New Clothes for the Landscape

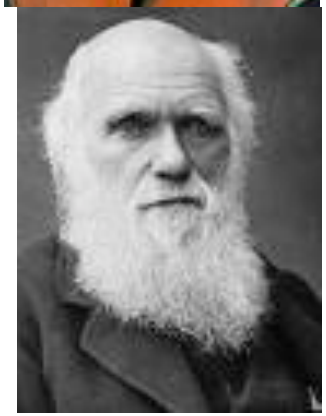
Dieter Lüst, LMU (Arnold-Sommerfeld-Center)
and Max-Planck-Institut München

Colloquium at Nikhef in Amsterdam
during the Bert Schellekens Fest, 13. May 2022

Human kind had to accept several paradigm shifts in science history:

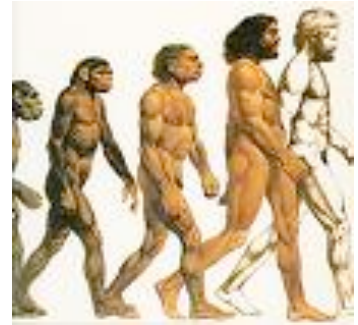
1543 Nikolaus Kopernikus:

Earth is not the center of the world!



1871: Charles Darwin:

Men originate from apes!



~ 2000: Some string theorists:

There exist a multiverse
and our universe
is not special at all!

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Outline

- Some contributions of Bert to theoretical physics

- The emperor's last clothes:
  Anthropic principle and the multiverse

- Restrictions on the landscape:
  The cosmological constant

- New clothes for the emperor:
  The swampland - towards uniqueness again?

Some contributions of Bert to theoretical physics:

Bert Schellekens made several profound contributions to theoretical physics.

First I like to recall a few string theory papers from the 80's.

1986: Superstrings from 26 dimensions:

Nuclear Physics B274 (1986) 315–348
North-Holland, Amsterdam

SUPERSTRINGS FROM 26 DIMENSIONS

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H. NICOLAI* and A. SCHELLEKENS

CERN, Geneva, Switzerland

Received 5 March 1986

Consistent closed superstrings are contained in the 26-dimensional bosonic closed string theory. We explain in detail how the states, operators and interaction vertices of superstrings emerge in this way. We also discuss possibilities for obtaining new string theories.

1. Introduction

The discovery of consistent ten-dimensional superstring theories [1–3] has fuelled hopes that a unified theory of gravity and matter may now be within reach. The cancellation of all anomalies for the gauge groups SO(32) [2] and $E_8 \times E_8$ [3, 4] and the one-loop finiteness of the corresponding string theories [2, 3] make the heterotic string theories [3] an interesting candidate, especially in view of speculations that the $E_8 \times E_8$ theory may actually be related to known physics. However, the question remains why there are at least five consistent theories where one would be enough. Freund was the first to suggest that the theories with gauge groups SO(32) or $E_8 \times E_8$ might arise as "soliton-type" solutions of the purely bosonic string theory in 26 dimensions, and that the latter should therefore be regarded as the fundamental string theory [5]. In ref. [6], it was furthermore proposed that all superstring theories, including the two type-II superstrings, are contained in the $D = 26$ theory. The conditions for such solutions to exist were investigated in [6], and, in particular, a mechanism for the emergence of space-time fermions and a tachyon-free solution out of a purely bosonic theory were described there. In this paper, we will give a detailed account of the construction performed in [6] and present some new results.

Before presenting the derivation of our results, we shall explain in qualitative terms why space-time supersymmetry is expected to hide in the simpler bosonic theory. To generate space-time fermions from the bosonic string, one must meet at

* Address after April 1, 1986: Institut für Theoretische Physik, Universität Karlsruhe, Postfach 6380, D-75 Karlsruhe 1, FR Germany.

1987 & 1988: The elliptic genus:

Nuclear Physics B287 (1987) 317–361
North-Holland, Amsterdam

ANOMALIES, CHARACTERS AND STRINGS

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Received 27 October 1986

One-loop modular invariant heterotic and type II closed string theories are proved to be anomaly free, apart from terms proportional to $\mathrm{Tr}\,F^2 - \mathrm{Tr}\,R^2$. It is shown why this conclusion holds with remarkable generality for any conceivable fermionic string theory, regardless even of conformal invariance. A detailed discussion is given of the modular properties of character valued partition functions, upon which the proof is based. The fact that $\mathrm{Tr}\,F^2 - \mathrm{Tr}\,R^2$ terms remain in the fermionic contribution to the anomaly is shown to be a consequence of Quillen's holomorphic anomaly.

1. Introduction

It now seems clear that there is an intimate relationship between global anomalies on the string world sheet and local gauge and gravitational anomalies in the effective field theory of the string [1–3]. In this paper we will show that one-loop modular invariance of any "heterotic" or "type IIB" string in any (even) number of dimensions implies that the corresponding massless field theory has an anomaly that can be cancelled by the Green-Schwarz mechanism [4]. We find that in any dimension there are an infinite number of possible anomaly cancellable field theories. Moreover, the anomaly cancellation can be accomplished using the simplest possible Green-Schwarz mechanism, involving only a single, two-index antisymmetric tensor, $B_{\mu\nu}$. In other words, the anomaly from the fermion fields has a factor of $[\mathrm{Tr}(F^2) - \mathrm{Tr}(R^2)]$. It will also be shown that the fact that the anomaly from the fermion fields does not vanish entirely but factorizes in this manner, is due to the non-holomorphic factorization anomaly of Quillen [5].

