conducting research at international institutions; they are a testament to the legacy of the GFT.

Before starting with the physics we will present, I would like to thank Iraida Cabrera-Carnero, a talented scientist who began her scientific education at ICIMAF, for her editing and suggestions that improved this celebratory article. Let us conclude this section by stating that one central subject of research of the GFT is the application of quantum field theory (QFT) to a variety of physical problems. Their areas of research range from quantum chromodynamics and gravitational objects to low-dimensional condensed matter systems.

II. HIGH ENERGY PHYSICS THEORY, GRAVITATION AND STRINGS

The language of particle physics is QFT, and the language of gravitation is General Relativity (GR). These two frameworks are incompatible in regimes of large curvature and small distances, i.e., one cannot describe a quantum field theory of gravity. String Theory (ST) offers a framework to describe gravity at the quantum level. The work of the GFT-ICIMAF has focused on applications of QFT and GR; both avenues must be understood before studying ST. ST has the potential to describe the four fundamental interactions of nature. It leads to solutions that unify the electroweak and strong forces with gravity at the quantum level, at the Planck scale $M_{pl} = \sqrt{\hbar c/G_N} \sim 10^{19}$GeV.

Supersymmetry (SUSY) transforms boson fields into fermion fields. A theory with $\mathcal{N}$-supersymmetry possesses $\mathcal{N}$ spinorial generators that exchange spin statistics and leave the action invariant. For example, in $\mathcal{N} = 1$ SUSY in 4D, every complex boson field ϕ with spin 0 has a supersymmetric partner, a Weyl fermion ψ with spin 1/2. As a graded algebra, SUSY evades the Coleman-Mandula theorem [5], which establishes that internal and space-time symmetries in a theory cannot be mixed [6]. It also has phenomenologically interesting features, such as the unification of gauge interaction couplings and the treatment of the hierarchy problem.

In analogy to a relativistic point particle, strings are described in space-time coordinates by an action of a world-sheet, invariant under (super) reparametrizations. Consistency is achieved by quantizing that action, and Weyl (super)symmetry is maintained in 10D, requiring 6 extra dimensions. Those typically have a small radius R ($\sim l_s$) and are compact. The string scale l_s determines the masses n/l_s with $n \in \mathbb{N}$ of the tower of states. The massless modes of the spectrum give rise to the elementary particles. In the simplest case, they have the same structure at every point of space-time. General Relativity and gauge theories are related via the

Kaluza-Klein hypothesis [7, 8]. In ST, these extra dimensions are given by Calabi-Yau (CY) varieties [9, 10].

III. SWAMPLAND AND LANDSCAPE

The compactification leads to an ample landscape of vacua; CY varieties with fluxes give $\mathcal{N} = 1$ in 4D, where in principle all moduli (scalar fields) can be stabilized and could acquire masses as well. For the statistics, an estimate of the flux vacua is given by L^K, where L is the number of fluxes, and K is the number of cycles of the CY compactification [11]. Vacua of compactified string theory with fluxes are finite [12, 13]. This results from flux conditions and restrictions from SUSY and dualities. The number of string vacua is estimated to be $\mathcal{O}(10^{500})$ [14]. Characteristics such as the value of the cosmological constant and the scale of SUSY breaking can be analyzed statistically. In non-perturbative type IIB strings (F-theory), there is an estimate of $\mathcal{O}(10^{272000})$ solutions [15].

The landscape [16] is the set of apparently consistent semi-classical theories that come from quantum gravity. Thus, the question arises: how big is the landscape in the larger space of semi-classical descriptions of quantum gravity without a UV completion? [16, 17] The landscape constitutes islands in the Swampland. It is the set of all effective theories consistent with a UV completion of gravity [18]. The latter yields restrictions on the consistency of effective field theories; some of these are conjectural and are known as the Swampland conjectures.

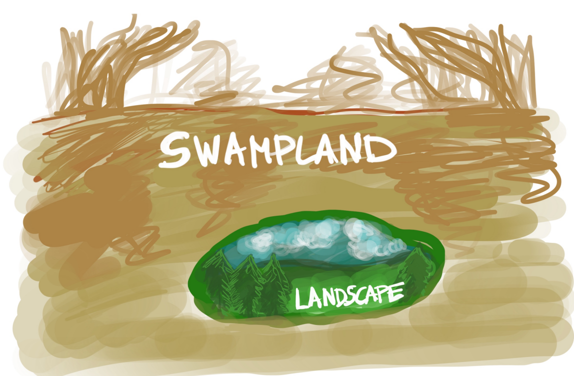

Figure 1. The landscape and the swampland of string theory are represented. The set of field theories consistent with quantum gravity (landscape) is expected to be a set of zero measure with respect to the Swampland.

