A Gentle Hike Through the Swampland

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# Abstract

## 摘要

At first sight, it might seem that any quantum field theory, regarded as a low-energy effectve field theory (EFT), can be coupled to Einsteinian gravity. Over the past few years, a large body of work has challenged this view, arguing that not every EFT arises as the IR of a consistent theory of quantum gravity. EFT's that do not descend from quantum gravity are said to be in the "Swampland". This chapter provides a bird's eye view over some of the recent efforts in delineating the boundaries of the Swampland, collectively known as the "Swampland Program". We focus on recent progress that may not have been covered in existing reviews. We first give an introduction to the oldest Swampland Conjecture, the absence of global symmetries, but from a modern point of view of topological symmetry operators and its generalization to non-invertible symmetries. We then introduce a certain extension of the absence of global symmetries, known as the Cobordimsm Conjecture, and discuss its applications to constrain the Landscape of minimal supergravity in more than six dimensions. These better-established conjectures are connected to other conjectured properties of quantum gravity which we cover in this chapter. These include the Weak Gravity Conjecture, its phenomenological implications and generalizations to de Sitter space (Festina Lente), the Distance Conjecture, ranging from recent connections to EFT strings to the Emergent String Conjecture and implications for potentials, and conjectures involving the vacuum energy.

乍看之下，任何量子场论作为低能有效场论 (EFT)，都可以与爱因斯坦引力耦合。过去几年，大量研究对这一观点提出了质疑，指出并非所有有效场论都能源自自洽量子引力理论的红外端。那些无法从量子引力导出的有效场论被认为属于“沼泽地”。本章概述了近年来在划定沼泽地边界方面的部分研究工作，这些工作统称为“沼泽地计划”。我们聚焦现有综述未曾覆盖的最新进展。首先我们从拓扑对称性算符的现代视角介绍最古老的沼泽地猜想——不存在全局对称性，并介绍它向非可逆对称性的推广。随后我们介绍对不存在全局对称性猜想的拓展，即配边猜想，讨论它在约束六维以上最小超引力弦景观中的应用。这些已得到更充分研究的猜想与本章涵盖的量子引力其他猜想性质存在关联，这些猜想包括弱引力猜想及其唯象学意义、它在德西特空间的推广 (慢即紧猜想)、从有效场论弦的最新联系到涌现弦猜想及对势的启示的距离猜想，以及关于真空能的相关猜想。

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## Keywords

## 关键词

Swampland program - Weak gravity - Distance conjecture - de Sitter conjecture - Cobordism conjecture - Global symmetries - Quantum gravity - Festina Lente

沼泽地计划 - 弱引力 - 距离猜想 - 德西特猜想 - 配边猜想 - 全局对称性 - 量子引力 - 费斯蒂纳伦特

## Introduction

## 引言

Other chapters in this volume of the Handbook on Quantum Gravity have focused on the basics of String Theory, the tools to construct vacua, and used them to present a class of vacua where the low energy physics, controlled by a low-energy Effective Field Theory (EFT), has semi-realistic features, such as chiral fermions, weakly coupled abelian and non-abelian gauge fields, or axions. All of these features are important properties of the Standard Model, and it is reassuring and encouraging that String Theory can incorporate them in a natural way.

本卷量子引力手册的其他章节都聚焦于弦论基础、构造真空的工具，并利用这些工具给出了一类真空，其低能物理由低能有效场论 (EFT) 控制，具备半现实特征，比如手征费米子、弱耦合阿贝尔与非阿贝尔规范场，或是轴子。所有这些特征都是粒子物理标准模型的重要性质，弦论能够自然地容纳它们，这一点让人安心且振奋。

On the other hand, the detailed features of all the string models analyzed so far: number of generations, precise couplings, etc do not match the Standard Model (SM), and indeed, we have not succeeded thus far in obtaining a fully satisfactory embedding of the SM in String Theory (however, some parts of the construction, such as the correct choice of gauge group, can be realized; see for instance [1] for examples of some recent efforts). One big hurdle in finding the compactification that describes our world (if it exists) is that there are so many ingredients: choice of compactification manifold, internal fluxes, gauge bundle, branes, orientifolds... and they can be combined in so many different ways that a systematic search is next to impossible. The Standard Model could very well be hiding inside this vast Landscape of possible solutions [2], and while direct searches and explicit constructions are an essential part of the quest to match String Theory to the real world, there is a real danger that we may just miss the concrete construction that yields the string vacuum describing our world.

另一方面，迄今为止分析的所有弦模型的细节特征: 代的数量、精确耦合等等，都与标准模型 (SM) 不符，而且我们至今也未能成功将标准模型完全令人满意地嵌入弦论 (不过，该构造的部分环节是可以实现的，比如正确选定规范群；近期相关研究实例可参见文献 [1])。如果描述我们世界的紧致化确实存在，找到它的一大障碍在于，构造所需的要素太多: 紧致化流形的选择、内通量、规范丛、膜、orientifold……这些要素的组合方式数不胜数，系统搜索几乎不可能实现。标准模型完全有可能就藏匿在这片广阔的可能解景观之中 [2]。尽管直接搜索和显式构造是将弦论与真实世界匹配的核心环节，但我们确实面临着错过描述我们世界的具体弦真空构造的风险。

Fortunately, there is another way to make progress. Even in the vast swaths of the Landscape, there seem to be certain patterns that always hold, even in very different string compactifications. For instance, as we will review in detail, in every effective field theory that we know how to derive from String Theory, there is a particle whose mass is lower than its charge in Planck units. If this statement (known as the Weak Gravity Conjecture (WGC)) is true universally, in every Quantum Gravity vacuum, it should also be true about our own world; and indeed, in the real world, the electron satisfies the WGC. Although postdicting an upper bound for the mass of a particle is not too impressive, variations of these ideas have recently been used to provide a novel understanding in inflationary physics, the Hierarchy Problem, our understanding of neutrino masses, and even formal aspects of string theory itself among others.

幸运的是，还有另一条前进的路径。哪怕是在景观的广阔区域中，似乎也存在某些始终成立的规律，哪怕是在差异极大的弦紧致化中也是如此。例如，我们后续会详细回顾: 在所有我们能从弦论导出的有效场论中，都存在一个粒子，其质量以普朗克单位衡量低于其电荷。如果这个命题 (即弱引力猜想 WGC) 在所有量子引力真空中普遍成立，那它对我们的世界也必然成立；而在真实世界中，电子确实满足弱引力猜想。尽管仅预言粒子质量的上边界并不算惊人，但这套思路的变体近来已经被用于为暴涨物理、等级问题、中微子质量认知乃至弦论本身的形式问题等诸多领域提供全新的理解。

The basic idea that there are universal constraints in the low-energy EFT's that come from Quantum Gravity, and that these can lead to phenomenologically interesting consequences, is radically innovative and lies at the core of the topic of this chapter, the Swampland Program. This funny nickname, proposed by C. Vafa in the foundational paper [2], is meant to emphasize that the ”nice” EFT that can actually arise as the low-energy limit of a consistent QG are surrounded by a vast Swampland of EFT's that cannot be embedded in quantum gravity, even if they are completely fine as quantum field theories (see Fig. 1). The Swampland is a very active topic and constitutes one of the main avenues of research in String Phenomenology nowadays; there are comprehensive excellent reviews such as [3-5].

来自量子引力的低能有效场论存在普适约束，且这些约束能产生唯象上有趣的结论，这一基本思路极具创新性，也是本章主题——沼泽地计划——的核心。这个有趣的名字由 C. Vafa 在奠基性论文 [2] 中提出，意在强调: 那些真正能作为自洽量子引力低能极限的“好的”有效场论，被广阔的沼泽地包围着；沼泽地里尽是无法嵌入量子引力的有效场论——哪怕它们作为量子场论本身完全自洽 (参见图 1)。沼泽地是当前非常活跃的研究方向，也是如今弦唯象学最主要的研究方向之一；目前已有多篇出色的综述，比如 [3-5]。

An important aspect of the program is that it is not just botany, i.e. we do not merely extrapolate patterns from known string theory compactifications and propose they are always true. There is a massive effort to determine the fundamental principles underlying the proposed Swampland statements. In some cases, such as the WGC alluded to above, one can view the statements as consequences of features of Quantum Gravity that we believe are essential, such as background independence or topology change. But this is certainly not the case for all of the Swampland and, in any case, proofs are limited to particular contexts, since we presently lack a framework to prove things in Quantum Gravity in an universal way. Because of this, the Swampland is often organized in terms of conjectures, statements with different degrees of support and validity that are interconnected and reinforce each other. This chapter will provide an overview of some of the most relevant conjectures in the recent Swampland literature, their support, rationale, and phenomenological implications. We stress that this is intended as introductory material; the Swampland is a field that develops pretty quickly, and we do not attempt to properly cover the huge amount of work that has been devoted to the Swampland Program recently. The interested reader is encouraged to further delve into the Swampland Program by reading any of the excellent reviews [3-5]. Our main emphasis is on the new developments since the last review on the Swampland was written. Thus, this chapter together with previous reviews mentioned would give the readers a comprehensive, up-to-date overview of the Swampland program.

该计划的一个重要特点在于，它并非只是“分类归纳”: 我们并非仅仅从已知的弦紧致化中外推规律，再提出这些规律普遍成立。学界付出了大量努力，旨在探究沼泽地猜想背后的基本原理。在部分场景下，例如前文提及的弱引力猜想，我们可以将这些猜想视为量子引力核心特征的推论，比如背景独立性或拓扑变化，这些特征被认为是量子引力不可或缺的。但这显然不适用于沼泽地的所有内容，而且无论如何，现有证明仅局限于特定场景，因为我们目前还缺乏一个能在量子引力中通用证明结论的框架。正因如此，沼泽地的内容通常以猜想的形式呈现: 这些命题有着不同程度的支撑与合理性，它们相互关联、彼此印证。本章将概述近期沼泽地研究中最受关注的部分猜想，介绍它们的支撑依据、基本逻辑以及唯象学意义。需要强调的是，本章仅作入门介绍；沼泽地是一个发展十分迅速的领域，我们无法完整涵盖近年来学界投入沼泽地计划的海量工作。欢迎感兴趣的读者通过阅读优秀综述文献 [3-5] 进一步深入了解沼泽地计划。本文的核心重点放在上一篇沼泽地综述发表后的新进展上。因此，本章结合提及的既往综述，就能为读者提供一份全面、最新的沼泽地计划概述。

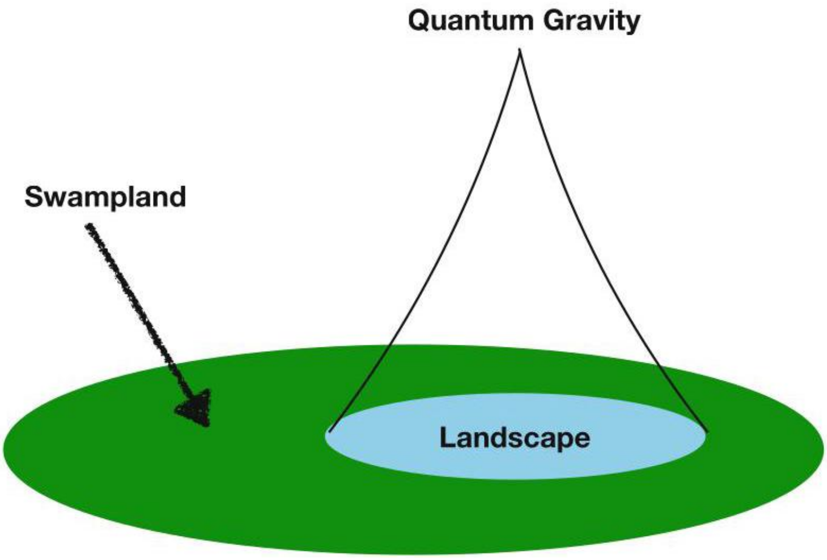



Fig. 1 Schematic representation of the basic idea underlying the Swampland. Most low-energy effective field theories lie in the green-shaded region, the Swampland, and do not have an uplift to a UV consistent quantum gravity

图 1 沼泽地核心思想的示意图。大多数低能有效场论都位于绿色阴影区域即沼泽地中，无法 uplift 到一个紫外自洽的量子引力

This chapter will be organized as follows: We will start, with the oldest, most fundamental, and best established Swampland Conjecture, the absence of global symmetries in quantum gravity, and a natural extension of it involving space time topology, the Cobordism Conjecture. We will then move on to cover the closely related Weak Gravity and Distance conjectures, before moving on to applications of the Swampland to Cosmology and spacetimes with positive vacuum energy, such as de Sitter space.

本章结构安排如下: 我们首先从沼泽地最古老、最基础也最成熟的猜想开始，即量子引力中不存在全局对称性，以及它关于时空拓扑的自然推广——配边猜想。随后我们会介绍与之密切相关的弱引力猜想与距离猜想，之后再讲解沼泽地在宇宙学以及具有正真空能的时空 (例如德西特空间) 中的应用。

## A Quick Tour of the Swampland Conjectures

## 沼泽地猜想速览

## No Global Symmetries and Cobordism Conjectures

## 无全局对称性与配边猜想

We start our tour of the Swampland by discussing what is arguably the oldest Swampland conjecture: absence of global symmetries in Quantum Gravity. More precisely, if the low energy EFT derived from a consistent quantum theory of gravity has global symmetries, these symmetries and their conservation laws must be broken, possibly at the non-perturbative level. Versions of this statement date back to the 1980s [6, 7], and even in some form, to Wheeler [8].

我们从沼泽地项目中公认最古老的沼泽地猜想开始讲解: 量子引力不存在整体对称性。更准确地说，若从自洽量子引力理论得到的低能有效场论存在整体对称性, 那么这些对称性及其守恒律必须被破缺，破缺可能发生在非微扰层面。这一表述的雏形可追溯至 20 世纪 80 年代 [6, 7]，甚至某种形式的相关论断最早出自惠勒 [8]。

To formulate the statement precisely, we must first explain what is a global symmetry. We will first focus on the case of a continuous global symmetry, and then generalize appropriately. The classical notion of symmetry that pervades most textbooks invokes Noether's theorem to trade the symmetry by a conserved charge that generates it (see e.g. a [9] for a review in the context of the absence of global symmetries); the conservation of the charge operator $Q$ is then encoded in the fact that it commutes with the Hamiltonian.

为了精确表述这个结论，我们必须先解释什么是全局对称性。我们会先聚焦连续全局对称性的情况，再做恰当的推广。绝大多数教科书中通行的经典对称性概念都会调用诺特定理，将对称性和生成它的守恒荷对应起来 (例如，参阅文献 [9] 了解全局对称性不存在背景下的综述)；电荷算符 $Q$ 的守恒则体现在它与哈密顿量对易这一点上。

While this notion is perfectly adequate in quantum mechanics, it is not well suited to quantum field theory, where one typically has local operators $\mathcal{O}(x)$ that depend on a spacetime point $x$ . Both the charge $Q$ and the Hamiltonian $H$ are defined in terms of integrals of local expressions over a spatial $(d-1)$ -dimensional surface $\sum$ , which corresponds to a choice of foliation of spacetime:

尽管这一定义在量子力学中完全适用，但它并不适配量子场论——在量子场论中，我们通常都会得到依赖于时空点 $x$ 的局域算符 $\mathcal{O}(x)$ 。电荷 $Q$ 与哈密顿量 $H$ 均由局域表达式在空间 $(d-1)$ 维曲面 $\sum$ 上积分定义，这对应于对时空选定的一种叶状结构:

$$H=\int_{\sum} d^{d-1}xT_{\mu\upsilon}n^{\mu}_{\sum}n^{\upsilon}_{\sum},\ Q=\int_{\sum} d^{d-1}xJ_{\mu}n^{\mu}_{\sum}, \tag{1}$$

where $n^{\mu}_{\sum}$ is the normal vector to $\sum$ . The operators $H$ and $Q$ depend on the choice of $\sum$ , but the fact that they commute $[H,Q]=0$ does not. Furthermore, an ordinary internal symmetry does not only commute with $H$ , but also with rotations (generated by the angular momentum genrator), boosts, and translation. Since all these operators are generated by integrals of different components of the stress-energy tensor $T^{\mu\upsilon}$ , it is not difficult to convince oneself that the requirement that $Q$ is conserved means that it commutes with all the components of $T^{\mu\upsilon}$ . But the stress-energy tensor is itself the generator of infinitesimal diffeomorphisms, so that deforming the surface $\sum$ to a nearby one $\sum'$ is implemented as

其中 $n^{\mu}_{\sum}$ 是垂直于 $\sum$ 的法向量。算符 $H$ 与 $Q$ 依赖于 $\sum$ 的选取，但它们对易这一性质 $[H,Q]=0$ 却不依赖。此外，普通的内部对称性不仅与 $H$ 对易，还与 (由角动量生成元产生的) 旋转、洛伦兹 boost 以及平移对易。由于所有这些算符都由能量动量张量 $T^{\mu\upsilon}$ 的不同分量的积分生成，不难发现，$Q$ 守恒的要求等价于它与 $T^{\mu\upsilon}$ 的所有分量对易。而能量动量张量本身就是无穷小微分同胚的生成元，因此将曲面 $\sum$ 形变到邻近曲面 $\sum'$ 可表示为

$$Q'=\int_{\sum'} J_{\mu}n^{\mu}_{\sum'}\approx\int_{\sum} d^{d-1}x\left(J_{\mu}n^{\mu}_{\sum}+[T^{\mu\upsilon}\upsilon^{\mu}\upsilon^{\upsilon},Q]\right)=Q, \tag{2}$$

where $\upsilon^{\mu}$ is the generator of the infinitesimal diffeomorphism that takes one from $\sum$ to $\sum'$ . In other words, having a global symmetry is equivalent to demanding that the associated charge operator $Q$ , defined on a condimension 1 surface $\sum$ , is topological, that is, independent of the choice of $\sum$ . Finally, it is more convenient to discuss the symmetry operators

