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学 位 論 文 題 目　Structure of String Landscape on Toroidal Orientifolds and Its Phenomenological Implications

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# 博士論文の要旨

氏　　名：石黒 奎弥

論文題目：Structure of String Landscape on Toroidal Orientifolds and Its Phenomenological Implications

In this thesis, we discussed structures of the string landscape, focusing on its statistics, symmetries, and dualities, while all the topics we exhibited were based on phenomenological motivations. The thesis is separated into two parts.

In the former part, we explained our works on the flux compactifications of type IIB string theory. There we obtained the whole flux vacua on several toroidal orientifold and defined a concept of the probability on each point in the moduli space. Indeed, the finiteness of the flux vacua plays a crucial role, and the probabilities tell us that which vacua we can live on naturally, with an assumption that we effectively treat the flux quanta as free parameters, while they are constrained by an important consistency condition.

As a result of analysis, we have shown the structures of the landscape highly depends on the geometrical details of underlying toroidal orbifolds. Indeed, on T^6/Z'_6 orientifold we found the usual modular symmetry is broken to its certain congruence subgroup, and further enlarged by its outer automorphism group. As a result, the distribution of flux vacua with degeneracy on the simple T^6/(Z_2×Z'_2) orientifold and that on the T^6/Z'_6 one are different dramatically. However, there is a common feature: the fixed points, in particular the elliptic points, are statistically favored in the landscape. The elliptic points are originated from symmetries and dualities on the toroidal orientifolds. Thus, this motivates us to study further geometrical properties of the toroidal orientifolds in future.

These calculations of the explicit flux vacua with the probabilities are also important from the bottom-up viewpoint of the modular flavor symmetry, which claims that the flavor symmetry is realized as the modular symmetry. This framework is indeed appealing since the modular symmetry contains non-Abelian finite subgroups, which have been suggested as candidates of the flavor symmetry. In those modular flavor symmetric models, there is a (or, possibly many) massless scalar field that is transformed under the modular group, the modulus field, governs the breaking of such flavor symmetries. These additional moduli fields may become a bridge between the bottom-up and the top-down approaches. In fact, string theory has also generically many moduli fields that are transformed by the modular group or its symplectic generalizations. Furthermore, on string-based models whose extra dimensions respect the modular symmetry, a certain class of the moduli fields enter in the Yukawa

couplings and make the effective theory is compatible with the modular flavor symmetric models. Although the concrete embedding is beyond the scope of this thesis, if the embedding is possible, type II sting theory can give the moduli fields the scalar potential in a natural way (moduli stabilization with the flux compactifications). From the bottom-up viewpoint, there are some favorable modulus vacuum expectation values (VEVs) so that the model well explains the observed values. Then, under the embedding, type II string theory can predict the VEV of the identified modulus field. Since the VEVs sometimes exclude a proposed model and sometimes support such a model, the dataset of flux vacua which we obtained is also important in this context.

The landscape on the T^6/(Z_2 × Z_4) orientifold is interesting in this point. Since it has the Hodge number h^{2,1} = 1, the F-term condition becomes linear in the moduli. On the other hand, there are typical points where many modular flavor symmetric models have been proposed, and they are the elliptic points of the modular group. Then, the linearity and integral flux quanta implies that the VEVs are in a certain quadratic field, and only one of those elliptic points appears in the landscape. This means that the problem of choosing a model can be interpreted as the problem of choosing extra dimensions. Indeed, the allowed elliptic point in the landscape turns out to differ between the T^6/(Z_2 × Z_4) orientifold and the T^6/Z'_6 orientifold.

Since the difference is originated from differences of symmetries and dualities appear in the geometry of the orientifolds, it is again interesting to consider more general toroidal orientifolds and classify the possible geometrical symmetries and dualities.