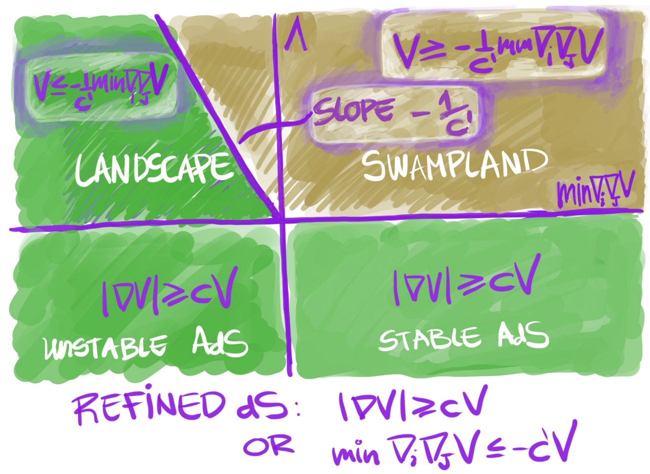

Figure 2. The refined dS conjecture is represented. On the x-axis, we have the minimum eigenvalue of the mass matrix, and on the y-axis, the value of the potential at the vacua, i.e., the cosmological constant.

One of the swampland conjectures is the non-stable dS conjecture. This conjecture states that in any low energy limit of a consistent quantum gravity theory:

$$\left|\nabla \mathrm{V}\right| \geq \mathrm{cV}, \tag{1}$$

or

$$\min \nabla_i \nabla_j \mathrm{V} \leq -\mathrm{c}'\mathrm{V}, \tag{2}$$

with $c, c' > 0$ and $c, c' \sim \mathcal{O}(1)$ in Planck units. Examples: 1) A single scalar field ϕ with potential $V = \frac{m^2\phi^2}{2}$ has $\frac{|\nabla V|}{V} = \frac{2}{|\phi|}$, which can be trusted for $|\phi| \leq 1$. 2) AdS vacua fulfill the conjecture, as $V < 0$. This is supported by the fact that so far, all the dS vacua constructions in string theory are not fully controlled solutions. We consider extrema of a scalar potential (V) given by $\nabla_i V = 0$ (string vacua) [19–22].

IV. EXPLORING THE STRING LANDSCAPE WITH ML

Machine learning allows to explore large amounts of data for specific patterns. It provides in shorter times more exhaustive checks than standard programming. Artificial neural networks (ANNs) algorithms, inspired by the biological learning process have been used in several fields. The use of machine learning techniques to solve classification problems with supervised learning applied to high energy physics has seen many developments in recent years [23]. Employing supervised machine learning, consisting of a ANN coupled to a Genetic Algorithm(GA) [24–26], we were able to determine more than sixty thousand flux configurations yielding a scalar potential with at least one critical point. Unstable dS vacua with small tachyonic mass and large energy are absent, in accordance to the Refined de Sitter Conjecture.

Hierarchical fluxes [27, 28] favor perturbative solutions with small values of the vacuum energy and moduli masses, as well as scenarios with the lightest modulus mass much smaller than the AdS vacuum scale.

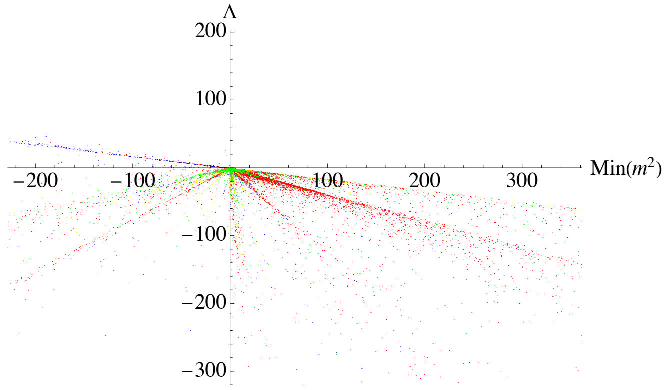

Figure 3. Cosmological constant versus minimum of the mass eigenvalues in the vacua solutions. There are not stable dS as dictates the refined dS conjecture. This figure was originally presented in [1].