其中 $\upsilon^{\mu}$ 是将人们从 $\sum$ 带到 $\sum'$ 的无穷小微分同胚的生成元。换句话说，存在整体对称性等价于要求定义在余维 1 曲面 $\sum$ 上的关联荷算符 $Q$ 是拓扑的，即不依赖于 $\sum$ 的选取。最后，这样讨论对称算符会更方便

$$U_{\theta}\left(\sum\right)=\exp\left(i\theta Q\right) \tag{3}$$

that actually implement the symmetry transformation, rather than the symmetry generators themselves. Among other reasons, this is because (3) generalizes to the case of discrete symmetries, where the operator $Q$ does not exist. This leads to the modern notion of a global symmetry in quantum field theory, introduced in [10]: an ordinary global symmetry with symmetry group $G$ means that the QFT has topological operators supported in codimension-1 surfaces, called the symmetry operators, and labeled by the elements of $G$ , and satisfying the corresponding group law:

它实际是实现对称性变换，而非对称性生成元本身。除其他原因外，这是因为 (3) 可以推广到离散对称性的情况，而在该情况下算子 $Q$ 并不存在。由此便得到了文献 [10] 中提出的量子场论中全局对称性的现代定义: 具有对称性群 $G$ 的普通全局对称性，意味着量子场论存在支撑在余维 1 曲面上的拓扑算子，称为对称算子，由 $G$ 的元素标记，且满足对应群定律:

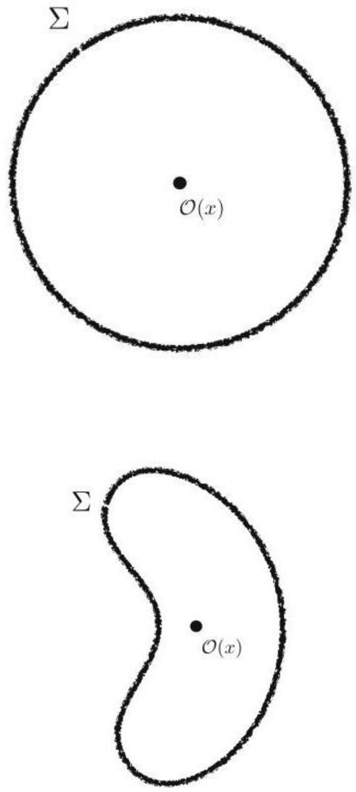
$$U_g\left(\sum\right) U_{g'}\left(\sum\right) = U_{gg'}\left(\sum\right). \tag{4}$$

The argument we gave for topological invariance of the operators $U_g\left(\sum\right)$ is only true if they are inserted at smooth points of spacetime; it may fail when one puts the symmetry operators on top of other operator insertions one may have in the path integral. If one is inserting a local operator $\mathcal{O}(x)$ , the topological character of the symmetry operator means that the correlator cannot change as long as $\sum$ does not cross the point $x$ , but it may change if this happens. Operators $\mathcal{O}(x)$ with this property are said to be charged under the symmetry generated by the $U_g\left(\sum\right)$ , and (4) implies that moving $\sum$ past $x$ results in a modification of the correlator by some representation of the group $G$ , as illustrated in Fig. 2. In the usual picture of quantum field theory, where operators create particles, we may view $\mathcal{O}(x)$ as creating a particle at point $x$ charged in representation $\mathcal{R}$ of the global symmetry $G$ ; the topological operator then implements the symmetry, acting with it when it crosses a charged operator and doing nothing otherwise.

我们对算符 $U_g\left(\sum\right)$ 拓扑不变性的论证仅在它们插入时空光滑点时成立；当我们把对称算符放在路径积分中已有的其他算符插入点上方时，该论证可能不成立。如果插入一个局域算符 $\mathcal{O}(x)$ ，对称算符的拓扑特性意味着，只要 $\sum$ 不穿过点 $x$ ，关联函数就不会发生变化，但如果确实发生了穿过，关联函数就可能改变。具备该性质的算符 $\mathcal{O}(x)$ 被称为带由 $U_g\left(\sum\right)$ 生成的对称性的电荷，而 (4) 式表明，移动 $\sum$ 使其经过 $x$ 会让关联函数被群 $G$ 的某个表示修改，如图 2 所示。在量子场论的常规图景中，算符产生粒子，我们可以将 $\mathcal{O}(x)$ 视作在点 $x$ 产生了一个处于整体对称性 $G$ 的表示 $\mathcal{R}$ 下的带电粒子；拓扑算符会实现该对称性，当它穿过带电算符时就会作用，否则不作用。

$$\langle \ldots \mathcal{O}(x)\, U_g\left(\sum\right) \ldots \rangle$$

$$\langle \ldots \mathcal{O}(x)\, U_g\left(\sum\right) \ldots \rangle$$




$$\mathcal{R}_{\mathcal{O}}(g)\langle \dots\, \mathcal{O}(x)\, U_g(\textstyle\sum) \dots\rangle\, \mathcal{R}_{\mathcal{O}}(g)\langle \dots\, \mathcal{O}(x)\, U_g(\textstyle\sum) \dots\rangle = \mathcal{R}_{\mathcal{O}}(g)\langle \dots\, \mathcal{O}(x) \dots\rangle$$


Fig. 2 Representation of a correlation function involving insertions of both a symmetry operator $U_g(\sum)$ and a charged operator $\mathcal{O}(x)$ . Because $U_g(\sum)$ is topological, we can deform $\sum$ as depicted in the panels (top left to right bottom), and the correlator only changes when $\sum$ crosses the location of $\mathcal{O}(x)$ . Even when this happens, the only effect of the crossing is to introduce an action of the group $G$ on the correlator, via the representaiton $\mathcal{R}_{\mathcal{O}}$ associated to $\mathcal{O}(x)$

> 图 2 包含对称算符 $U_g(\sum)$ 和带电算符 $\mathcal{O}(x)$ 插入的关联函数示意图。由于 $U_g(\sum)$ 是拓扑的，我们可以如各面板 (从左上到右下) 所示形变 $\sum$，只有当 $\sum$ 穿过 $\mathcal{O}(x)$ 的位置时，关联函数才会改变。即便发生了这种穿过，穿过带来的唯一影响就是群 $G$ 通过关联到 $\mathcal{O}(x)$ 的表示 $\mathcal{R}_{\mathcal{O}}$ 对关联函数作用。

There is one last generalization of the above ideas that we will need: as we have seen, topological symmetry operators are inserted in codimension one surfaces, and they act nontrivially when they cross local point charged operators. This picture still works if one replaces the 0-dimensional charged operators with operators living in dimension $p$ and the $d-1$ -dimensional symmetry operators by $d-p-$ 1-dimensional topological symmetry operators. This is called a p-form generalized global symmetry; the charged operators create $p+1$ dimensional charged objects. Generalized global symmetries are the proper language to describe theories with conserved charges carried by extended objects, which are plentiful in quantum field theory.

> 我们还需要对上述思想做最后一个推广: 如我们所见，拓扑对称算符插入余维 1 曲面，当它们穿过局域点带电算符时会发生非平凡作用。如果我们将 0 维带电算符替换为居住在 $p$ 维的算符，将 $d-1$ 维对称算符替换为 $d-p-$ 个一维拓扑对称算符，这一图景仍然成立。这被称为 p 形式广义整体对称性；带电算符产生 $p+1$ 维带电物体。广义整体对称性是描述携带守恒荷的延展物体所属理论的恰当语言，这类理论在量子场论中十分常见。

The above paragraphs are a crash course in the modern notion of symmetry, and they may be a bit arid without examples and details; the interested reader is encouraged to look at [10] or the recent review [11] for further details. All these generalizations are necessary for the current applications in the Swampland program. In any case, now that we know what a global symmetry is, we can understand the Swampland Conjecture: Absence of (generalized) global symmetries means exactly that these topological operators never actually exist in any consistent quantum theory of gravity.

> 以上几段是对现代对称性概念的速成介绍，没有例子和细节，内容可能有点枯燥；感兴趣的读者可以查阅文献 [10] 或最新综述 [11] 获取更多细节。所有这些推广对当前沼泽地纲领的应用都是必要的。无论如何，既然我们已经知道了什么是整体对称性，我们就可以理解沼泽地猜想了: 不存在 (广义) 整体对称性，恰恰意味着在任何自洽的量子引力理论中，这些拓扑算符都根本不存在。

To give a concrete example, the Standard Model has an exact global symmetry, baryon number minus lepton number, commonly called $B-L$ and preserved in all (even non-perturbative) processes. However, since there are no global symmetries in quantum gravity, $B-L$ must be either broken (so that there are physical processes that violate this quantity; one example would be neutrinoless double $\beta$ decay, which can happen in the presence of $B-L$ -violating Majorana masses) or gauged. $B-L$ being gauged means that that there is a yet to be discovered fifth force, similar to electromagnetism, for which $B-L$ plays the role of electric charge (By "gauged" we really refer to the case where there is a massless $U(1)$ charge coupled to $B-L$ . The case of a spontaneously broken gauge symmetry counts as a broken symmetry in our language, as there is simply no associated conservation law.). This possibility is compatible with the no global symmetries conjecture because in the case of a gauge symmetry the symmetry operators such as (3) are not gauge invariant, and therefore are absent from the spectrum. If $B-L$ is gauged, its gauge coupling must be tiny, since otherwise we would have seen it experimentally already. Even this possibility is constrained by Swampland ideas [12].

举一个具体的例子: 粒子物理标准模型存在一个精确的整体对称性，即重子数减去轻子数，通常记作 $B-L$，在所有 (甚至非微扰) 过程中都守恒。但由于量子引力中不存在整体对称性，$B-L$ 要么被破缺 (即存在物理过程破坏该量；一个例子是无中微子双 $\beta$ 衰变，该过程可在存在 $B-L$ 破坏的马约拉纳质量时发生)，要么被规范。$B-L$ 被规范意味着存在一种尚未被发现的第五种力，类似电磁相互作用，而 $B-L$ 在其中扮演电荷的角色 (我们说“规范”实际指存在一个无质量 $U(1)$ 荷耦合到 $B-L$ 的情形。在我们的术语中，自发破缺的规范对称性属于破缺对称性，因为它根本不存在对应的守恒定律)。这种可能性符合无整体对称性猜想，因为在规范对称性的情形下，(3) 这类对称性算子不是规范不变的，因此不会出现在谱中。如果 $B-L$ 被规范，它的规范耦合必须极小，否则我们早就通过实验观测到它了。即使这种可能性也受到沼泽地思想的约束 [12]。

Another setup where the no global symmetries conjecture is relevant is inflationary physics. A successful inflationary model must engineer a very large field range with a very flat potential [13]. A simple idea to do so is to start with a scalar which has an exact shift symmetry,

无整体对称性猜想的另一个相关应用场景是暴涨物理。一个成功的暴涨模型需要构造出范围极大、势能极平的场 [13]。实现这一点的一个简单思路是从一个具有精确平移移位对称性的标量场出发，

$$\phi \to \phi + c, \; c \in \mathbb{R} \tag{5}$$

which is then broken explicitly by some small, controlled effect. The fact that there are no global symmetries in quantum gravity means that (5) is impossible, so one cannot construct a suitable inflationary potential as a two-step process, first engineering the symmetry and then breaking it, as one would do in field theory. This is at the core of the difficulties in attaining parametrically large field ranges in UV-complete inflationary models [13], and the recent revival of the Swampland program after the BICEP2 results.

再通过某个可控制的小效应明确破缺该对称性。量子引力中不存在整体对称性这一结论意味着 (5) 的构造不可能，因此人们无法通过“先构造对称性再破缺”的两步过程得到合适的暴涨势能——这是场论中常用的思路。这也是在紫外完备的暴涨模型中获得参数化大场范围存在困难的核心原因 [13]，还是 BICEP2 实验结果公布后沼泽地计划重新兴起的核心原因。

These two examples are about using the no global symmetries conjecture to limit what can happen in a theory. We will discuss one last example that illustrates how the no global symmetries conjecture can be used to predict new objects in a theory, and that underlies the connection between the no global symmetries conjecture and another Swampland Conjecture, the Completeness Principle [14]. Roughly speaking, the Completeness Principle demands that in a consistent quantum theory of gravity all possible charges compatible with Dirac quantization must be present in the theory. For instance, in a $U(1)$ gauge theory with electrically charged particles and monopoles, the electric charge of the smallest electric particle $e$ and the smallest magnetic charge $g$ satisfy

以上两个例子都是利用无整体对称性猜想约束一个理论允许的内容。我们最后再举一个例子，说明无整体对称性猜想如何可以用来预言理论中的新对象，同时解释无整体对称性猜想和另一个沼泽地猜想——完备性原理 [14]——之间的关联。大致来说，完备性原理要求: 在一个自洽的量子引力理论中，所有满足狄拉克量子化条件的可能电荷都必须存在于该理论中。例如，在一个存在带电粒子和磁单极子的 $U(1)$ 规范理论中，最小带电粒子 $e$ 的电荷和最小磁荷 $g$ 满足

$$e \cdot g = 2\pi n, \ n \in \mathbb{Z}. \tag{6}$$

where $n$ is an integer. One can construct consistent field theories with any $n$ ; however, in quantum gravity, the Completeness Principle demands that $n = 1$ necessarily. The relation to the no global symmetries conjecture is that, when $n \neq 1$ , the $U(1)$ gauge theory has a $\mathbb{Z}_n$ 1-form generalized symmetry, with charged operators being Wilson or 't Hooft lines. Breaking these symmetries means that the charged line operators are able to end in charged local operators, which create new electrically or magnetically charged states ensuring that $n = 1$ in (6). The relationship between these two conjectures has been explored in [15, 16] , where the statement has been generalized to include non-invertible symmetries which have recently begun to be discussed in the QFT literature. In particular, [15] argues that the fully general version of the no global symmetries conjecture is the statement that there are no topological operators in quantum gravity.

> 其中 $n$ 是一个整数。人们可以对任意 $n$ 构造自洽的场论；但在量子引力中，完备性原理要求必须满足 $n = 1$ 。它和无整体对称性猜想的关联是: 当 $n \neq 1$ 时，$U(1)$ 规范理论存在一个 $\mathbb{Z}_n$ 1 形式广义对称性，带电算子是威尔逊线或't 霍夫特线。破缺这些对称性意味着带电线算子可以在带电局域算子处终止，这些局域算子会产生新的电或磁荷态，从而保证 (6) 式满足 $n = 1$ 。这两个猜想之间的关系已经在 [15, 16] 中被研究，相关结论已经被推广到最近量子场论文献中开始讨论的不可逆对称性。特别地，文献 [15] 提出，最广义版本的无整体对称性猜想可以表述为: 量子引力中不存在拓扑算子。

So far, we have stated the no global symmetries conjecture and discussed some of its consequences. But why should it be true? The most fundamental motivation is appealing to a radical version of background independence. It is a standard fact that background independence implies that there are no local operators in quantum gravity, since objects such as $\mathcal{O}(x)$ manifestly break diffeomorphism invariance by depending on the spacetime point $x$ . The same applies to operators localized on a specific submanifold of spacetime. All true observables in quantum gravity are relational. Interestingly, that leaves open in principle the possibility to have topological operators, such as the symmetry operators we constructed above, since then the dependence on a submanifold is spurious. But radical background independence means that there should be no local data the theory can depend on, not even the topology. If topology itself fluctuates, there can be no nontrivial topological operators, since a topology fluctuation can always make it shrink as in Fig. 2. Therefore, absence of global symmetries is an extension of background independence to include topology change, rather than just fluctuations of the metric with respect to a given background. We have ample evidence that topology fluctuations occur in quantum gravity, being one of the essential ingredients in the recent successes in reproducing the Page curve of evaporating black holes [17].

> 到目前为止，我们已经阐述了无全局对称性猜想并讨论了它的一些推论。但它为什么成立？最根本的动机源于一种激进版本的背景无关性。背景无关性意味着量子引力中不存在局域算符，这是一个公认结论，因为像 $\mathcal{O}(x)$ 这类对象依赖于时空点 $x$ ，显然会破坏微分同胚不变性。这同样适用于定域在时空特定子流形上的算符。量子引力中所有真正的可观测量都是关系性的。有趣的是，这原则上并未排除拓扑算符存在的可能性——比如我们上文构造的对称算符，因为这类算对子流形的依赖是伪依赖。但激进的背景无关性意味着，理论不应当依赖任何局域数据，哪怕是拓扑数据也不行。如果拓扑本身会涨落，就不可能存在非平凡拓扑算符，因为拓扑涨落总能让它收缩，如图 2 所示。因此，不存在全局对称性是背景无关性的延伸，它将拓扑变化纳入其中，而非仅局限于给定背景下的度规涨落。我们有充分证据表明，量子引力中确实存在拓扑涨落，它也是近年成功重现蒸发黑洞佩奇曲线的核心要素之一 [17]。

There are other arguments, involving paradoxes with black hole entropy [7], that are often invoked to support the conjecture. But the real point here is that absence of Global symmetries stands out among the Swampland Conjectures as being the one which has by far the strongest support coming from hard evidence and rigorous arguments. We have proofs in perturbative string theory [18], holography [19], flat space holography [20], and it is manifestly true in every string compactification ever constructed. The reader is encouraged to consult any of the longer reviews [3-5] for details about these arguments. In the end, the amount of evidence for the conjecture is so vast that it is hard to find anyone who considers it anything less than certain. Still, the reader should keep in mind that so far there is no universal proof that works in complete generality.

还有其他支持该猜想的论证，比如涉及黑洞熵悖论的论证 [7]。但核心点在于，在所有沼泽地猜想中，无全局对称性猜想是得到确凿证据和严谨论证支持最多的一个。我们在微扰弦论 [18]、全息原理 [19]、平坦空间全息 [20] 中都完成了证明，而且在所有已构造的弦紧致化中它都显然成立。建议读者查阅更长的综述文献 [3-5] 了解这些论证的细节。归根结底，支持该猜想的证据如此充分，几乎没人认为它不是确定成立的。但读者仍需注意，迄今为止还不存在一个适用于完全一般情形的普适证明。

In spite of all its appealing features, the conjecture has a serious drawback: it makes no prediction as to the energy scale at which the symmetry breaking effects must take place. For instance, if $B-L$ is broken in our universe, the conjecture does not tell us how often should we expect to see $B-L$ -violating processes. If they turn out to be so rare that we never expect to encounter a single instance of them, we might as well say there is a global symmetry after all! Recent work [21,22] has addressed this point, and in particular reference [22] suggests that global symmetries must be broken by effects which are $\mathcal{O}(1)$ at the Planck scale. By doing this, it was possible to connect the no global symmetries conjecture to other Swampland principles in a quantitative manner. Although appealing, these works leave open the question as to why the breaking should be relatively strong.