In the second part, we adopted a certain machine-learning-based approach to analyze the string landscape. More concretely, we attempted to extract hidden features from type IIA intersecting D-brane models, via the so-called autoencoder models. As this thesis is written from the viewpoints of statistics, the motivation to adopt such method again comes from the statistics of the string landscape. In fact, there have been many studies on this topic; in the context of type IIA intersecting D-brane models, generating D-brane configurations which satisfy some concrete phenomenological models and investigating their statistics have been an important methodology. Here, our aim of study was to partially go beyond the statistical methods.

The autoencoder models are neural-network-based models, which try to replicate the input data while having intermediate layers with sufficiently small dimensions. Then, ideal autoencoder models will extract important features from the input data. What we mean here by partially going beyond statistical methods is that the features that could be extracted via the autoencoder models are automatically ensured to be one of the most important features that is needed to replicate the input data.

In this thesis, we indeed performed the feature extraction. Due to the essential difficulties of such machine-learning-based studies, we could not extract all the features. However, we found that the tadpole charges of hidden sector characterize the clusters that appeared in their latent layers. As a result of analysis, it was suggested

that at least one other feature is hidden in the latent layers. Although we could not find the other feature, it is interesting to investigate the role of the tadpole charges of hidden sector in more detail.

（別紙１ Separate Sheet 1）

**Results of the doctoral thesis defense**

# 博士論文審査結果

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氏　　名　石黒　奎弥

Title
論文題目 Structure of String Landscape on Toroidal Orientifolds and Its Phenomenological Implications

石黒奎弥君の学位論文は、トロイダルオリエンティフォルドにコンパクト化された超弦理論によって得られる多数の真空解 ＝「ランドスケープ」 の統計的解析と、その結果から示唆される現象論的考察に関する一連の彼自身の著作をまとめたものである。

トロイダルオリエンティフォルドとは、超弦の１０次元時空のうち余剰次元部分をトーラスにとってそれをある離散対称性で割り、さらにその固定面に関して弦自身の向きづけをも離散対称変換して同一視して得られる理論である。３つの相互作用が単一の単純群ゲージ理論に統一する大統一理論にはならないものの、標準模型に近い模型構築が比較的容易で具体的計算が可能なため、特に LHC により重いヒッグズと低エネルギー超対称性の不存在が確定する以前、研究がかつて精力的になされた。本論文では、３つの２次元トーラスの直積を離散対称性で割ったタイプ IIB 弦理論のオリエンティフォルドコンパクト化を考え、モジュラー対称性を利用した新しい視点から４つのテーマについて議論が行われた。

１つ目は、2-フォーム場の磁場にあたる「フラックス」の導入によってきまるポテンシャルの極小点 ＝「フラックス真空」の数を統計的に調べ、その複素スカラー場の値の分布が基本領域の「楕円点」、特にトーラスの形が菱形になるようなモジュラス１点のみに真空の大半が集中することを見出した。２つ目は、この解析に KKLT シナリオで考えるような非摂動項を導入し、楕円点に集中する真空解がどのようにずれるかを調べた結果、モジュラスの値が楕円点から絶対値にして $10^{-5}$ 離れたところに最も高い確率でずれることを見出した。 ３つ目は、１で行った解析を１とは異なる別の離散対称性によるオリエンティフォルドで行ない、１と同様な結果が得られることを確かめた。さらには、４つ目のテーマとして、「左右等しい世代数をもつ」などの現象論的に好まれる模型が実現する特徴を機械学習によって得ることを目指した研究について報告した。これらの内容はすべて学術的にも大変有意義で興味深い。またこれらは全てすでに査読付き英文雑誌に掲載または掲載が決定している。これらの論文執筆における全般的な石黒君の主体的寄与が確認された。

本学位論文は明快でわかりやすい、人間味のある英語で書かれ、また海外での国際会議でも英語での口頭発表経験を有するなど、博士の学位取得に相応しい英語能力を十分に有していることも認められた。

以上により、委員会は本論文が博士論文の内容として必要な水準を遥かに超えるものであることを評価認定し、博士論文本審査を合格とすることで全員が一致した。