The perturbative regime $g_s \ll 1$ is associated to a small value of the scalar potential in the minimum $|\Lambda| \ll 1$, suggesting a correspondence $\Lambda = \pm\exp(-1/g_s)$. There is a statistical compatibility with the refined dS conjecture. The vacua explored in the plane Λ vs. $\min(m^2)$ are in the region $V_{min} \leq -\min(m^2)/c'$. Most of the extrema have $c' < 6$. Then, there are 9 points with $c' \sim 10^{-1}$ and there is a point with $c' = 0.033 \sim 10^{-2}$. This could be the boundary of the string theory landscape. We find also an AdS scale separation: $\min(m^2)L^2_{AdS} \leq c$, with c of order 1.

We observe the redefined dS conjecture in the distribution of the extrema for the scalar potential of the figure. Red and blue points represent critical points with hierarchical fluxes whereas green and yellow points correspond to critical points with non-hierarchical fluxes.

V. CONCLUSIONS AND OUTLOOK

The vacua exploration employing ANN+GA was successful and the method is ready to be applied in other setups. We can consider more extensive datasets and more refined selection criteria in different string theory setups that give rise to scalar potentials. In the future we intend to check:

1. The existence of hierarchies between the 4D and internal 6D scale [29].
2. Type IIB flux compactifications in Calabi-Yau varieties with few moduli, such as those with a single complex structure $h^{21} = 1$. These models possess more generic features of the string landscape.
3. Incorporate constraints from 10D Einstein equations into the classification [30, 31] with an ANN.

Finally, let us mention that we are exploring whether quantum corrections have a say in the dS conjecture [32] in collaboration with two GFT members, Elizabeth González and Alejandro Cabo, and also with Oscar Loaiza and Damián Mayorga. The idea is to consider the effective QFT arising from a ST compactification for one of the discussed models, and to compute the corrected scalar potential for a scalar field that still has no vacuum expectation value (vev). In the work [32], corrections obtained by the coupling of fermions to scalars were tested to give a contribution to the scalar potential, that can rise the energy at the vacuum, i.e., the value of the scalar potential at the vev of a given scalar ϕ, $V(\phi)$.

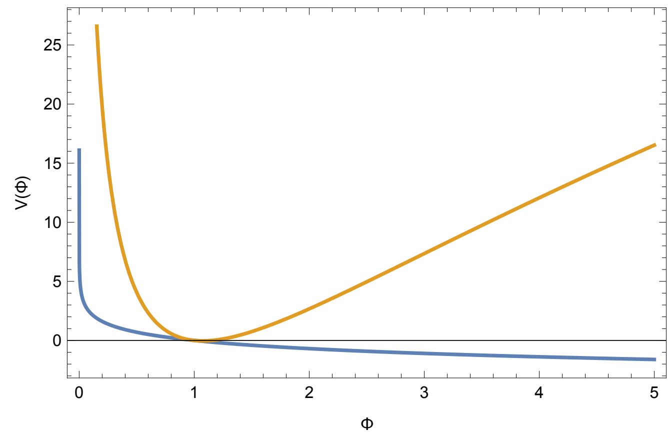

Figure 4. Schematic illustration of the scalar potential generated for a string theory modulus field $V(\Phi)$. The yellow line represents the one-loop contribution $V_1(\Phi)$, while the blue line represents the combined one and two-loop contributions $V_1(\Phi) + V_2(\Phi)$ [32]. The minimum of the potential has a positive cosmological constant $\Lambda > 0$. This is an effective QFT mechanism to stabilize moduli proposed by A. Cabo [32–34].

VI. ACKNOWLEDGEMENTS

I would like to thank Ernesto Altshuler, Milagros Bizet Franco, Alejandro Cabo Montes de Oca, Alejandro Cabo Bizet, Iraida Cabrera, and Alejandro Salinas for their valuable comments that greatly improved the manuscript.

I acknowledge financial support from the Institutional Call for Scientific Research (CIIC) at the University of Guanajuato under Projects 148/2021, 264/2022, 224/2023, and 251/2024. Additionally, I acknowledge support from CONACYT Project A1-S-37752. I am grateful to the Isaac Newton Institute for Mathematical Sciences, Cambridge, for their support and hospitality during the programme "Black holes: bridges between number theory and holographic quantum information,"where significant work for this article was carried out. This research was supported by EPSRC grant no EP/R014604/1. I would also like to acknowledge support from the ICTP through the Associates Programme (2023-2028).