尽管这个猜想有诸多吸引人的特点，但它存在一个严重缺陷: 它无法预言对称性破缺效应必然出现在哪个能标。例如，如果 $B-L$ 在我们的宇宙中破缺，该猜想无法告诉我们应当预期多久会观测到一次 $B-L$ 破坏过程。如果这类过程极其罕见，我们永远都遇不到一次，那我们其实完全可以说这里存在全局对称性！近期工作 [21,22] 已经讨论了这个问题，其中文献 [22] 特别指出，全局对称性必须被普朗克尺度下为 $\mathcal{O}(1)$ 的效应破缺。通过这种方式，人们得以将无全局对称性猜想定量地与其他沼泽原理联系起来。尽管这个思路很有吸引力，但这些工作仍未解决破缺为什么应当相对较强的问题。

Due to the above, the no global symmetries conjecture was often regarded as a nice proof of principle of the Swampland program which however lacked teeth. Recent progress has been able to challenge this view, at least in the case of supersymmetric quantum theories of gravity. While these are not of direct phenomenological relevance, they are still a rich part of the quantum gravity Landscape where progress is possible.

由于上述原因，无全局对称性猜想常被认为只是沼泽地计划中一个漂亮的原理性证明，本身缺乏实际约束力。近期进展已经对这种观点提出了挑战，至少在超对称量子引力理论中是如此。尽管这类理论和唯象学没有直接关联，但它们仍然是量子引力景观中一个内容丰富、能够取得研究进展的部分。

The basic idea, pioneered in [23], is to use the fact that the Completeness Principle described above often demands the existence of charged extended objects, and if these objects are supersymmetric, anomaly inflow on their worldvolume can be used to rule out putative quantum gravities. There are by now several papers that use anomaly inflow on strings [24, 24-32] or other objects to rule out supersymmetric EFT's. Although the assumption of BPS completeness (that the objects predicted by the Completeness Principle are actually supersymmetric, if they can be) has a couple mild counterexamples [33], these cases are probably anecdotical, and the constraints placed by anomaly inflow are there to stay.

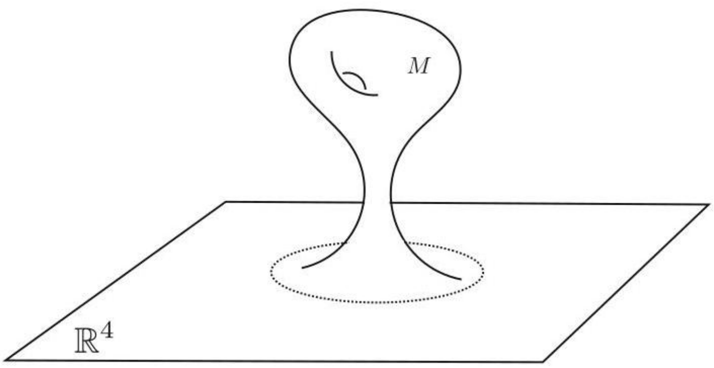
这一基本思路由文献 [23] 开创，其核心是利用上文描述的完备性原理往往要求存在带电延展物体这一事实: 如果这些物体是超对称的，就可以利用它们世界体积上的反常流入排除掉部分假设的量子引力。目前已经有多篇文章利用弦上 [24, 24-32] 或其他物体的反常流入排除了超对称有效场论。尽管 BPS 完备性 (即完备性原理预言的物体只要可能就应当是超对称的) 存在少量反例 [33]，但这些案例大概率只是个例，反常流入给出的约束仍然成立。

Some variants of the anomaly inflow arguments rely heavily in a recent outgrowth of the no global symmetries conjecture, dubbed the Cobordism Conjecture [34]. The Cobordism Conjecture is an application of the principle that there are no global symmetries in quantum gravity to the case of topological symmetries involving the spacetime topology itself. To illustrate the idea, we will follow [34] and consider a five-dimensional theory of gravity that reduces to General Relativity at low energies. For concreteness, consider the theory on the manifold $\mathbb{R}^5 = \mathbb{R}^4 \times \mathbb{R}$ . The spatial slices have $\mathbb{R}^4$ topology, and in principle, one may consider excising a point and gluing an arbitrary four-manifold, as in Fig. 3. The resulting configuration looks like a particle on $\mathbb{R}^4$ from far away, a kind of ”topological soliton” in an otherwise flat space.

反常入流论证的部分变体高度依赖于无全局对称性猜想的一个最新延伸，即配边猜想 [34]。配边猜想是将量子引力中不存在全局对称性这一原理应用到涉及时空拓扑本身的拓扑对称性的结果。为阐明这一思路，我们将沿用文献 [34] 的思路，考虑一个低能下约化为广义相对论的五维引力理论。为具体说明，我们考虑流形 $\mathbb{R}^5 = \mathbb{R}^4 \times \mathbb{R}$ 上的该理论。空间切片具有 $\mathbb{R}^4$ 拓扑，原则上，我们可以切掉一个点，再粘上任意一个四维流形，操作如图 3 所示。最终得到的构型从远处看就像是 $\mathbb{R}^4$ 上的一个粒子，是平直空间中的一种“拓扑孤子”。

Fig. 3 If spacetime topology is dynamical, one can consider excising a small ball of $\mathbb{R}^4$ and gluing a manifold $M$ as depicted in the figure. For all intends and purposes, the object constructed in this way looks like a particle in $\mathbb{R}^4$ , a kind of topological soliton

Fig. 3 如果时空拓扑是动力学的，我们可以如图所示切掉 $\mathbb{R}^4$ 的一个小球，再粘上一个流形 $M$ 。无论从哪个角度看，这样构造出的物体都像是 $\mathbb{R}^4$ 中的一个粒子，是一种拓扑孤子



If topology change is indeed allowed in quantum gravity, we might expect transitions from flat space to geometries of the kind depicted in Fig. 3. However, we will now see that not every geometry is allowed. The most general topology-changing transition permitted in semiclassical gravity is depicted in Fig. 4: There is a smooth geometry $\mathcal{C}$ that interpolates between the manifolds $M$ and $M'$ . Crucially, the interpolating geometry has to be smooth, if we want to be sure that the process is allowed in semiclassical gravity. Other processes involving singularities may or may not be allowed, but the ones depicted in Fig. 4 is the minimal set that can be allowed if topology-changing transitions are allowed.

如果量子引力中确实允许拓扑改变，我们应当能预期从平直空间到图 3 所示这类几何的转变。但我们接下来会看到，并非所有几何都是被允许的。半经典引力中允许的最一般拓扑改变转变如图 4 所示: 存在一个光滑几何 $\mathcal{C}$ ，插值连接流形 $M$ 和 $M'$ 。关键在于，如果我们要确定该过程在半经典引力中是允许的，这个插值几何必须是光滑的。其他涉及奇点的过程是否允许尚无定论，但如果拓扑改变转变是允许的，图 4 所示的过程就是可允许的最小集合。

Figure 4 is the standard mathematical picture for a cobordism: two manifolds are said to be cobordant if their union is the boundary of another manifold in one dimension higher. Interpreting the horizontal axis in the Figure as (Euclidean) time, the cobordism is a proper mathematical notion encoding topology-changing processes. Cobordism is an equivalence relation, and the set obtained by quotienting all manifolds modulo cobordisms admits a canonical abelian group structure (given by either disjoint union or connected sum of manifolds; the two are canonically cobordant to each other). The resulting abelian group of cobordism classes of $d$ -dimensional manifolds is denoted by

图 4 是配边的标准数学图像: 如果两个流形的并集是更高一维流形的边界，则称它们是配边的。将图中的横轴视为 (欧氏) 时间，配边就是描述拓扑改变过程的恰当数学概念。配边是一种等价关系，将所有流形按配边做商得到的集合具有规范阿贝尔群结构 (由流形的不交并或连通和给出；二者在规范意义下彼此配边)。由此得到的 $d$ 维流形配边等价类的阿贝尔群记为

$$\Omega_d^{\bullet} \tag{7}$$

where the dot is a placeholder for any additional structure that the physical theory under consideration may have. For instance, theories where orientation matters are controlled by oriented bordes groups, theories with fermions are formulated on Spin or Spin$^c$ manifolds, and there are various other generalizations of these structures that are relevant in different quantum theories of gravity. Which bordism theory to use depends on the details of the physical theory under consideration and is part of the data needed to properly specify the theory.

其中的点是占位符，代表所研究的物理理论可能具有的任何额外结构。例如，需要考虑取向的理论由定向配边群刻画，含费米子的理论在 Spin 或 Spin$^c$ 流形上构建，这些结构还有多种其他推广，在不同的量子引力理论中都有其相关性。选择哪种配边理论取决于所研究物理理论的具体细节，是正确指定理论所需数据的一部分。

The simple fact about cobordism groups with Swampland implications is simply that in general they do not vanish. Going back to our example of five-dimensional gravity and transitions among it, the relevant cobordism group is (assuming we would like to be able to define fermions as well, so that a Spin structure is demanded)

对沼泽地有启示的关于配边群的一个简单结论就是，一般而言配边群非零。回到我们的五维引力及其内部转变的例子，相关的配边群是 (假设我们还需要能够定义费米子，因此要求 Spin 结构)

$$\Omega_4^{\text{Spin}} = \mathbb{Z} \tag{8}$$

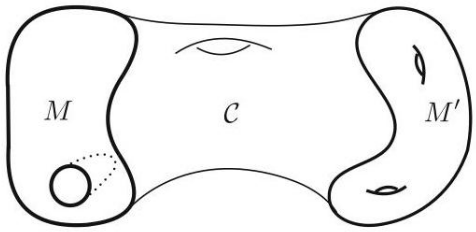



Fig. 4 If topology is allowed to fluctuate, the most general transition involving smooth geometries is depicted in the figure, with (Euclidean) time running from left to right. The manifold $M$ transitions into a topologically distinct one, $M'$ . The transition is mediated by a manifold $\mathcal{C}$ , of one dimension more, such that its boundary is $M \cup M'$ . This is the mathematical definition of a cobordism

Fig. 4 如果允许拓扑涨落，图中给出了涉及光滑几何的最一般转变，(欧氏) 时间从左向右流逝。流形 $M$ 转变为拓扑不同的流形 $M'$ ，转变由高一维的流形 $\mathcal{C}$ 介导，$\mathcal{C}$ 的边界为 $M \cup M'$ 。这就是配边的数学定义

Empty flat space sits in the trivial cobordism class (Cobordism is commonly defined for compact manifolds. For all purposes in this review, we may replace flat space $\mathbb{R}^n$ by the sphere $S^n$ , which is the boundary of the $(n+1)$ -dimensional ball.), while the generator of the cobordism group can be represented by K3. What this means is that, if there is initially a K3 glued to our spacetime as in Fig. 3, there is no way for topology-changing transitions of the kind described above to make this disappear. There is a conserved quantum number, which is roughly ”how many copies of K3” are there in the four-manifold that we glue, and that can in fact be computed as the integral of a local density, the first Pontryagin class

空平直空间属于平凡配边类 (配边通常是对紧致流形定义的。在本综述的所有讨论中，我们都可以将平直空间 $\mathbb{R}^n$ 替换为球面 $S^n$ ，它是 $(n+1)$ 维球的边界)，而配边群的生成元可以由 K3 曲面表示。这意味着，如果最初有一个 K3 曲面像图 3 那样粘在我们的时空中，上述这类拓扑改变跃迁无法让它消失。这里存在一个守恒量子数，大致就是我们粘的四维流形中“有多少个 K3 副本”，它实际上可以通过对局部密度——第一庞特里亚金类——积分计算得到

$$p_1 = -\frac{1}{8\pi^2}\,\mathrm{tr}\,(R \wedge R) \tag{9}$$

The number $\int p_1$ is called the first Pontryagin number of the manifold [35]. At least at the level of the low-energy EFT, the Pontryagin number is a conserved integer-valued charge, and therefore it corresponds to a global $U(1)$ symmetry in the theory. More generally, any nontrivial class of the cobordism group will correspond to a global symmetry. In general, the group $\Omega_p^{\bullet}$ in a $d$ -dimensional quantum theory of gravity labels a $(d-p-1)$ -form global symmetry [34].

数 $\int p_1$ 被称为流形的第一庞特里亚金数 [35]。至少在低能有效场论层面，庞特里亚金数是守恒的整数值荷，因此它对应理论中的一个整体 $U(1)$ 对称性。更一般地说，配边群的任何非平凡类都对应一个整体对称性。一般而言，$d$ 维量子引力理论中的群 $\Omega_p^{\cdot}$ 标记了一个 $(d-p-1)$ 形式整体对称性 [34]。

In some theories, it may happen that these global symmetries are gauged. For instance, $\int p_1$ contributes to NS5-brane charge in heterotic string theory [36]. But in other theories, such as type IIA string theory, the symmetry is not gauged, as the low-energy supergravity manifestly lacks the requisite couplings. In this case, absence of global symmetries dictates that the symmetry must be broken: There must be some (necessarily singular) configurations that allow the K3 (or any other manifold) to shrink to a point, as illustrated in Fig. 5. The statement of the cobordism conjecture is that, once all these defects and singularities are included, there are no more global symmetries left, so

在某些理论中，这些整体对称性可能会被规范。例如，$\int p_1$ 对杂弦理论中的 NS5 膜荷有贡献 [36]。但在其他理论中，比如 IIA 型弦论，该对称性不是规范对称性，因为低能超引力明显缺少必要的耦合。在这种情况下，无整体对称性要求对称性必须破缺: 必须存在某些 (必然是奇异的) 构型允许 K3(或任何其他流形) 收缩为一个点，如图 5 所示。配边猜想的表述是: 一旦包含所有这些缺陷和奇点，就不再存在整体对称性，因此

$$\Omega_d^{QG} = 0 \tag{10}$$

The power of the cobordism conjecture lies not so much in (10), but rather in the fact that it can be used to predict new defects in a quantum theory of gravity, in the manner illustrated in Fig. 5. Although string theory often makes sense in mildly singular manifolds such as orbifolds, in general there is no way to tell whether a particular quantum gravity must admit this or that singularity. The cobordism conjecture provides a way to do just that, in cases where the singularity is required to "kill" a certain cobordism class. These ideas were used in [37] to place strong constraints in minimally supersymmetric theories in seven, eight, and nine dimensions. These theories are labeled by a parameter $r$ , called the rank of the theory, and which is simply the number of vector multiples appearing in the low-energy supergravity Lagrangian at a generic point in moduli space.

配边猜想的影响力与其说来自式 (10)，不如说来自它可以用来预言量子引力理论中的新缺陷，其方式如图 5 所示。尽管弦论通常在轨形这类轻度奇异流形上是自洽的，但一般来说我们无法判断特定量子引力是否必须存在某类奇点。配边猜想在奇点需要“消除”某个配边类的情况下，恰好提供了这样一种判断方法。这些想法在文献 [37] 中被用来对七、八、九维的极小超对称理论给出强约束。这些理论由参数 $r$ 标记，该参数称为理论的秩，它就是模空间一般点处低能超引力拉格朗日量中出现的矢量多重态的数目。

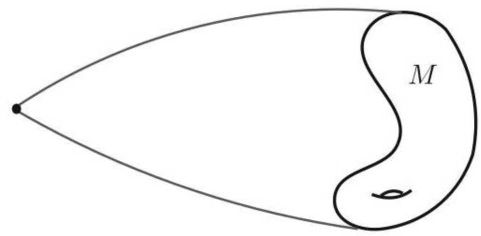


Fig. 5 The cobordism conjecture implies that every manifold $M$ is a boundary in quantum gravity, but this may involve singular configurations, depicted schematically as a point in the left part of the picture. The power of the cobordism conjecture lies precisely in requiring particular singularities to exist in order to trivialize cobordism classes that can be represented by smooth manifolds. Often, these added new singularities can be used to constrain the theory in significant ways

图 5 配边猜想意味着量子引力中每个流形 $M$ 都是一个边界，但这可能涉及奇异构型，在图的左侧被示意性地画为一个点。配边猜想的影响力恰恰在于，为了平凡化可以由光滑流形表示的配边类，它要求特定奇点必须存在。通常，这些新增的奇点可以用来对理论给出非常强的约束

The cobordism conjecture predicts certain defects that can be used as building blocks in compactifications of the parent theory. In eight and nine dimensions, the resulting lower-dimensional theory had a gravitational anomaly, rendering the theory inconsistent, unless the rank satisfies the condition

配边猜想预言了一些可作为母理论紧化构造模块的缺陷。在八维和九维中，除非秩满足条件，否则得到的低维理论会存在引力反常，导致理论不自洽

$$r \equiv 1,2 \mod 8 \text{ in 9d and 8d, respectively.} \tag{11}$$

This is precisely matched by the known string constructions in eight and nine dimensions. Since then, a new component of moduli space has been found [33], also satisfying (11). This shows that the principle that there are no global symmetries (in the form of cobordism conjecture) can become quite powerful in combination with supersymmetry. Reference [37] also used the same techniques to make predictions about the global form of the gauge group that could appear in these higher rank theories at particular points in moduli space For instance, if at any point a symplectic factor appears in the gauge group, reference [37] predicted that

这与已知的八维和九维弦构造完全吻合。此后人们发现了模空间的一个新分支 [33]，也同样满足式 (11)。这说明不存在整体对称性的原理 (以配边猜想的形式) 结合超对称性可以变得非常强大。文献 [37] 还使用相同技术对这些高秩理论在模空间特定点处可能出现的规范群整体形式做出了预言。例如，如果在任意点规范群中出现辛因子，文献 [37] 预言

$$\frac{Sp(k)}{\mathbb{Z}_2} \text{ for } k \equiv 1,2 \mod 4 \text{ are in the Swampland.} \tag{12}$$

At the time of publication of [37], this was a prediction, since symplectic factors are known to occur at special points of moduli space of the rank 9 theory in nine dimensions (the CHL string), but their global form was not computed. These predictions where later verified by explicit string theory calculations in [38]. This reference found that on the moduli space of the CHL string one can find groups containing factors

在文献 [37] 发表时，这属于一个预测: 因为已知辛因子会出现在九维秩为 9 的理论 (即 CHL 弦) 模空间的特殊点上，但它们的整体形式尚未被计算出来。这些预测后来在文献 [38] 中通过明确的弦论计算得到了验证。该文献发现，在 CHL 弦的模空间上可以找到包含如下因子的群

$$Sp(1), Sp(2), Sp(4), Sp(10) \text{ and } Sp(8)/\mathbb{Z}_2. \tag{13}$$

all of which are manifestly compatible with (12). Thus, this is an example where the Swampland prediction was later verified by string theory calculations. Reference [30, 39] also verified constraints of the global form of the gauge group coming from the Green-Schwarz terms of the effective action and a smart interplay with anomaly inflow in the string of the worldsheet coupled to the anti symmetric 2- form tensor which is always present in the gravity multiplet. Since then, variations of the above argument, in combination with the completeness Principle [14] and Bekenstein bound [40] have been used to completely characterize the space of consistent quantum gravities in eight and nine dimensions from a Swampland perspective [41, 42]. The results perfectly match what one obtains from known top-down string constructions, realizing an idea commonly referred to as string universality or the String Lamppost Principle: at least in high dimensions and in the arena of supersymmetric theories, every low-energy effective field theory that can be embedded at all in quantum gravity can in fact be embedded in string theory.

所有这些因子都显然与 (12) 相容。因此，这是沼泽地猜想的预测后来被弦论计算验证的一个实例。文献 [30, 39] 也验证了来自有效作用量格林-施瓦茨项的规范群整体形式约束，以及它与世界面弦上反常流入的巧妙相互作用，这里世界面弦耦合了引力多重态中始终存在的反对称二阶张量。此后，上述论证的变体结合完备性原理 [14] 和贝肯斯坦界 [40]，已被用于从沼泽地视角完全刻画八维和九维中一致量子引力的空间 [41, 42]。所得结果与已知的自上而下弦构造完全吻合，印证了通常被称为弦普遍性或弦路灯原理的观点: 至少在高维以及超对称理论的范畴内，任何能够嵌入量子引力的低能有效场论，都确实可以嵌入弦论。

Recent research in the cobordism conjecture has focused on questions such as whether there is a way to guess the correct structure carried by cobordism groups beyond supergravity [43], and the interplay of cobordism with more familiar charges in string theory such as K-theory [44-46]. One very interesting, novel line of research is that of ”dynamical cobordism”, which focuses on endowing the proposed cobordism defects with reasonable metrics satisfying Einstein’s equations and other equations of motion [47-50]. It is often the case that this can be done, and there are signs of universal behaviors in the corresponding solutions, which seem to be classified by just a few critical exponents [50]. Finally, the cobordism conjecture suggests a reinterpretation of some previously known singular backgrounds of supergravity, such as the Mourad-Dudas background [45], as non-supersymmetric cobordism defects associated to non-supersymmetric string theories, thereby providing some mild support for their existence and consistency. Recent work [51] uses Ricci flow to endow cobordisms with a natural metric.

配边猜想的近期研究聚焦于以下问题: 除超引力外，是否存在方法推断配边群承载的正确结构 [43]，以及配边与弦论中 K 理论这类更常见荷之间的相互作用 [44-46]。一个非常有趣的全新研究方向是“动力学配边”，该方向研究为提出的配边缺陷赋予满足爱因斯坦方程和其他运动方程的合理度规 [47-50]。研究发现这种构造通常是可行的，且有迹象表明对应的解存在普适行为，似乎仅由少数几个临界指数分类 [50]。最后，配边猜想提示我们对一些先前已知的超引力奇异背景 (例如 Mourad-Dudas 背景 [45]) 重新诠释，将其视为与非超对称弦论关联的非超对称配边缺陷，从而为这些理论的存在性和自洽性提供了一定支持。近期工作 [51] 利用里奇流为配边赋予了自然度规。

We have saved for last a very far-reaching speculation related to the cobordism conjecture. As a generalization of the absence of no global symmetries, it is supposed to hold on any quantum gravity, even in those beyond string theory. With that in mind, consider the cobordism group $\Omega_0^{QG}$ . This is just the group of d-dimensional quantum gravities, where two quantum gravities are regarded as equivalent if they can be joined by a domain wall of finite tension. The cobordism conjecture then implies that this group vanishes, i.e.

that any two quantum theories of gravity can be connected by a domain wall.

最后我们来讨论一个与配边猜想相关的影响深远的推测。作为不存在整体对称性的推广，该猜想被认为适用于任何量子引力，哪怕是弦论以外的量子引力。据此考虑配边群 $\Omega_0^{QG}$ 。这就是 d 维量子引力构成的群: 若两个 d 维量子引力能被一张有限张力的畴壁连接，则二者被视为等价。配边猜想指出该群是平凡群，即任意两个量子引力理论都可以通过畴壁连接。

We usually regard vacua connected by permeable domain walls as two different vacua of a single theory. If this limiting case of the cobordism conjecture is true, then it implies that there is a single quantum theory of gravity in each dimension. Since we already know string theory vacua in every dimension down to four, it would follow that every quantum theory of gravity is part of string theory, in the sense that it may be connected to it by domain walls. Of course, many of these vacua may turn out to be completely different from the known string theory solutions. But as a point of principle, there would be a single quantum theory of gravity. The really interesting point is that this speculation may be tested more rigorously for spacetimes with a negative cosmological constant, where holography allows us to trade difficult questions about gravity by questions in field theory, where they may be more manageable. In particular, as explained in [52], a cobordism domain wall between two AdS vacua maps to a conformal interface between the two dual CFT's. So the question becomes whether any two CFT's can be connected by a permeable conformal interface, which has been explored in the holographic literature [53]. We still know very little about the general properties that such a conformal interface may have; but it is exciting that a fundamental question such as the uniqueness of quantum gravity in AdS can be formulated in sharp, rigorous terms, in a context where progress is in principle possible.

我们通常将可穿透畴壁连接的真空视为同一个理论的两个不同真空。如果配边猜想的这个极限情形成立，那就意味着每个维度仅存在一个量子引力理论。既然我们已经知道弦论在四维及以上每个维度都存在真空，就能推出所有量子引力理论都属于弦论——具体来说，它们都可以通过畴壁和弦论连接起来。当然，这些真空中有许多可能与已知的弦论解完全不同。但就原理而言，量子引力只会是唯一的。真正有趣的点在于，对于负宇宙常数的时空，这个推测可以得到更严格的检验: 在这类时空中，全息原理允许我们将困难的引力问题转化为场论问题，处理起来会更容易。正如文献 [52] 所述，两个反德西特 (AdS) 真空之间的配边畴壁，对应于两个对偶共形场论 (CFT) 之间的共形界面。于是问题转化为: 任意两个 CFT 是否都能通过可穿透共形界面连接，这个问题已在全息文献中得到探讨 [53]。目前我们对这类共形界面的一般性质仍知之甚少，但令人兴奋的是，AdS 量子引力唯一性这样的基础问题，可以在一个原则上能够取得进展的框架下，以清晰、严谨的方式表述出来。

## The Weak Gravity Conjecture

## 弱引力猜想

If global symmetries are forbidden by quantum gravity, how does gravity obstruct gauge symmetries from becoming global by taking the weak coupling $g \to 0$ limit? The Weak Gravity Conjecture (WGC) [54] quantifies how approaching a global symmetry limit from a gauge symmetry is obstructed by quantum gravity. In its simplest form, the WGC heuristically requires that "In a consistent EFT coupled to gravity, there must be at least one state on which gravity acts as the weakest force." In particular, it does not mean that gravity is the weakest force on all states. This conjecture applies to charged particle states as well as charge p-branes. By now, there are many inequivalent and stronger versions of this conjecture [55-57] which we will review.

Before doing so, let us start with the simplest version to illustrate the main idea.

如果整体对称性被量子引力所禁，那么当耦合取弱耦合 $g \to 0$ 极限时，引力是如何阻碍规范对称性成为整体对称性的？弱引力猜想 (WGC)[54] 量化了量子引力如何阻碍从规范对称性趋近整体对称性极限。其最简单的形式从直观上要求:“在一个自洽的、耦合引力的有效场论中，至少存在一个态，使得引力是作用于该态的最弱力。”特别需要注意，这并不意味着引力是所有态上的最弱力。该猜想既适用于带电粒子态，也适用于带荷 p 膜。目前该猜想存在多个不等价的更强版本 [55-57]，我们会对其逐一回顾。在此之前，我们先从最简单的版本出发，说明其核心思想。

Mild WGC Consider a $U(1)$ gauge theory coupled to gravity. Then, there must exist an object of charge $q$ and mass $m$ satisfying

弱形式 WGC 考虑一个耦合引力的 $U(1)$ 规范理论。那么该理论中必须存在一个带荷 $q$ 、质量为 $m$ 的物体，满足

$$\frac{|q|}{m} \geq \left.\frac{|Q|}{M}\right|_{\text{ext}} \tag{14}$$

where $\left.\frac{|Q|}{M}\right|_{\text{ext}}$ stands for the charge-to-mass ratio of an arbitrarily large extremal black hole. We will refer to objects obeying (14) as superextremal. There are two ways we can see why (14) obstructs global symmetries. A pure $U(1)$ gauge theory without any charged matter has a 1-form global symmetry [10]. This global symmetry is broken by charged matter, though the charged state in question can be very massive. The WGC (14) can be viewed as an upper bound on how massive the charged object can be. Another, perhaps more direct, way to see the weak coupling limit to global symmetries is obstructed is to apply (14) to magnetically charged objects. This brings us to the Magnetic WGC. Again, consider the 1-form version of WGC for simplicity, though our discussion can be easily generalized to p-forms. Objects with magnetic charges coupling to the 1-form gauge field are magnetic monopoles. The mass of a magnetic monopole receives contributions from the energy stored in its magnetic field. This energy is UV divergent unless we put a cutoff $\Lambda$ on the effective theory beyond which the description of a monopole as a particle breaks down. Thus, in the absence of fine-tuned cancellation between this field energy and its bare mass,

其中 $\left.\frac{|Q|}{M}\right|_{\text{ext}}$ 对应任意大极值黑洞的荷质比。我们将满足 (14) 的物体称为超极值物体。我们可以从两个角度理解为什么 (14) 会阻碍整体对称性。不含任何带电物质的纯 $U(1)$ 规范理论拥有 1 形式整体对称性 [10]。该整体对称性会被带电物质破缺，不过对应的带电态可以质量极大。WGC(14) 可以看作是对带电物体的质量给出了上限。另一种或许更直接理解弱耦合极限会被阻碍的方式，是将 (14) 应用到磁荷物体上。这就引出了磁 WGC。同样，我们为简单起见讨论 1 形式版本的 WGC，但我们的讨论可以很容易推广到 p 形式。与 1 形式规范场耦合带磁荷的物体就是磁单极子。磁单极子的质量包含其磁场储存的能量贡献。除非我们给有效理论引入一个截断 $\Lambda$ ——超过该能标后磁单极子的粒子描述失效，否则这部分能量会紫外发散。因此，若不对场能量与裸质量进行精细调谐抵消，就会得到

$$m_{\text{monopole}} \sim \frac{\Lambda}{g^2} \tag{15}$$

where g is the electric gauge coupling. Dirac quantization implies that the magnetic gauge coupling is given by $2\pi/g$ . The magnetic WGC thus puts a cutoff on the scale of new physics of the $U(1)$ gauge theory to be:

其中 $g$ 是电规范耦合。狄拉克量子化给出磁规范耦合为 $2\pi/g$ 。因此磁 WGC 给 $U(1)$ 规范论的新物理能标截断给出了约束:

$$\Lambda \lesssim g M_P \tag{16}$$

The magnetic WGC therefore suggests an obstruction to taking the $g \to 0$ limit as the cutoff for new physics becomes vanishingly small. The theory in question (e.g. the $U(1)$ gauge theory here) ought to be replaced by a more UV complete description.

因此磁 WGC 表明，取 $g \to 0$ 极限会被阻碍，因为新物理的截断会变得无穷小。讨论中的理论 (例如此处的 $U(1)$ 规范理论) 应当被更紫外完备的描述替代。

As it stands, the mild WGC alone (14) seems rather toothless as the required superextremal state can be very massive. For example, large (but finite size) black holes are a minimal option to fulfill (14) without the need of superextremal particles within the EFT. On the other hand, heuristic arguments (to be reviewed shortly) as well as all known examples string theory both point to stronger statements than the mild WGC. As one may expect, the implications of the WGC to phenomenology and cosmology hinge on substantiating these stronger versions of the conjecture. Since the conjecture was first proposed, continuous efforts have been made in strengthening the WGC. Counterexamples have been found for some of the proposed strong forms. However, there are two related strong versions of the WGC that stand numerous tests and scrutiny:

就目前来看，仅弱形式 WGC(14) 约束力很弱，因为它要求的超极值态可以质量极大。例如，大质量 (但尺寸有限) 黑洞就可以在不需要有效场论内存在超极值粒子的情况下，满足 (14) 的要求，是一个满足条件的最小选项。另一方面，我们很快会回顾的直观论证，以及弦理论中所有已知实例，都指向比弱形式 WGC 更强的结论。正如可预见的那样，WGC 唯象学与宇宙学的推论依赖于这些更强版本猜想的成立。自该猜想首次提出以来，人们一直在努力强化 WGC，部分提出的强形式已经找到了反例。不过，有两个相关的强 WGC 版本通过了大量检验与推敲:

Tower WGC [57] For every site in the charge lattice $\mathbf{q} \in \Gamma$ , there exists a positive integer $n$ such that there is a superextremal state of charge $n\mathbf{q}$ .

塔 WGC[57] 对于荷晶格 $\mathbf{q} \in \Gamma$ 中的每一个格点，都存在一个正整数 $n$ ，使得存在一个电荷为 $n\mathbf{q}$ 的超极值态。

Sublattice WGC [55, 56] There exist a positive integer $n$ such that for any site in the charge lattice $\mathbf{q} \in \Gamma$ , there is a superextremal state of charge $n\mathbf{q}$ .

子晶格 WGC [55, 56] 存在一个正整数 $n$ ，使得对于荷晶格 $\mathbf{q} \in \Gamma$ 中的任意格点，都存在一个电荷为 $n\mathbf{q}$ 的超极值态。

It is easy to see that the sublattice WGC is stronger than the tower WGC because the integer $n$ in the latter can be chosen independently of $\mathbf{q}$ . Such $q$ -independent $n$ is referred to as the coarseness of the sublattice. The tower WGC implies that in any charge direction $\hat{q}$ , there exists an infinite tower of superextremal states. While this is sometimes how the tower WGC is formulated, consistency with dimensional reduction upgrades this formulation to the formal definition above. Taking $n = 1$ in the sublattice WGC would certainly strengthen the conjecture further but counterexamples to this stronger lattice WGC [58] have been found [55, 56]. It remains an open problem finding an upper bound on $n$ , as various loopholes on the WGC rely on the possibility of having a coarse sublattice. The evidence for the tower/sublattice WGC comes mostly from string theory. Consistency with dimensional reduction lends additional support to the necessity of an infinite tower of superextremal states. The fact that a charged state in string theory is accompanied by a tower of excited states with increasing charge and mass follows from a basic property of string theory, namely modular invariance. The excited string states are expected to transition into black holes as we turn on the string coupling. The tower of charged states therefore interpolates between (light) particles and black holes (see Fig. 6). The correspondence principle [59] only demands the entropy of black holes to match with the string entropy up to an $\mathcal{O}(1)$ factor. Such approximate matching is not enough to show that the masses of the tower of charged states stay on the same side of the extremal curve upon the string-black hole transition. In special cases, however, the entropy matching is exact (due to anomaly matching), and we can identify the massive superextremal states required by the tower/sublattice WGC as black holes [60]. The evidence for tower/sublattice WGC goes beyond perturbative string theory as the conjecture has since been verified in F-theory [61-63].

不难看出，子格 WGC 比塔 WGC 更强，因为后者中的整数 $n$ 可独立于 $\mathbf{q}$ 选取。这种不依赖 $q$ 的 $n$ 被称为子格的粗度。塔 WGC 表明，任意电荷方向 $\hat{q}$ 都存在无限多超极端态构成的塔。虽然这有时是塔 WGC 的表述方式，但维数约化的一致性会将该表述升级为上文的正式定义。在子格 WGC 中取 $n =$ 为 1 当然会进一步加强猜想，但这种更强的格 WGC 已被找到反例 [55, 56]。为 $n$ 寻找上界仍是一个开放问题，因为 WGC 的诸多漏洞都依赖存在粗子格的可能性。塔/子格 WGC 的证据大多来自弦论，维数约化的一致性为存在无限超极端态塔的必要性提供了额外支撑。弦论中的带电粒子会伴随一组电荷和质量不断增加的激发态塔，这一点源自弦论的一个基本性质，即模不变性。当我们开启弦耦合时，激发弦态预期会转变为黑洞。因此带电态塔在 (轻) 粒子和黑洞之间形成过渡 (参见图 6)。对应原理 [59] 仅要求黑洞熵和弦熵在相差一个 $\mathcal{O}(1)$ 因子的范围内匹配。这种近似匹配不足以证明，在弦-黑洞转变过程中，带电态塔的质量始终保持在极端曲线同侧。但在特殊情况下，熵匹配是精确的 (因反常匹配)，我们可以将塔/子格 WGC 要求的大质量超极端态识别为黑洞 [60]。塔/子格 WGC 的证据并不局限于微扰弦论，该猜想已在 F 理论中得到验证 [61-63]。

Very recently, an interesting example has been put forth [64] of an explicit string compactification that seems to violate the tower and lattice versions of the WGC, with only a finite number of particles being stable and all other putative higher states of the tower being seemingly absent. Although this question is not settled, one outstanding feature is that the $U(1)$ gauge fields for which this happens are not weakly coupled. This suggests a simple rationale for the absence of the tower: In explicit examples, it is often the case that the charge-to-mass ratio decreases as the charge of the states in the tower increases. In such a setup, it is kinematically possible for the states high-up in the tower to decay to the small charge ones, which end up being the only stable states. For couplings which are $\mathcal{O}(1)$ , it stands to reason that these decays are very fast, and so the lattice states decay so quickly that they cannot be detected with explicit calculations. In some sense, the tower is perhaps there, but the states are so short-lived that do not even count as resonances. Conversely, in cases where where the $U(1)$ coupling goes to zero, interactions switch off, and the decay rates of highly charged states drop to zero even if it is kinematically allowed for them to decay. Therefore they become long-lived, and are detectable with perturbative techniques, reproducing a complete tower. Interestingly, the arguments in [55-57] take place in such a perturbative limit.