REFERENCES

[1] N. Cabo Bizet, C. Damian, O. Loaiza-Brito, D. Mayorga Peña, and J. Montañez Barrera, Eur. Phys. J. C. **80**, 766 (2020).

[2] A. Cabo Montes de Oca, N.G. Cabo Bizet, and A. Cabo-Bizet, Eur. Phys. J. C. **64**, 133 (2009).

[3] A. Cabo Montes de Oca, S. Curilef, A. González, N.G. Cabo Bizet, and C.A. Vera, J. Stat. Mech. Th. Exp. P02012, 1 (2011).

[4] C. Tsallis, Journal of Statistical Physics. **52**, 479 (1988).

[5] S. Coleman and J. Mandula, Phys. Rev. **159**, 1251 (1967).

[6] R. Haag, J.T. Lopuszanski, and M. Sohnius, Nucl. Phys. B. **88**, 257 (1975).
[7] T. Kaluza, Sitzungsber. Preuss. Akad. Wiss., Berlin, 966 (1921).
[8] O. Klein, Z. Phys. **37**, 895 (1926).
[9] E. Calabi, Alg. Geom.: Top. Symp. Hon. S. Lefschetz Princeton Univ. Press, 78 (1957).
[10] S.T. Yau, Comm. Pure App. Math. **31**, 339 (1978).
[11] R. Bousso and J. Polchinski, J. High Energ. Phys. **06**, 006 (2000).
[12] M.R. Douglas, Ecole d'Ete de Phys. Th., 76. Springer, Berlin, Heidelberg, 1 (2002).
[13] S.K. Ashok and M.R. Douglas, J. High Energ. Phys. **2004**, 060 (2003).
[14] F. Denef and M.R. Douglas, J. High Energ. Phys. **05**, 72 (2004).
[15] W. Taylor and Y. Wang, J. High Energ. Phys. **05**, 80 (2015).
[16] C. Vafa, arXiv:0509212, 1 (2005).
[17] H. Ooguri and C. Vafa, Nucl. Phys. B. **766**, 21 (2007).
[18] N. Arkani-Hamed, L. Motl, A. Nicolis, and C. Vafa, J. High Energ. Phys. **06**, 060 (2007).
[19] G. Obied, H. Ooguri, L. Spodyneiko, and C. Vafa, arXiv:1806.08362v3, 1 (2018).
[20] P. Agrawal, G. Obied, P.J. Steinhardt, and C. Vafa, Phys. Lett. B. **784**, 271 (2018).
[21] S.K. Garg and C. Krishnan, J. High Energ. Phys. **11**, 075 (2019).
[22] H. Ooguri, E. Palti, G. Shiu, and C. Vafa, Phys. Lett. B. **788**, 180 (2019).
[23] F. Ruehle, Phys. Rep. **839**, 1 (2020).
[24] C. Damian, L.R. Diaz-Barron, O. Loaiza-Brito, M. Sabido, J. High Energ. Phys. **06**, 109 (2013).
[25] C. Damian and O. Loaiza-Brito, Phys. Rev. D. **88**, 046008 (2013).
[26] C. Damian and O. Loaiza-Brito, Fortsch. Phys. **67**, 1 (2019).
[27] P. Betzler and E. Plauschinn, Fortsch. Phys. **67**, 1900065 (2019).
[28] N. Cabo Bizet, C. Damian, O. Loaiza-Brito, et al., J. High Energ. Phys. **09** 123 (2019).
[29] N. Cabo Bizet, O. Loaiza-Brito, and I. Zavala, J. High Energ. Phys. **10**, 082 (2016).
[30] J. Maldacena and C. Nuñez, Phys. Rev. Lett. **86**, 588 (2001).
[31] S.B. Giddings, S. Kachru, and J. Polchinski, Phys. Rev. D. **66**, 106006 (2002).
[32] A. Cabo Montes de Oca, Eur. Phys. J. C. **71**, 1620 (2011).
[33] A. Cabo Montes de Oca, M. Roos and E. Erfani, Int.J.Mod.Phys.E. **20**, 245 (2011).
[34] A. Cabo Montes de Oca, R. Brandenberger, M. Roos and E. Erfani, Astrophys. Sp. Sci. **340**, 381 (2012).