最近，文献 [64] 提出了一个有趣的显式弦紧致化例子，它似乎违反了 WGC 的塔版本和格版本：该例子中只有有限个粒子是稳定的，塔中所有其他假定的高能态似乎都不存在。虽然这个问题尚无定论，但一个突出特点是，发生这种情况的 $U(1)$ 规范场都不是弱耦合的。这为塔不存在给出了一个简单解释：在显式例子中，塔内态的荷质比往往会随态电荷的增加而降低。在这类设定中，塔高处的态在运动学上可以衰变为小电荷态，最终只有小电荷态是稳定的。对于耦合为 $\mathcal{O}(1)$ 的情况，这些衰变显然会非常快，因此格点态衰变太快，无法通过显式计算探测到。从某种意义上说，塔或许存在，但这些态寿命极短，甚至不能算作共振态。相反，在 $U(1)$ 耦合趋于零的情况下，相互作用会关闭，即便高电荷态在运动学上允许衰变，它们的衰变率也会降至零。因此这些态会变成长寿命态，可以被微扰技术探测到，从而重现完整的塔。值得注意的是，文献 [55-57] 的论证都是在这类微扰极限下进行的。

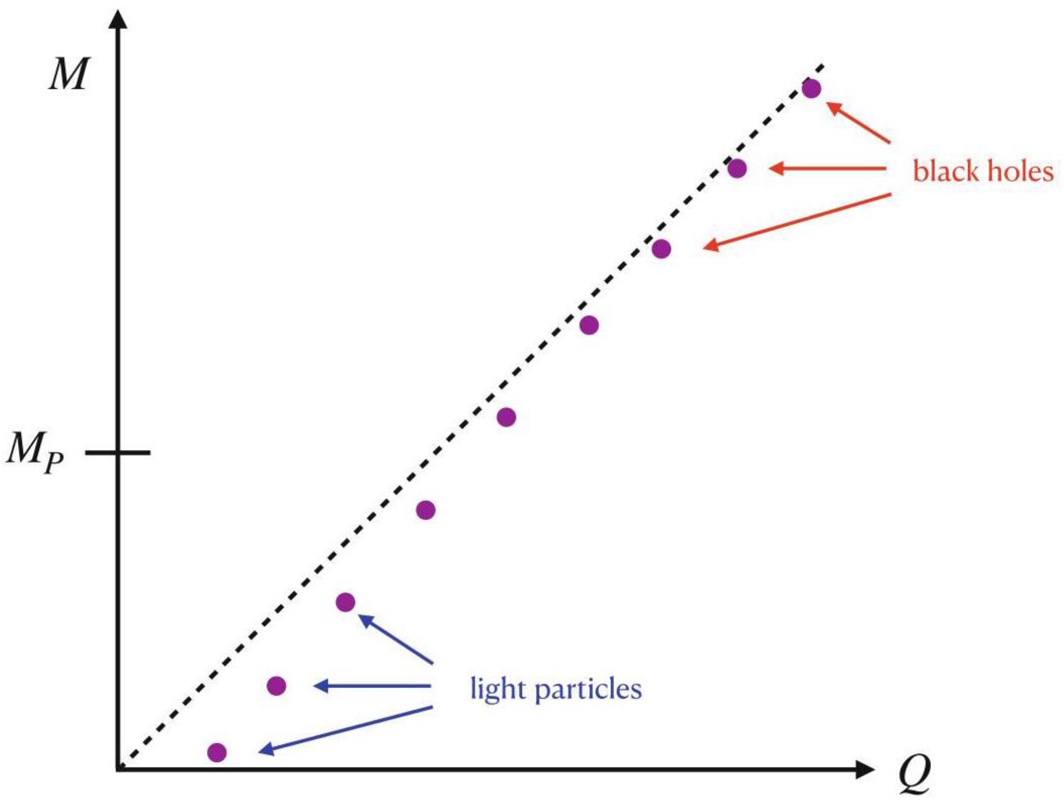



Fig. 6 A schematic picture showing that the tower of states satisfying the WGC can interpolate between light particles (perturbative string states) and black holes. The dashed line $M \propto Q$ corresponds to the extremality bound for an arbitrarily large Reissner-Nordström black hole in asymptotically flat spacetime

图 6 满足 WGC 的态塔可以在轻粒子 (微扰弦态) 和黑洞之间形成过渡的示意图。虚线 $M \propto Q$ 对应渐近平直时空内任意大赖斯纳-努德斯特伦黑洞的极端性边界

One may wonder if there are similar swampland constraints on rotating black holes. After all, in string theory, charges and angular momenta are simply different excitations of a string. On the other hand, black hole instability does not seem to impose constraints on the spectrum of states. Rotating black holes, even extremal ones, can lose their angular momentum and energy via superradiance. Moreover, in six and higher dimensions, black holes with a given mass can have arbitrary large angular momentum, at least for pure gravity [65]. There is no extremality bound for such higher-dimensional rotating black holes. Curiously, a spinning WGC for the BTZ black hole was shown to follow from the c-theorem of the dual CFT [66]. This appears to be just a curiosity. As was shown in [67] using string dualities that map rotating to charged black holes, the usual charged WGC reviewed above does not always imply a spinning WGC.

> 人们或许会好奇，旋转黑洞是否也存在类似的沼泽地约束。毕竟在弦论中，荷与角动量不过是弦不同的激发态。另一方面，黑洞不稳定性似乎不会对态谱施加约束。旋转黑洞，哪怕是极端旋转黑洞，也可以通过超辐射损失角动量和能量。此外，在六维及更高维中，至少对纯引力而言，给定质量的黑洞可以拥有任意大的角动量 [65]，这类高维旋转黑洞不存在极端性界。有趣的是，BTZ 黑洞的自旋 WGC 可以从对偶 CFT 的 c 定理导出 [66]，这目前看来只是个巧合。正如文献 [67] 通过将旋转黑洞映射为带电黑洞的弦对偶性所示，我们上述回顾的常规带电 WGC 并不总能推导出自旋 WGC。

While our discussion above can be easily generalized to other $p$ -form gauge symmetries (with the replacement of mass $m$ in say Eq. (14) by tension), the $p = 0$ case is much more subtle. Interestingly, the $p = 0$ version of the WGC is what leads to much of the interesting phenomenological consequences. A 0-form gauge field is a periodic scalar known as an axion, and the objects charged under this 0- form symmetry are (-1)-branes, also kown as instantons. A naive extrapolation of the extremality bound for $p - 1$ -branes to $p = 0$ does not lead to sensible results, indicating that there is no clear notion of extremality. Thus, the sharp bound in the WGC we have seen e.g. in (14) (and analogous sharp bounds on the charge-to-tension ratio of $p - 1$ -branes for $p > 0$ ) is replaced by a $\gtrsim$ in the axion WGC to reflect the unknown $\mathcal{O}(1)$ coefficient that sets the extremality bound:

> 尽管我们上述的讨论可以很容易推广到其他 $p$ -形式规范对称性 (只需将例如式 (14) 中的质量 $m$ 替换为张力)，但 $p = 0$ 的情况要微妙得多。有意思的是，恰恰是 WGC 的 $p = 0$ 形式衍生了大量有趣的唯象学结果。0-形式规范场是一种被称为轴子的周期标量，而在这种 0-形式对称性下带荷的物体是 (-1)-膜，也叫瞬子。将 $p - 1$ -膜的极端性界直接外推到 $p = 0$ 得不到合理结果，说明极端性在这里没有清晰的定义。因此，我们之前看到的 WGC 中的严格界，例如式 (14)(以及 $p > 0$ 中 $p - 1$ -膜荷-张力比的类似严格界)，在轴子 WGC 中被替换为 $\gtrsim$ ，以反映设定极端性界的未知 $\mathcal{O}(1)$ 系数:

Axion WGC For an axion with axion decay constant $f$ coupled to quantum gravity, there must exist an instanton of instanton number $n$ such that

> 轴子 WGC: 对于与量子引力耦合、轴子衰变常数为 $f$ 的轴子，必然存在一个瞬子数为 $n$ 的瞬子，满足

$$\frac{nM_P}{f} \gtrsim S_{\text{inst}} \tag{17}$$

This $\mathcal{O}(1)$ ambiguity has to do with which type of gravitational instantons (known as core instantons, D-instantons, and wormholes) one should use to define the extremality bound. Some evidence for the axion WGC has been found by analyzing the charge-to-action ratio of Euclidean axion wormholes [68, 69]. However, questions have been raised as to whether Euclidean wormholes in axion gravity are perturbatively unstable, in the sense quadratic fluctuations around the wormhole solution could have negative modes that lower the action. Even for the simplest case, namely, Euclidean wormholes in pure axion gravity [70], conflicting results to this question have populated the literature in the past quarter of a century [71- 73]. If these wormholes are perturbatively unstable, they are not genuine saddle points that contribute to the path integral, casting doubts whether they are suitable for setting the extremality bound. In [74], it was shown that when gauge invariance and correct boundary conditions are imposed, which have not been simultaneously accounted for in previous works, there are no negative modes. While it remains to be seen whether perturbative negative modes continue to be absent when the axion-gravity system couples to additional massless scalars (aka dilatons), the findings in [74] eliminate a fundamental objection of using wormholes to set the axion WGC bound.

> 这种 $\mathcal{O}(1)$ 不确定性和我们应该用哪类引力瞬子 (核心瞬子、D-瞬子和虫洞) 来定义极端性界有关。通过分析欧几里得轴子虫洞的荷-作用量比，人们已经找到了轴子 WGC 的部分证据 [68, 69]。但学界一直存在疑问: 轴子引力中的欧几里得虫洞是否存在微扰不稳定，即虫洞解附近的二次涨落可能存在负模，从而降低作用量。哪怕是最简单的情况，也就是纯轴子引力中的欧几里得虫洞 [70]，过去二十五年来文献对这个问题一直存在矛盾的结论 [71-73]。如果这些虫洞确实是微扰不稳定的，它们就不是对路径积分有贡献的 genuine 鞍点，这让人们怀疑它们是否适合用来设定极端性界。文献 [74] 指出，当同时要求规范不变性和正确的边界条件 (此前的工作都没有同时满足这两个条件)，这类负模并不存在。虽然当轴子-引力系统耦合额外的无质量标量 (即伸缩子) 时，微扰负模是否仍不存在还有待验证，但文献 [74] 的结果消除了用虫洞设定轴子 WGC 界的一个核心反对意见。

Besides generalizing the WGC to $p$-form gauge symmetries, another axis to extend the WGC is to theories with more fields, such as theories with multiple $U(1)$ gauge fields or massless scalars. Requiring black holes charged under multiple $U(1)$ gauge symmetries to discharge turns (14) into a convex hull condition [75]. In theories with massless scalar fields, whether an object is superextremal is distinct from whether a pair of such objects will repel each other at long distance. This distinction brings us to the repulsive force conjecture.

> 除了将 WGC 推广到 $p$-形式规范对称性，另一个扩展 WGC 的方向是多场理论，例如多个 $U(1)$ 规范场或无质量标量的理论。要求带多个 $U(1)$ 规范对称性荷的黑洞放电，会将式 (14) 变为凸包条件 [75]。在存在无质量标量场的理论中，一个物体是超极端的，和一对该物体在长程下相互排斥，这两个命题并不等价。这个区别就引出了斥力猜想。

Repulsive Force Conjecture (RFC) [76] In any theory of a single Abelian gauge field coupled to gravity, there is a self-repulsive charged particle.

> 斥力猜想 (RFC)[76]: 在任意一个单个阿贝尔规范场与引力耦合的理论中，都存在一个自斥的带电粒子。

This RFC was referred to as the scalar WGC in [76] and was subsequently studied in [77, 78] and generalized to theories with more than one gauge field [79].

> 这个 RFC 在文献 [76] 中被称为标量 WGC，随后在文献 [77, 78] 中得到研究，并被推广到多个规范场的理论 [79]。

Yet another direction to extend the WGC is to spacetimes with different asymp-totics. Formulating the WGC in AdS spacetimes [56, 80] has the added advantage of exploiting the powerful machineries of holography. Reference [81] provides a universal, bottom-up argument for a version of the WGC in AdS, using the Ryu-Takayanagi proposal to compute holographic entanglement entropies. Specifically, theories with stable AdS planar extremal black holes (which violate the WGC) have a volume law for entanglement entropy and exponential decay of correlators, properties that are in tension with rigorous theorems about entanglement entropy in the dual CFT. The most simple way to have this black holes be unstable and shed their charge is to have a particle satisfying the WGC. More recently, the RFC above when applied to AdS spacetimes has motivated a charge convexity conjecture [82] that may hold for any CFT, not just those with weakly coupled and weakly curved gravitational duals.

扩展 WGC 的另一个方向是研究具有不同渐近性质的时空。在 AdS 时空中表述 WGC[56, 80] 的额外优势在于可以利用全息术的强大工具。文献 [81] 利用 Ryu-Takayanagi 提议计算全息纠缠熵，为 AdS 中的一个 WGC 版本提供了普适的自下而上论证。具体而言，存在稳定 AdS 平面极端黑洞 (这类黑洞违反 WGC) 的理论中，纠缠熵满足体积律，关联函数呈指数衰减，这些性质与对偶 CFT 中关于纠缠熵的严格定理存在矛盾。让这类黑洞变得不稳定并释放电荷的最简单方法，就是存在一个满足 WGC 的粒子。最近，上述应用于 AdS 时空的 RFC 引出了电荷凸性猜想 [82]，该猜想可能适用于任意 CFT，而不仅限于具有弱耦合、弱弯曲引力对偶的 CFT。

If instead of AdS one considers black hole discharge in dS space, one is led to the following Festina Lente (FL) bound.

如果人们考虑的不是 AdS，而是 dS 空间中的黑洞放电，就会得到如下的“慢行道”(Festina Lente, FL) 边界。

Festina Lente [83,84] In dS space, the mass $m$ for every state of charge 1 under a $U(1)$ gauge field with coupling g satisfies

慢行道猜想 [83,84]: 在 dS 空间中，对于耦合为 $g$ 的 $U(1)$ 规范场，电荷为 1 的每个态的质量 $m$ 满足

$$\frac{m^4}{4\pi\alpha} \geq V \tag{18}$$

where $\alpha = g^2/4\pi$ is the fine structure constant and $V = \Lambda/8\pi G_N$ (with $G_N$ the Newton constant) is the gravitational vacuum energy. Note that in contrast to the usual WGC (14), the mass of a state with a given charge (set to be 1 here) is bounded from below rather than from above. We refer to the excellent review [85] for further details.

其中 $\alpha = g^2/4\pi$ 是精细结构常数，$V = \Lambda/8\pi G_N$ 是引力真空能 ( $G_N$ 为牛顿常数)。注意，和通常的 WGC(14) 不同，给定电荷 (此处设为 1) 的态的质量是有下界而非上界。更多细节可以参考出色的综述文献 [85]。

It should be clear from the above discussion that what is commonly referred as the WGC is really a suite of distinct but closely related ”weak gravity conjectures”. These conjectures, if proven, have varying degrees of predictive power. Rightfully, they also have varying degrees of evidence and support. The evidence ranges from string theory constructions to general principles (often using black holes as test objects). Naturally, supporting evidence for the stronger forms of the WGC tends to come from concrete UV completions. There have been attempts to prove the WGC (mostly its mild form) using holography [56,81], unitarity/causality [86-88] (see also [57, 89]) (This program of using unitarity, causality, and analyticity bounds to constrain Wilson coefficients of the effective theory is sometimes referred as the S-matrix bootstrap. It has more recently been used to obtain other Swampland bounds, see. e.g. [90].), black hole thermodynamics [91-95] and entropy [86, 96, 97]. There is also an intriguing relation between the mild WGC and the cosmic censorship conjecture [98, 99]. At the time of writing, we do not have a fully proof of the WGC from general principles. This is not unexpected as each of these general principles is only a facet of what constitutes a consistent quantum theory of gravity. It is encouraging that with our currently incomplete knowledge of quantum gravity, a subset of the known governing principles already point us to these conjectured properties.

从上述讨论可以清楚看出，通常所说的 WGC 实际上是一组不同但密切相关的“弱引力猜想”。这些猜想若得证，会具备不同程度的预言能力，相应地，它们也拥有不同程度的证据支持。证据范围从弦理论构造到一般性原理 (通常以黑洞作为测试对象)。自然而然，更强形式 WGC 的支持证据往往来自具体的紫外完备。已有尝试利用全息术 [56,81]、幺正性/因果性 [86-88](另见 [57, 89])(这项利用幺正性、因果性和解析性边界约束有效理论威尔逊系数的研究有时被称为 S 矩阵自举，最近它已被用于得到其他沼泽地边界，参见例如 [90])、黑洞热力学 [91-95] 和熵 [86, 96, 97] 证明 WGC(主要是其温和形式)。温和 WGC 和宇宙监督猜想 [98, 99] 之间还存在有趣的关联。在撰写本文时，我们还未能从一般性原理出发完全证明 WGC。这并不意外，因为这些一般性原理中的每一个都只是一致量子引力理论某一方面的体现。令人鼓舞的是，即使我们目前对量子引力的知识尚不完整，一部分已知的基本原理已经指向了这些猜想性质。

The resurgence of interest in the WGC is due largely to its potentially wide-ranging phenomenologial implications. The WGC was first proposed in 2006, but it was not until almost a decade later that it has attracted wide attention. The (non-)observation of primordial gravitational waves by BICEP2 has triggered a critical rethinking of whether trans-Planckian field ranges are possible in quantum gravity. In the context of axion inflation (i.e., inflation with periodic axions), the question is whether trans-Planckian axion decay constants can be realized in controlled constructions of quantum gravity. This was the backdrop for several groups in sharpening the axion WGC and applying it to axion inflation [100-103].

WGC 重新引发兴趣很大程度上源于它潜在的广泛唯象学意义。WGC 最早于 2006 年提出，但直到近十年后才引起广泛关注。BICEP2(未) 观测到原初引力波，引发了人们重新思考量子引力中是否可能存在跨普朗克能标的场范围。在轴子暴胀 (即由周期性轴子驱动的暴胀) 背景下，问题变为: 在可控的量子引力构造中能否实现跨普朗克轴子衰变常数？这正是多个研究团队 sharpen 轴子 WGC 并将其应用于轴子暴胀 [100-103] 的背景。

Versions of the WGC has also been used to put phenomenological constraints on dark photons [12] and dark matter scenarios [104]. Stronger versions of the WGC [105] have been used to link the observed value of the cosmological constant with the neutrino masses (which for fixed Yukawa couplings, set the weak scale) [106, 107]. Ideas to stabilize the Higgs mass using the WGC in the presence of scalars have been explored [77, 108]. We referred the readers to other reviews in the literature, in particular the focused review [109] for further discussions.

不同版本的 WGC 也被用于对暗光子 [12] 和暗物质模型 [104] 给出唯象学约束。更强形式的 WGC[105] 被用于联系观测到的宇宙学常数数值和中微子质量 (对于固定汤川耦合，中微子质量决定了弱能标)[106, 107]。人们也已经研究了在存在标量时利用 WGC 稳定希格斯质量的想法 [77, 108]。我们建议读者参考文献中的其他综述，尤其是专题综述 [109] 获取更多讨论。

## The Swampland Distance Conjecture

## 沼泽地距离猜想

Most fully controlled, top-down examples of effective field theories coming from quantum gravity that we know are supersymmetric, and they come with scalars parametrizing exactly flat directions (with no potential), commonly referred to as the moduli. Moduli fields control the couplings of the effective field theory, as well as the masses of massive particles and extended objects in the theory. A natural question is how these quantities vary with the moduli, and this is the topic we will address in this section.

我们目前所知、源自量子引力且控制度最高的自顶向下有效场论例子大多是超对称的，其中包含标量场参数化恰好平坦的方向 (无势能)，这类标量通常被称为模。模场控制着有效场论的耦合，也控制着理论中已有质量粒子和延展物体的质量。一个自然的问题是这些物理量如何随模变化，这正是本节我们要讨论的主题。

The space of moduli fields (the moduli space) comes equipped naturally with a Riemannian metric, coming from the kinetic terms of the moduli in the low-energy effective field theory Lagrangian. Indeed, the function $g_{ab}(\phi)$ in

模场的空间 (即模空间) 自然带有一个黎曼度量，该度量源自低能有效场论拉格朗日量中模的动能项。确实，$g_{ab}(\phi)$ 函数在

$$S_{kin} = \int \sqrt{-g}\frac{1}{2}g_{ab}\partial_\mu\phi^a\partial^\mu\phi^b \tag{19}$$

is bilinear, symmetric, and positive-definite, and thus constitutes a metric. It turns out that moduli spaces are often (but not always) non-compact with respect to the topology induced by the metric, and there are incomplete geodesics of unbounded length. Such geodesics are said to reach out to ”points at infinite distance”. The Swampland Distance conjecture (SDC) concerns the behavior of the masses of heavy states as the moduli approach an infinite distance point. Specifically, choose any geodesic of infinite length, and let $\phi$ be an affine parameter. As we get close to the infinite distance point, there is some tower of states that becomes light in Planck units in an exponential way, i.e. such that their masses behave as

中是双线性、对称且正定的，因此构成了一个度量。研究发现，在该度量诱导的拓扑下，模空间通常 (但不总是) 是非紧的，存在长度无界的不完备测地线。这类测地线被认为延伸到了“无穷远点”。沼泽地距离猜想 (SDC) 关注的是当模趋近无穷远点时，重态质量的变化行为。具体来说，任取一条无穷长测地线，令 $\phi$ 为仿射参数。当我们趋近无穷远点时，会存在一个态塔，其质量在普朗克单位下呈指数下降，即它们的质量满足

$$m_n(\phi) = m_n(\phi = \phi_0)\,e^{-\alpha\phi} \tag{20}$$

as one approaches $\phi \to \infty$ from a reference point $\phi = \phi_0$ . The precise value of the constant $\alpha$ , which controls the rate at which the states become light in Planck units, has been the focus of much recent attention in the literature. The reason for this is the impact that $\alpha$ has in what is arguably the most important phenomenological application of the Distance Conjecture, that is, to inflation. Models of large field inflation must sustain a field displacement typically of order 1 in Planck units, all while in the regime of validity of the effective field theory. This is in tension with (20), since after a field displacement of orders few times $1/\alpha$ in Planck units, many fields of the tower will enter the effective field theory of inflation, signaling its breakdown. In [110], this was quantified to produce a precise relationship between $\alpha$ , the field range $\Delta\varphi$ , the amplitude of scalar perturbations $A_s$ , and the tensor-to-scalar ratio $r$ , both measurable quantities:

当我们从参考点 $\phi = \phi_0$ 向 $\phi \to \infty$ 趋近时。控制态在普朗克单位下变轻速率的常数 $\alpha$ 的精确值，是近年文献关注的重点。原因在于 $\alpha$ 对距离猜想最重要的唯象应用——暴涨——有着关键影响。大场暴涨模型需要在有效场论的有效适用范围内，维持量级约为 1 普朗克单位的场位移。这与式 (20) 存在矛盾，因为在场位移达到数倍 $1/\alpha$ 普朗克单位后，态塔中的许多场会进入暴涨的有效场论，意味着原有效场论失效。在文献 [110] 中，研究者对此进行量化，得到了 $\alpha$ 、场范围 $\Delta\varphi$ 、标量扰动振幅 $A_s$ 以及可测量的张标比 $r$ 之间的精确关系:

$$\Delta\varphi < -\frac{1}{2\alpha}\left(\log\frac{\pi^2 A_s}{2} + \log r\right). \tag{21}$$

Due to its direct relevance for inflationary cosmology, there has been a great deal of work on the Swampland Distance Conjecture in the last years, and in particular, checking and providing evidence for it in String Theory. Unlike other statements such as absence of global symmetries or the WGC, the Distance Conjecture lacks a clear, simple rationale from general principles of quantum gravity (with one exception that we will discuss briefly below, the Emergence proposal) and is much more based on examples, but the string theory evidence behind it is vast. The pioneering work in this line was [111], which focused on infinite distance limits in the complex structure moduli space of 4 d N = 2 effective field theories arising from compactification of type II strings on Calabi-Yau manifolds. Grimm et al. [111] used the theory of Mixed Hodge Structures to identify infinite orbits of BPS states and show there is always one that becomes light in the infinite distance limit, including in limits outside of the regime of validity of the original supergravity description. The results have been extended to other setups and constitute one of the main technical tools to study the Distance Conjecture in quantum gravity, including Kahler moduli spaces and the study of asymptotic potentials [112-114] as well as a far-reaching generalization, the Tameness Conjecture [115, 116]. These are also related to questions of finiteness of quantum gravity vacua [117].

由于与暴涨宇宙学直接相关，近年关于沼泽地距离猜想的研究非常多，尤其是在弦论中对其检验并提供证据。和“不存在整体对称性”、弱引力猜想等其他沼泽地陈述不同，距离猜想缺乏从量子引力一般原理出发清晰简洁的基础 (我们会在下文简要讨论一个例外: 涌现纲领)，它更多建立在例子之上，但弦论中支持它的证据非常丰富。该方向的开创性工作是文献 [111]，研究聚焦于 II 型弦紧化在卡拉比-丘流形上得到的 4 d N = 2 有效场论的复结构模空间的无穷远极限。Grimm 等人 [111] 利用混合霍奇结构理论识别出 BPS 态的无穷轨道，证明始终存在一个轨道会在无穷远极限下变轻，哪怕是在原超引力描述适用范围之外的极限。该结果已经被推广到其他 setup，是研究量子引力中距离猜想的核心技术工具之一，研究涵盖凯勒模空间和渐近势 [112-114]，还包括影响深远的推广: 驯顺性猜想 [115, 116]。这些内容也和量子引力真空的有限性问题 [117] 相关。

The Weak Gravity Conjecture, and in particular its sublattice and tower versions, are intimately related to the Distance Conjecture. Indeed, often the tower of states posited by the WGC happens to drop in mass exponentially near an infinite distance point, simply because the gauge coupling itself does, thereby fulfilling the Distance Conjecture. Examples of such setups are perturbative limits of string theories and infinite distance limits in complex structure moduli space of Calabi-Yau compactifications. From this point of view, the only question that remains to recover [117, 118] is why the gauge coupling is dropping exponentially. In the infinite distance limit, the gauge coupling goes to zero, the tower of states must be included in the description, and the theory is no longer a d-dimensional quantum gravity. It is an experimental fact that in every infinite distance limit there is some gauge coupling (for either an ordinary or a higher form gauge field) that goes to zero, and in fact it has been conjectured that this is always the case [118].

弱引力猜想 (尤其是其子晶格版本和塔版本) 与距离猜想密切相关。事实上，弱引力猜想所预言的态塔通常会在无穷远点附近指数级降质，原因很简单: 规范耦合本身就会指数级减小，这刚好满足了距离猜想的要求。弦论的微扰极限以及卡拉比-丘紧化复结构模空间的无穷距离极限都是这类结构的例子。从这个角度来看，要得到文献 [117, 118] 的结论，剩下的唯一问题就是规范耦合为何会指数衰减。在无穷距离极限下，规范耦合趋于零，描述中必须包含态塔，此时理论不再是 d 维量子引力。实验规律表明，在每一个无穷距离极限下，都存在某个规范耦合 (对应普通规范场或高阶形式规范场) 趋于零，且实际上已有猜想指出这一结论普遍成立 [118]。

The observation that vanishing gauge couplings, infinite distances, and towers of states of vanishing mass are related is the starting point for a rationale for the Distance Conjecture and the Emergence Proposal [111, 119]. Based on similar mechanisms that take place in field theory [120], the Emergence Proposal reverses the roles and claims that, rather than having states becoming massless at an exponential rate at infinite distance limits, the fact that there are charged states becoming massless will cause the moduli space metric to diverge and send the point where the gauge coupling vanishes to infinite distance. The basic mechanism is that the kinetic term of the moduli controlling the gauge coupling receives corrections from the charged states in the tower running in loops. Importantly, one must cut off this sum at the energy scale at which gravity becomes strongly coupled, as dictated by the so-called species bound [121]. Resumming the diagrams produces a dependence (see [111, 117] for details)

零规范耦合、无穷距离与零质量态塔相互关联的观测，是距离猜想和涌现猜想 [111, 119] 的逻辑出发点。基于场论中已有的类似机制 [120]，涌现猜想颠倒了二者的因果关系: 它主张，并不是态在无穷距离极限下以指数速率变为零质量，恰恰相反，带电态变为零质量这一事实会导致模空间度量发散，进而将规范耦合归零的点推到无穷远处。基本机制是: 控制规范耦合的模的动能项会受到态塔中带电态的圈修正。重要的是，按照所谓的种类界 [121] 的要求，必须在引力变成强耦合的能标处截断这个求和。重新对图求和后得到了如下依赖关系 (细节见 [111, 117])

$$\delta g_{\phi\phi} \sim \left(\frac{\partial_\phi m}{m}\right)^2 \tag{22}$$

which would yield an exponential gauge coupling, if it was the leading (or the only) term. The picture of the Emergence Proposal is that kinetic terms for all gauge fields are somehow vanishing in the UV and generated by loop effects as one flows down to the IR. There is a lively follow-up in the literature, extending the idea to towers of states other than particles [122, 123] to try to derive more features of the theory, such as the scalar potential.

如果它是领头项 (或是唯一项)，就会得到指数形式的规范耦合。涌现猜想的图景是: 所有规范场的动能项在紫外都会趋近于零，在向红外流的过程中通过圈效应生成。该想法提出后已有大量后续研究，将其拓展到粒子以外的态塔 [122, 123]，试图推导出理论的更多性质，例如标量势。

The Emergence Proposal fits well with another attempt at providing a bottom-up rationale for the Distance Conjecture, recently discovered by Stout in [124, 125]. The basic idea here is that information theory provides a natural notion of distinguishability of theories living in a moduli space, that such a notion yields naturally a metric, and furthermore that this metric coincides with the moduli space metric described above. In this picture, infinite distance points corresponds to theories which can be distinguished with certainty from others with a finite number of measurements. This fits naturally with the fact that vanishing gauge couplings signal the emergence of a global symmetry, in which protected correlators are exactly zero. A single measurement of these correlators is enough to be able to tell that one is not at the infinite distance limit. This approach is quite novel and merits further research, particularly in the connection with the properties of the tower of states.

> 涌现猜想与另一种为距离猜想提供自下而上解释的尝试十分契合，该尝试近期由 Stout 在 [124, 125] 中提出。这里的基本思路是: 信息论为模空间中不同理论的可区分性给出了自然定义，这种定义自然会引出一个度量，且该度量恰好与上述模空间度量一致。在这个图景中，无穷距离点对应可以通过有限次测量与其他理论明确区分的理论。这与零规范耦合预示着整体对称性涌现的结论自然契合，整体对称性下受保护的关联函数严格为零。只需对这些关联函数做一次测量，就足以判断当前不在无穷距离极限处。这个方法相当新颖，值得进一步研究，尤其是它与态塔性质的关联。

A different attempt to understand the origin of the Distance Conjecture was undertaken in [27, 126] , where the infinite distance limits were related to the low-codimension strings and membranes that must exist in supersymmetric theories due to the Completeness Principle. In particular, in [27], it was shown how the the WGC for strings implies the Swampland Distance Conjecture. These works, together with the Dynamical Cobordism papers reviewed in the previous section, emphasize the connections between the different conjectures of the Swampland Program (in this case, the Distance Conjecture, Cobordism Conjecture, and Completeness Principle), which tie together the different statements and lends support to the global picture.

> 另有研究者在 [27, 126] 中尝试探究距离猜想的起源，该研究指出，由于完备性原理，无穷远极限与超对称理论中必然存在的低余维弦和膜相关。特别地，文献 [27] 证明了弦的弱引力猜想如何推出沼泽地距离猜想。这些工作，加上上一节回顾的动态协边理论论文，都强调了沼泽地计划不同猜想之间的关联 (此处即距离猜想、协边猜想与完备性原理)，这种关联将不同论断联系在一起，也为整体图景提供了支撑。

A lot of the patterns and observations related to the Distance Conjecture described above can be recovered, and superseded, by a much stronger conjecture: the Emergent String Conjecture [127]. This posits that every infinite distance limit in quantum gravity is either a decompactification limit, where the endpoint is a higher-dimensional quantum theory of gravity, or a perturbative string limit, amenable to worldsheet string perturbation theory. Therefore, the Emergent String Conjecture tells us how to resolve the infinite tower of states that becomes light in the infinite distance limit, and tells us that the only two possibilities are the ones that we have encountered so far.

> 上述与距离猜想相关的大部分模式和观测，都可以被一个强得多的猜想——涌现弦猜想 [127]——重现甚至涵盖。该猜想指出，量子引力中所有无穷距离极限要么是退紧致化极限，其终点是一个更高维的量子引力理论，要么是可以用世界面弦微扰论处理的微扰弦极限。因此，涌现弦猜想告诉我们如何解决无穷距离极限下变轻的无穷态塔问题，并且指出仅存在我们迄今已经遇到过的两种可能性。

Unlike previous conjectures, the Emergent String Conjecture is purely motivated by empirical evidence, and supported by dualities. It is rather surprising that every time that we know how to resolve an infinite distance limit in quantum gravity, we encounter either decompactification or a perturbative string limit. The simplest example of this phenomenon is T-duality, by which compactification on a circle of small radius is equivalent to a decompactification limit described by a circle of very large radius. More complicated avatars of the same idea, such as mirror symmetry, or heterotic type II duality only reinforce this point.

与此前的猜想不同，涌现弦猜想完全由经验证据推动，且得到对偶性的支持。相当令人惊讶的是，每当我们能够解决量子引力中的无限距离极限时，我们都会遇到退紧致化或是微扰弦极限。T 对偶性是该现象最简单的例子: 在小半径圆周上紧致化，等价于大半径圆周描述的退紧致化极限。同一思想更复杂的体现，比如镜像对称、杂化-? 型对偶，只会进一步印证这一结论。

If the Emergent string Conjecture is true, a number of the patterns described above have simple explanations. Infinite distance limits have a vanishing gauge coupling corresponding to KK photons, and perturbative string limits have a vanishing coupling for the gauged 1-form symmetry that couples to the $B$ field, the anti-symmetric 2-form that the strings couple electrically to. The towers of states that becomes light are simply the KK modes and the perturbative string states, respectively. Perhaps even Emergence in the decompactification limit becomes a feature of the dimensional reduction of the higher-dimensional supergravity theory. And of course, it becomes possible to fully classify the values of $\alpha$ consistent with perturbative string or decompactification limits, a task that was recently performed in [128]. The result is that there seems to be an upper bound

如果涌现弦猜想成立，上文描述的诸多规律都能得到简单解释。无限距离极限中对应 KK 光子的规范耦合会趋于零，而在微扰弦极限中，与 $B$ 场 (弦对其发生电耦合的反对称 2 形式) 耦合的规范 1 形式对称性的耦合也会趋于零。逐渐变轻的态塔分别就是 KK 模式和微扰弦态。甚至退紧致化极限中的涌现性都可能成为高维超引力理论维度约化的固有特征。当然，我们也可以对与微扰弦极限或退紧致化极限相容的 $\alpha$ 取值进行完整分类，这一工作近期已在文献 [128] 中完成。结果似乎显示存在一个上界

$$\alpha \geq \frac{1}{\sqrt{d-2}} = \frac{1}{\sqrt{2}} \ (d=4) \tag{23}$$

on the parameter $\alpha$ . The result is still under scrutiny, because there are examples where the leading known tower does not satisfy the bound; but of course, it may just be that there are other towers yet to be found, leading to (23) being obeyed [128, 129].

约束参数 $\alpha$ 。该结论仍在接受检验，因为已有例子中已知的领头态塔不满足这个界；但当然，这也可能只是因为尚有其他态塔未被发现，最终式 (23) 仍会成立 [128, 129]。

The Swampland Distance Conjecture also has interesting consequences on the behavior of potentials which we will review in the next section.

沼泽地距离猜想对势的行为也存在有趣的结论，我们将在下一节回顾这些内容。

## Conjectures on Vacuum Energy

## 真空能猜想

In addition to the implications of the Distance Conjecture to formal aspects of string compactifcations, there is also a large body of work discussing the Distance Conjecture in connection with potentials and the vacuum energy. This connection for spacetimes with positive and negative vaccum energy have taught us different lessons about quantum gravity. We will review this connection in this section. Spacetimes with negative vacuum energy (anti de Sitter (AdS) space) have the advantage of having holographic duals, making it possible to verify or formulate the conditions on potentials from a CFT perspective. On the other hand, our universe appears to have undergone two accelerating phases, one in the early universe and another in its current state. These accelerating phases seem to be well described by spacetimes with positive vacuum energy (de Sitter space). However, de Sitter space in string theory is currently not as well understood as its AdS counterpart. We will begin our discussion with the conjectures on AdS space, before moving to the more challenging case of de Sitter.

除了距离猜想对弦紧化的形式层面的启示外，已有大量工作讨论距离猜想与势和真空能的关联。带正真空能与负真空能的时空给我们带来了关于量子引力的不同启发，我们将在本节回顾这一关联。带负真空能的时空 (即反德西特 (AdS) 空间) 的优势在于它存在全息对偶，因此我们可以从共形场论 (CFT) 的角度验证或构造对势的约束条件。另一方面，我们的宇宙似乎经历了两个加速膨胀阶段: 一个发生在早期宇宙，另一个就是当前的加速膨胀阶段。这类加速阶段可以被带正真空能的时空 (即德西特空间) 很好地描述。但目前弦论中的德西特空间远不如反德西特空间被我们充分理解。我们将先讨论反德西特空间的相关猜想，再转向更具挑战性的德西特情形。

The connection between the Distance Conjecture and negative vacuum energy was pioneered by [130], which proposed the Anti de Sitter Distance Conjecture (ADC). This version of the conjecture states that, given an infinite one-parameter family of spacetimes with negative cosmological constant $\Lambda$ that goes to zero in Planck units, there is a tower of states whose masses go to zero as $\Lambda^{\beta}$ , for $\beta$ an order one number. The strong version of the conjecture states that in fact $\beta = 1/2$ , and implies that there are internal dimensions or other towers of light states at the AdS length scale already, thus one can never have an effective $d$ dimensional theory in $AdS_d$ . The theory is always stringy or higher dimensional. In this way, the Swampland makes contact with the recent discussions on stringy constructions of scale-separated vacua, where there is a hierarchy between the size of the extra dimensions and the AdS length scale, which is a topic of very active research in the literature. It is also possible to study the Distance Conjecture holographically, from the point of view of the dual CFT, as done in [131,132]. The results are similar to the bulk counterparts of the conjecture: Infinite distance limits are always accompanied of infinite towers of states that become light. See [133] for a holographic argument that the limit $g \to 0$ is obstructed in Einstein gravity, a milder statement than the Distance Conjecture itself.

距离猜想与负真空能之间的关联由文献 [130] 开创，该工作提出了反德西特距离猜想 (ADC)。这个版本的猜想指出: 给定一个无穷单参数族带负宇宙常数 $\Lambda$ 的时空，且宇宙常数在普朗克单位下趋于零，则存在一个态塔，其质量随 $\Lambda^{\beta}$ 趋于零，其中 $\beta$ 是一阶量级的数。该猜想的强形式指出实际上满足 $\beta = 1/2$ ，这意味着在 AdS 尺度就已经存在内禀维度或其他轻态塔，因此在 $AdS_d$ 中永远不可能存在有效的 $d$ 维理论——该理论始终是弦论性质的，或是高维的。通过这种方式，沼泽地计划与近期关于尺度分离真空的弦论构造讨论建立了联系；尺度分离指额外维尺度与 AdS 尺度之间存在层级，这是目前学界非常活跃的研究课题。我们也可以像文献 [131,132] 那样，从对偶 CFT 的角度全息研究距离猜想。所得结果与猜想在体空间的对应结论一致: 无穷距离极限始终伴随着变轻的无穷态塔。关于极限 $g \to 0$ 在爱因斯坦引力中被阻碍这一比距离猜想更弱的结论，参见文献 [133] 中的全息论证。

The cosmological constant introduced by Einstein was originally thought to be his ”biggest blunder”. Yet, a variety of modern cosmological observations are giving increasingly strong support to an accelerating universe that can be described by a positive (albeit extremely small) cosmological constant. Whether the unknown component of the universe (aka dark energy) that drives the accelerated expansion of the universe is the cosmological constant (corresponding to an equation of state $w = -1$ ) or not is a question of great experimental interest. Ever since the discovery of dark energy, finding a full-fledged top-down de Sitter vacua (or something like it, such as quintessence) that is well under theoretical control has been a top problem in quantum gravity. The dark energy problem really only arises in the presence of gravity since the energy of the vacuum is immaterial without gravity. It is moreover a question for quantum gravity because classically we can tune the vacuum energy to be zero (or very small) at will. In the past two decades, there have been a great deal of efforts in constructing de Sitter vacua in string theory. We refer the readers to some recent reviews [134-136] for a discussion of the current status of these attempts. Despite tremendous advances in string compactifications, constructing de Sitter vacua in string theory is still work in progress. Some of the widely studied scenarios such as [137-139] probably contain important elements of the truth, but it is fair to say that they all involve a leap from string theoretical data (compactification space, fluxes, branes, etc) to 4D EFT that are not explicitly computable with our current technologies. This situation has improved in the last years, thanks to the efforts of [140-143] which have succeeded (modulo demonstrating the smallness of certain corrections coming from string-sized cycles in the construction; see, however, [144]) in producing examples of flux-stabilized AdS vacua with small superpotential. Having explicit realizations of such vacua is a first step towards realizing the KKLT proposal [137] concretely in string theory; further progress would be necessary to uplift the vacuum by introducing objects that explicitly break the supersymmetry, such as an anti-D3 brane. Metastability of anti-D3 branes requires a large enough warped throat which as argued in [145] leads to a singular bulk problem. The singularities of the internal metric may be resolved at the non-perturbative level [146] but the low energy effective theory is altered by the non-perturbative resolution; its theoretical control remains to be shown.

爱因斯坦提出的宇宙学常数最初被认为是他的“最大失误”。然而，各类现代宇宙学观测越来越强有力地表明，宇宙正在加速膨胀，这可以用一个正的 (尽管数值极小) 宇宙学常数来描述。驱动宇宙加速膨胀的未知宇宙成分 (即暗能量) 究竟是不是宇宙学常数 (对应物态方程 $w = -1$ )，这是一个极具实验研究价值的问题。自暗能量被发现以来，在理论控制范围内构建完整的自上而下德西特真空 (或类似模型，比如精质模型) 一直是量子引力领域的核心问题。暗能量问题只有在引力存在的情况下才会出现，因为没有引力时真空能量并不产生实质影响。此外这是一个量子引力层面的问题: 在经典力学中，我们可以随意将真空能量调为零 (或极小值)。过去二十年间，弦论领域已有大量研究工作致力于构建德西特真空。关于这些研究的现状，读者可以参考近期的综述文献 [134-136]。尽管弦紧致化研究已经取得了巨大进展，在弦论中构建德西特真空仍在进行中。广泛研究的部分经典方案 (例如 [137-139]) 大概率包含了正确的重要内容，但平心而论，所有这类构建都需要从弦论数据 (紧致化空间、流、膜等) 跃迁至四维有效场论，而以目前的研究技术还无法明确计算这一步。近几年这一情况得到了改善，这得益于 [140-143] 的工作: 他们成功构建出了具有小超势的通量稳定反德西真空实例 (不过还需证明构建中弦尺度闭链带来的某些修正确实很小；但参见 [144])。得到这类真空的明确实现，是在弦论中具体实现 KKLT 方案 [137] 的第一步；要抬升真空能量，还需要引入反 D3 膜这类明确破缺超对称的对象，这方面仍需进一步研究。反 D3 膜的亚稳态要求足够大的弯曲喉道，正如 [145] 指出的，这会引发体空间的奇点问题。内禀度规的奇点可以在非微扰层面得到解决 [146]，但非微扰解决方法会改变低能有效理论，其理论可控性仍有待证明。

More generally, the Swampland program does not see any proposed EFT as given, unless one can demonstrate that it descends from a full-fledged UV completion. This calls for a 10d description of de Sitter vacua in string theory. Some partial successes have been achieved, e.g., in lifting some key ingredients of de Sitter constructions such as gaugino condensates to 10d [147-153]. These 10d lifts help quantify the assumptions and approximations made in going from a string construction to its coarse-grained 4d EFT. Nonetheless a full-fledged top-down construction of de Sitter vacua in string theory is perhaps still a long way to go.

更一般地说，沼泽地纲领不接受任何未经证明的有效场论，除非能证明它可以从一个完备的紫外完备理论导出。这要求我们给出弦论中德西特真空的十维描述。目前已经取得了部分成功，例如将德西特构造中的核心要素如戈金斯凝聚提升到了十维 [147-153]。这些十维提升有助于量化从弦构造到粗粒化四维有效场论过程中所作的假设与近似。尽管如此，在弦论中给出一个完备的自上而下德西特真空构造，或许仍有很长的路要走。

On the other hand, these exist several no-go theorems for de Sitter vacua [154- 165], albeit with limited ingredients. These partial no-go theorems can be useful if properly interpreted as they help narrow down the search for de Sitter vacua. It is easy to dismiss these no-go theorems because in the same vein: "One might as well claim that atoms don't exist, because they are classically unstable." [166]. However, the lack of a full-fledged top-down de Sitter construction together with these partial no-go theorems raise the question whether metastable de Sitter vacua may be incompatible with quantum gravity [9, 134, 150, 167, 168] .

另一方面，尽管涉及的要素有限，目前仍存在若干关于德西特真空的禁成定理 [154-165]。若阐释得当，这些局部禁成定理能够发挥作用，帮助缩小德西特真空的搜索范围。人们很容易否定这些禁成定理，就如同这句话所说:「我们大可以声称原子不存在，因为原子在经典力学中是不稳定的。」[166]。然而，目前缺乏完备的自顶向下德西特构造，再加上这些局部禁成定理，不禁让人提出疑问:亚稳态德西特真空是否可能与量子引力不相容 [9, 134, 150, 167, 168] 。

One of the main challenges in constructing de Sitter vacua is to ensure theoretical control in the sense that all possible (known and unknown) corrections to the proposed vacua are quantifiably small. This challenge, known as the Dine-Seiberg problem [169], is not unique to de Sitter though stabilizing vacua with positive vacuum energy poses further requirements. The Dine-Seiberg problem can be summarized as the tension between stabilizing moduli and calculability. A local minimum can only arise if at least two terms of different orders compete. It is a little more demanding for de Sitter vacua which require a balance of three or more different order terms. (See Fig. 7). If terms of different orders compete to give a minimum, why aren't higher order terms that we ignore important? One way to solve the Dine-Seiberg problem is to have parametric control. But if the number of vacua is finite (which is the case for e.g. [137, 138]), the stabilized coupling, while can be made small, is not parametrically weak. Other classes of flux compactifications (in massive IIA supergravity) [170] can in principle evade the Dine-Seiberg problem because one of the fluxes is unbounded. But when going from AdS to dS, one finds that parametrically weak coupling still cannot be realized in this setting [171, 172]. See [113] for an analysis leading to similar conclusions in many other limits beyond weak coupling.

构建德西特真空的主要挑战之一，是保证理论可控性，即所有对候选真空的已知和未知修正都在定量上很小。这一难题被称为戴恩-塞伯格问题 [169]，它并非德西特真空独有，但稳定正真空能真空仍额外要求满足该条件。戴恩-塞伯格格问题可概括为模稳定和可计算性之间的矛盾: 局部极小值只能在至少两个不同阶的项相互竞争时产生；对于德西特真空要求更高，需要三个或更多不同阶的项达到平衡 (见图 7)。若不同阶的项竞争产生极小值，那我们忽略的高阶项为什么不重要？解决戴恩-塞伯格问题的一种方法是参数控制，但如果真空数量有限 (例如文献 [137, 138] 中的情况)，稳定后的耦合虽然可以做得很小，但无法达到参数上的弱耦合。另一类通量紧化 (质量型 IIA 超引力中的紧化)[170] 原则上可以避开戴恩-塞伯格问题，因为其中一种通量是无界的；但从反德西特转向德西特时会发现，这类设定依然无法实现参数弱耦合 [171, 172]。关于弱耦合之外诸多其他极限下得到类似结论的分析，见文献 [113]。

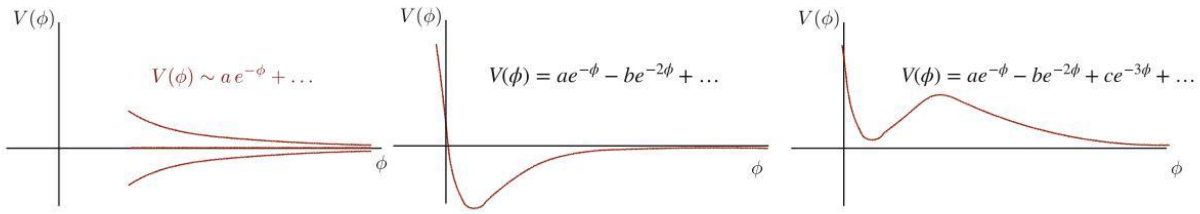



Fig. 7 The Dine-Seiberg Problem can be summarized as the tension between stabilizing moduli and calculability. If only leading order term in the potential is kept, there are two possibilities depending on the sign of the potential at large $\phi$ : the moduli $\phi$ has a runaway behavior or it is driven to the strong coupling region. A local minimum only arises if at least two terms of different orders compete. A de Sitter minimum requires a balance of at least three different order terms

图 7 戴恩-塞伯格问题可概括为模稳定和可计算性之间的矛盾。若只保留势中的领头阶项，根据势在大 $\phi$ 处的符号存在两种可能性: 模 $\phi$ 会出现逃逸行为，或是被驱动到强耦合区域。局部极小值只能在至少两个不同阶的项相互竞争时产生。德西特极小值需要至少三个不同阶的项达到平衡。

In fact, this kind of asymptotic behavior is expected. Reference [9] provides an explanation why for a positive potential, an exponential falloff is a universal behavior in any direction at parametrically large distances in field space. In spacetimes with a positive cosmological constant, there is a horizon and an entropy bound. As we go to large distances in field space, the distance conjecture suggests that a tower of states becomes light and saturates the entropy bound. This dictates the asymptotic form of the potential to be an exponential falloff. It should be noted that this result is stronger than the Dine-Seiberg argument as this behavior applies to any field direction and not just the dilaton. It is also stronger than arguments using the species bound which only bound the potential but not fixing its form [173]. The stronger condition on the asymptotic form of the potential found in [9] is often stated in a weaker form known as the refined de Sitter conjecture:

事实上，这类渐近行为是可以预期的。文献 [9] 给出了解释: 对于正势，在场空间参数大距离的任意方向上，指数衰减都是普适行为。在具有正宇宙学常数的时空中存在视界和熵界；根据距离猜想，当我们走向场空间的大距离处，一列态会变得轻，并且饱和熵界，这就要求势的渐近形式必须是指数衰减。需要注意的是，这个结果比戴恩-塞伯格的论证更强，因为该行为适用于任意场方向，不只是 dilation；它也比基于种类界的论证更强，后者仅对势给出界，无法确定势的形式 [173]。文献 [9] 得到的对势渐近形式的更强条件通常以更弱的形式表述，即精细化德西特猜想:

(Refined) de Sitter Conjecture [9,167] A potential $V(\phi)$ for scalar fields in the asymptotic regime of a low energy effective theory of any consistent quantum gravity must satisfy either,

(精细化) 德西特猜想 [9,167]: 任意自洽量子引力的低能有效理论渐近区域中，标量场的势 $V(\phi)$ 必须满足以下二者之一:

$$|\nabla V| > \frac{c}{M_P} \cdot V, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_P^2} \cdot V \tag{24}$$

Here $c, c' > 0$ are some $\mathcal{O}(1)$ constants. The first condition was conjectured in [167], while the entropy argument in [9] reviewed above suggests the refinement that the first condition needs to be imposed only if the second condition is violated (in which case, the semi-classical picture of a de Sitter horizon breaks down). Similar conjectures were made in [168, 174, 175] based on the partial no-go results reviewed above, though without any physical reasoning given. The "asymptotic" qualification refers to the fact that the supporting evidence is all centered around asymptotic corners of moduli space, where there is a parametrically small coupling that guarantees the validity of the supporting calculations.

此处 $c, c' > 0$ 是若干 $\mathcal{O}(1)$ 常数。第一个条件由文献 [167] 提出，上文回顾的文献 [9] 中的熵论证给出了精细化表述: 仅当第二个条件不满足时 (这种情况下德西特视界的半经典图像会失效)，才需要施加第一个条件。类似猜想基于上文回顾的部分禁则结果在 [168, 174, 175] 中已经被提出，但没有给出物理论证。“渐近”限定指的是，支持该猜想的证据都集中在模空间的渐近角落，那里存在参数小耦合，保证了支撑计算的有效性。

To get a sense of how these constants depend on the tower of states in the Distance Conjecture, let us review in more details the entropy argument in [9] in the asymptotically large field distance regime.

为了说明这些常数如何依赖距离猜想中的态列，我们更详细地回顾文献 [9] 中渐近大场距离区域的熵论证。

The entropy $S_{\text{tower}}$ associated with the tower of states depends on the number $N$ of light states (within the EFT) as well as the de Sitter radius $R$. According to the Distance Conjecture, the number of states increases exponentially as we approach large distances in field space:

与态列相关的熵 $S_{\text{tower}}$ 依赖于 (有效场论范围内) 轻态的数量 $N$ 以及德西特半径 $R$。根据距离猜想，当场空间趋近大距离时，态的数量指数增长:

$$N(\phi) \sim e^{b\phi} \tag{25}$$

The contribution of the tower of states to the entropy cannot exceed the Gibbons-Hawking entropy of de Sitter space,

态列对熵的贡献不能超过德西特空间的吉本斯-霍金熵,

$$S_{\text{tower}}(N, R) \leq S_{GH} = R^2 = \frac{1}{V(\phi)} \tag{26}$$

Since these light degrees of freedom dominate the Hilbert space in the asymptotically large field distance (i.e., weak coupling) regime, we expect them to saturate the above bound.

由于这些轻自由度在渐近大场距离 (即弱耦合) 区域支配希尔伯特空间，我们预期它们会饱和上述边界。

For large $N$ and $R$ , we can parametrize the entropy of the tower as:

对于大 $N$ 和 $R$ ，我们可以将层的熵参数化为:

$$S_{\text{tower}}(N,R) \approx N^{\gamma} R^{\delta} \tag{27}$$

The coefficient $c$ in the (refined) de Sitter conjecture is then given by:

(精细化) 德西特猜想中的系数 $c$ 因此可表示为:

$$c = \frac{2\gamma}{2-\delta} b \tag{28}$$

As an example (also considered in [5]), consider a KK circle compactification of string theory to $d$ spacetime dimensions, the exponent $\alpha$ in the distance conjecture (see Eq. (20)) associated with the KK tower is given by

举个例子 (文献 [5] 中也讨论过)，考虑弦理论紧致到 $d$ 维时空的 KK 圆紧致化，距离猜想中与 KK 层相关的指数 $\alpha$ (见式 (20)) 为

$$\alpha = \sqrt{\frac{d-1}{d-2}} \tag{29}$$

This allows us to estimate the number of states below the scale of quantum gravity (or species scale) $\Lambda_{UV} \approx N^{-1/(d-2)}$ (in Planck units):

这让我们可以估计量子引力能标 (或种类能标) $\Lambda_{UV} \approx N^{-1/(d-2)}$ (普朗克单位下) 以下的态数:

$$N \approx \frac{\Lambda_{UV}}{\Delta m} \approx \Delta m^{\frac{2-d}{d-1}} \tag{30}$$

where $\Delta m$ is the mass gap of the tower. This implies that

其中 $\Delta m$ 是该层的质量隙。由此可得

$$b = \frac{d-2}{d-1}\alpha = \sqrt{\frac{d-2}{d-1}} \tag{31}$$

Curiously, if the Hubble scale $H \sim R^{-1}$ which saturates the entropy bound (Eq. (26)) is identified with the species scale $\Lambda_{UV}$ ,

有趣的是，如果将饱和熵边界 (式 (26)) 的哈勃能标 $H \sim R^{-1}$ 等同于种类能标 $\Lambda_{UV}$ ，

$$\frac{\gamma}{2-\delta}=\frac{1}{d-2} \tag{32}$$

giving the coefficient $c$ in the de Sitter conjecture:

就可以得到德西特猜想中的系数 $c$ :

$$c=\frac{2}{d-1}\alpha=\frac{2}{\sqrt{(d-1)(d-2)}} \tag{33}$$

It should be clear from this example how the exponent of a positive potential in the asymptotic regime can be determined from the microphysics (tower of states that saturates the entropy bound). The value given above in Eq. (33) is not in any way representative; indeed other values can be found in [9]. A natural question is whether there is a lower bound on $c$ . This brings us to the Transplanckian Censorship Conjecture (TCC).

通过这个例子可以清楚看出，正势在渐近区域的指数如何从微观物理 (饱和熵边界的态层) 得到。上文式 (33) 给出的数值绝不具有代表性；事实上文献 [9] 中可以找到其他数值。一个自然的问题是 $c$ 是否存在下界。这就将我们引向超普朗克审查猜想 (TCC)。

Transplanckian Censorship Conjecture (TCC) [176] In a consistent quantum theory of gravity sub-Planckian quantum fluctuations should remain quantum and never become larger than the Hubble horizon. This requirement has two consequences:

超普朗克审查猜想 (TCC)[176] 在自洽的量子引力理论中，亚普朗克量子涨落应当始终保持量子特性，绝不会成长到大于哈勃视界。这一要求有两个推论:

- No dS minima in the asymptotic regime of the moduli space because

- 模空间的渐近区域不存在德西特极小值，因为

$$\frac{|\nabla V|}{V}\geq\frac{2}{\sqrt{(d-1)(d-2)}} \tag{34}$$

where $d$ is the number of spacetime dimensions.

其中 $d$ 是时空维数。

- A dS minimum can exist in the interior of the moduli space, but its lifetime $\tau$ is bounded from above:

- 德西特极小值可以存在于模空间内部，但其寿命 $\tau$ 存在上界:

$$\tau\leq\frac{1}{H}\log\frac{M_P}{H} \tag{35}$$

In the asymptotically large field regime, TCC is stronger than the (refined) de Sitter conjecture as it specifies the value of $c$ . It is an interesting coincidence that the illustrative example above (see Eq. (33)) gives the same value as the TCC requires. The phenomenological consequences of the TCC bound were explored in [177], leading to a low inflationary scale (below $10^9$GeV ) and a negligible amplitude of primordial gravitational waves.

在渐近大场区域, TCC 比 (精细化) 德西特猜想更强, 因为它指定了 $c$ 的取值。上文的示例 (见式 (33)) 恰好给出了和 TCC 要求一致的数值，这是一个有趣的巧合。TCC 边界的唯象后果已经在文献 [177] 中探究，它导出了一个低的暴涨能标 (低于 $10^9$GeV )，且原初引力波振幅可以忽略。

The TCC bound on the lifetime of de Sitter (35) is reminiscent of the scrambling time for black holes (if we replace the black hole entropy by the de Sitter entropy). It was shown in [178] by computing out-of-time-ordered correlators in de Sitter space that just like black holes, de Sitter space saturates the chaos bound. The scrambling time for 4 d de Sitter space is given by

德西特寿命的 TCC 边界 (35) 让人联想到黑洞的混沌 scrambling 时间 (只需将黑洞熵替换为德西特熵)。文献 [178] 通过在德西特空间中计算时间无序关联函表明，和黑洞一样，德西特空间也会饱和混沌边界。4 d 德西特空间的 scrambling 时间为

$$\tau_{\text{scrambling}} = \frac{1}{H} \log S_{dS} \sim \frac{2}{H} \log \frac{M_P}{H} \tag{36}$$

This scrambling time can be shown to be the shortest time for a static observer to decode info from the de Sitter horizon [178, 179]. However, this diagnostic does not indicate a breakdown of de Sitter space at this time scale. It was later found in [180] in studying Jackiw-Teitelboim gravity in de Sitter space that a static observer would inevitably encounter a singularity between the scrambling time and the Page time.

可以证明，这个 scrambling 时间是静态观测者从德西特视界解码信息所需的最短时间 [178, 179]。但这一诊断并不表明德西特空间会在该时间尺度发生破缺。后来文献 [180] 在研究德西特空间中的 Jackiw-Teitelboim 引力时发现，静态观测者在 scrambling 时间和佩奇时间之间不可避免会遇到奇点。

One may also wonder whether the specific bound in Eq. (34) has any physical meaning, as it appears to be satisfied by all known examples in string theory (see e.g. review work [181, 182] in verifying this bound). It is useful to note that string vacua in asymptotic limits of scalar field space are often supersymmetric, though there are notable exceptions such as [183]. In such cases, the scalar potential around a stable supersymmetric minimum can be written as:

人们或许也会好奇，式 (34) 给出的具体界是否具有物理意义，因为弦论中所有已知例子似乎都满足该界 (可参见验证该界的综述工作 [181, 182] )。值得注意的是，标量场空间渐近极限下的弦真空通常是超对称的，不过也存在诸如文献 [183] 这样值得注意的例外。在这些情况下，稳定超对称极小值附近的标量势可以写为:

$$V(\phi) \propto (d-2)(\nabla \mathcal{Z})^2 - (d-1)\mathcal{Z}^2 \tag{37}$$

where $\mathcal{Z} = e^{K/2}|W|$ with $K$ and $W$ the Kahler potential and superpotential respectively. If we further assume that both $V$ and $\mathcal{Z}$ have the same gradient flow, i.e., $V(\phi) \sim \exp(-c\phi)$ implies $\mathcal{Z} \sim \exp(-c\phi/2)$ , then demanding the potential $V$ to be positive gives

其中 $\mathcal{Z} = e^{K/2}|W|$ ，$K$ 和 $W$ 分别是凯勒势和超势。如果进一步假设 $V$ 和 $\mathcal{Z}$ 遵循相同梯度流，即 $V(\phi) \sim \exp(-c\phi)$ 蕴含 $\mathcal{Z} \sim \exp(-c\phi/2)$ ，那么要求势 $V$ 为正可得

$$c > 2\sqrt{\frac{d-1}{d-2}} \tag{38}$$

This observation was made in [184] for 4 d$\mathcal{N} = 1$ supergravities (and was straightforwardly generalized to $d$ spacetime dimensions in [185]). This bound on $c$ is stronger than (34) and would appear to rule out accelerating universes in the asymptotic regime of the moduli space. However, it is important to note that $V$ and $\mathcal{Z}$ do not in general follow the same gradient flow [27]. Further arguments that single-exponential potentials in string theory are too steep to allow for accelerating universe were made in [129].

> 这一结论是文献 [184] 针对 4 d$\mathcal{N} = 1$ 超引力得出的 (并在文献 [185] 中直接推广到了 $d$ 时空维数)。该对 $c$ 的界比式 (34) 更强，它似乎排除了模空间渐近区域中存在加速膨胀宇宙的可能。但需要注意，一般情况下 $V$ 和 $\mathcal{Z}$ 并不遵循相同梯度流 [27]。文献 [129] 还进一步提出论点，证明弦论中的单指数势斜率过大，无法支持宇宙加速膨胀。

We end this section with an exciting phenomenological application of the Emergent String and Distance Conjectures to a situation of positive vacuum energy, the Dark Dimension scenario [186]. The basic question that the Swampland tries to address is where in the string theory landscape sits our universe. In light of the above results, it might seem that, if it is to be found at all, it lies deep in the core of moduli space, out of reach of present techniques. Questions such as the origin of the Cosmological Constant and its smallness are then to be explained by anthropics, accidental features of our vacuum that are a precondition for our existence, but which are otherwise accidental. But one can take another point of view: that we are close to an infinite distance limit and that the smallest parameter that we have observed, the vacuum energy $\Lambda \sim 10^{-120}$ , is actually small because we are very close to infinite distance. Of course, then the Distance Conjecture implies that there is a tower of states, whose characteristic mass scale $m$ scales as $\Lambda^{\alpha}$ for some $\alpha$ of order 1. In fact, in a non-supersymmetric vacuum, such as our own universe, one would generically expect a contribution to the vacuum energy of all states in the light tower of order $m^d$ , where $d$ is the spacetime dimension. Additional contributions to the vacuum energy can be fine-tuned or absent due to strong coupling effects, but the leading effect of the tower of states is always present. Therefore, one may expect $\alpha \gtrsim 1/4$ , corresponding to an energy scale of roughly neutrino mass (a few meV). But are such light towers possible? A perturbative string limit is not possible, since then physics would become nonlocal at a scale of a few meV, which we know is not the case. And decompactification limits are severely constrained by tests on deviations of Newton's laws and astrophysical experiments, to the point that, for a tower scale (KK scale) of a few meV, the only possibility is a single large extra dimension, whose size is $l \lesssim 30\mu\text{m}$ . Thus, if we are living close to an asymptotic limit which drives the cosmological constant, the only possibility is a large extra dimension of size a few micrometers, very close to the experimental bounds. This Dark Dimension scenario is appealing because of its predictive power. It shares many features with the original Large Extra Dimensions (LED) scenario [187], with one fundamental difference: while LED attempted to solve the electroweak hierarchy problem, and were led to a Planck scale of order the TeV, the Dark Dimension scenario emphasizes the connection to the vacuum energy instead, and leads to a much higher Planck scale of order $10^{10}\text{GeV}$ . Even though the scenario is quite recent, there has been a flurry of activity, involving potential astrophysical signatures [188-192], as well as viable dark matter candidates in the scenario. By far its most appealing feature is that the prediction of a large extra dimension of order a micrometer may very well be testable in the near future, either vindicating or excluding once and for all the possibility that we live close to an asymptotic corner of moduli space.

我们本节以涌现弦猜想和距离猜想对正真空能场景——暗维度情景 [186]——一项激动人心的唯象应用作结。沼泽地纲领试图解决的基本问题是: 我们的宇宙在弦理论景观中处于什么位置。根据上述结论，假如我们的宇宙确实存在，它似乎位于模空间深处，超出了现有方法的研究范围。那么宇宙学常数的起源及其微小性这类问题，就只能用人择原理来解释: 它是我们真空的偶然特征，是人类存在的前提，但除此之外就只是偶然。但我们也可以换一种视角: 我们其实离无限距离极限很近，而我们观测到的最小参数——真空能 $\Lambda \sim 10^{-120}$ ——之所以很小，正是因为我们非常接近无限距离极限。当然，距离猜想由此暗示，这里存在一个粒子态 tower，其特征质量标度 $m$ 随 $\Lambda^{\alpha}$ 变化，其中 $\alpha$ 是一阶量。事实上，在类似我们宇宙这样的非超对称真空中，一般会预期这个轻态 tower 中所有态对真空能的贡献为 $m^d$ 量级，其中 $d$ 是时空维数。真空能的额外贡献可以通过微调消除，或是因强耦合效应不存在，但态 tower 的主导效应始终存在。因此我们可以预期 $\alpha \gtrsim 1/4$，对应的能标约为中微子质量 (几 meV)。但这样的轻 tower 真的存在吗？微扰弦极限不可能成立，因为那样的话几 meV 标度就会出现非局域物理，而我们知道事实并非如此。去紧致化极限则受到牛顿引力偏差检验和天体物理实验的严格限制，结论是对于几 meV 的 tower 标度 (KK 标度)，唯一可能就是存在一个额外大维度，其大小为 $l \lesssim 30\mu\text{m}$。因此，如果我们确实生活在一个让宇宙学常数变小的渐近极限附近，那么唯一可能就是存在一个大小为几微米的额外大维度，刚好处于实验边界附近。暗维度情景的吸引力在于它的预言能力。它和最初的大额外维度 (LED) 情景 [187] 有许多共同点，但有一个核心区别:LED 试图解决电弱层级问题，最终得到的普朗克标度为 TeV 量级，而暗维度情景则强调与真空能的关联，得到的普朗克标度高得多，为 $10^{10}$GeV 量级。尽管这个情景提出时间不长，已经有了大量研究工作，包括讨论潜在的天体物理信号 [188-192]，以及在该情景下找到可行的暗物质候选者。这个情景最吸引人的特点是，它预言了微米量级的额外大维度，这在不远的将来就可以得到检验，最终可以一劳永逸地证实或是排除我们生活在模空间渐近角落附近的可能性。

## Outlook

## 展望

In this chapter, we have taken the readers for a gentle hike through the Swampland. Just like guiding a tour through a vast forest, we have to strike a balance between presenting details and maintaining the big picture. Our goal is to present the readers with a bird's eye view of the Swampland program, while at the same time go into details of some recent developments that have not been covered by existing reviews. We hope that this way of zooming in and zooming out of the Swampland would prepare the readers for researching in this active and exciting area.

在本章中，我们带领读者轻松漫步了沼泽地。就像带领游客穿越广袤森林一样，我们必须在呈现细节和把握整体图景之间取得平衡。我们的目标是为读者提供沼泽地项目的全景概览，同时也深入介绍了现有综述未涵盖的部分最新进展。我们希望这种对沼泽地研究远近结合的呈现方式，能帮助读者做好准备，在这个活跃且令人振奋的领域开展研究。

Given our space limitations, we opted to focus on a few key conjectures (rather than exhaustively enumerate all their variations), starting with the basic idea, to presenting the evidence and their phenomenological implications. Remarkably, these conjectures form an interconnected web. Not only do these interconnections lend support to each of the proposed criteria of quantum gravity, they enable us to use the better established conjectures to make the less understood ones more precise. We do not know yet which of the conjectures play a more fundamental role in distinguishing the Landscape from the Swampland. As in the parable of "the blind men and the elephant", each swampland conjecture points us to a useful defining property of quantum gravity. Further progress in the Swampland will undoubtedly help us formulate the (minimal) criteria for consistently coupling quantum field theories to gravity.

受篇幅限制，我们选择聚焦于少数核心猜想 (而非穷举所有变体)，从基本概念出发，进而介绍相关证据及其唯象学意义。值得注意的是，这些猜想构成了一张相互关联的网络。这些关联不仅为每个提出的量子引力判据提供了支持，还让我们可以借助更成熟的猜想，让研究较少的猜想变得更加明确。我们目前还不清楚，在区分景观和沼泽地时，哪些猜想发挥着更基础的作用。就像"盲人摸象"的寓言所说，每个沼泽地猜想都为我们指出了量子引力一个有用的定义属性。沼泽地研究的进一步推进，无疑将帮助我们 formulize 出将量子场论自洽耦合到引力的 (最小) 判据。

It is perhaps instructive to compare the challenges we are currently facing in formulating the rules of quantum gravity with the early days of quantum mechanics. Before the laws of quantum mechanics were formulated, there was a state of confusion. Various experimental puzzles and theoretical (in)consistencies provided limited hints of the principles governing the subatomic world. It took the genius of the early pioneers of quantum mechanics to weave together these disparate hints into a coherent picture. It was only through the back-and-forths of hypothesis making and testing (and sometimes refinement) that a set of fundamental governing principles emerged. For example, drawing lessons from the measured spectral lines of atomic transitions, Bohr hypothesized that angular momenta are quantized even though the evidence for it was rather thin at the time. The role of hypothesis making is not only to explain the existing data but to make new predictions that can be verified. When enough evidence is accumulated, we can begin to uncover the underlying principles that tie together seemingly different hypothesis. For the Swampland program, the adventure is still only beginning!

将我们目前在 formulize 量子引力规则时面临的挑战，与量子力学的早期发展阶段做对比，或许会很有启发。在量子力学定律建立之前，学界一直处于混乱状态。各种实验谜题和理论 (不) 一致性，为理解亚原子世界的运行原理提供的线索十分有限。早年量子力学先驱们凭借天才将这些零散的线索整合为一幅自洽的图景。正是经过一次次提出假设、检验 (有时还会修正假设的反复过程，一套基本的运行原理才得以浮现。例如，玻尔从原子跃迁的实测谱线中得到启发，提出角动量量子化的假设，尽管当时支持这一假设的证据还相当不足。提出假设的作用不仅是解释现有数据，更是要做出可被验证的新预言。当积累足够多的证据后，我们才能逐步揭开将看似不同的假设联系在一起的底层原理。对于沼泽地项目而言，这场冒险才刚刚开始！

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