In order to obtain the anomaly of the field-theory limit of a general heterotic string we will need to add together the contributions of fields in very different representations of the gauge and Lorentz groups. The first step in simplifying this problem is not to consider the complete Lorentz anomaly, but to consider the

Nuclear Physics B299 (1988) 91–116
North-Holland, Amsterdam

ANOMALY CANCELLING TERMS FROM THE ELLIPTIC GENUS

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Received 16 July 1987

We calculate the heterotic string one-loop diagram in $2n+2$ dimensions with one external $B_{\mu\nu}$ and n external gravitons and/or gauge bosons. The result is a modular integral over the weight zero terms of the character valued partition function (or elliptic genus) of the theory, and can be directly expressed in terms of the factor which multiplies $\mathrm{Tr}\,F^2 - \mathrm{Tr}\,R^2$ in the field theory anomaly. The integrands have a non-trivial dependence on the modular parameter τ, reflecting contributions not only from the physical massless states but also from an infinity of "unphysical" modes. Some of them are identical to integrands which have been discussed recently in relation with Atkin-Lehner symmetry and the cosmological constant. As a corollary we find a method to compute these integrals without using Atkin-Lehner transformations.

1. Introduction

In a recent paper [1] we have calculated the $B\,\mathrm{Tr}\,F^n$ terms in the effective field theory of $2n+2$ dimensional heterotic strings*. Such terms were expected to be present since they are needed to cancel part of the local gauge and gravitational anomalies, and indeed they turned out to appear with precisely the coefficient predicted in ref. [3].

In addition to the $B\,\mathrm{Tr}\,F^n$ terms several other terms involving powers of lower traces of the gauge field two-form F and the curvature two-form R are expected to exist**. Although our previous calculation gives us no reason to doubt their existence there are several reasons for extending our previous calculations to include these terms.

First of all, the result of ref. [1] gives little insight into how the anomaly cancelling terms are related to the $2n$-form X_{2n} which multiplies $\mathrm{Tr}\,F^2 - \mathrm{Tr}\,R^2$ in the anomaly. The structure of this factor can be derived from the character valued

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* For related one-loop calculations in four dimensions see also ref. [2].

** These terms have been considered in a recent paper [7]. None of the modular space integrals was however calculated, and so the result is inconclusive even with regard to the existence of these terms.

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(North-Holland Physics Publishing Division)

1989: Extended chiral algebras:

Nuclear Physics B327 (1989) 673–703
North-Holland, Amsterdam

EXTENDED CHIRAL ALGEBRAS AND MODULAR INVARIANT PARTITION FUNCTIONS

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Received 12 April 1989

We show how the fusion rules can be used to associate with every rational conformal field theory a discrete group, the center. The center is generated by primary fields having unique fusion rules with any other field. The existence of a non-trivial center implies the existence of non-diagonal modular invariants, which are related to extended integer or fractional spin algebras. Applied to Kac–Moody algebras this method yields all known as well as many new infinite series of modular invariants. Some results on exceptional invariants are also presented, including an example of an exceptional integer spin invariant that does not correspond to a conformal embedding.

1. Introduction

The study of two-dimensional conformal field theories is central to the investigation of both two-dimensional critical phenomena and string theories. A lot of efforts have been made in order to classify all (rational) conformal field theories. It was suggested that one way to understand conformal field theories is in terms of extended chiral algebras [1], which include the Virasoro algebra as a sub-algebra. A conformal field theory with $c > 1$ which has an infinite number of primary fields with respect to the Virasoro algebra may turn out to have only a finite number of primary fields with respect to the bigger extended algebra. Moreover, one can understand the appearance of some non-diagonal modular invariant theories as arising from a theory which is diagonal with respect to the extended chiral algebra generated by certain currents with integer conformal spin.

Starting with the important work of Verlinde [2], the central role of the fusion rules of the conformal field theory became clear [2–6]. A great deal of the structure of the underlying conformal theory is encoded in the commutative and associative Verlinde algebra which these fusion rules define. There exists a deep relationship between the fusion algebra and the modular properties of the theory. The modular

* Work supported in part by the US–Israel Binational Science Foundation, and the Israel Academy of Science.

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Emperor's last clothes - Anthropic principle:

In a speech from the year 1998, Bert Schellekens proposed that there might exist an Anthropic Landscape of String Theory.

This speech then appeared as a paper „The Landscape avant la lettre“ in the the year 2006.

NIKHEF/2006-004
physics/0604134

The Landscape "avant la lettre"

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and

IMAPP, Radboud University, Nijmegen

Abstract

This is a translation of an inaugural speech given originally in Dutch in 1998. The topic of that speech, intended for a general audience, was what is now called "The Anthropic Landscape of String Theory".

1 Introduction

In 2003 L. Susskind published his paper entitled "The Anthropic Landscape of String Theory" [1], which I read with great pleasure. The reason was that, many years before, I had come to the conclusion that everything we knew about String Theory was pointing towards an "anthropic landscape" of vacua. I had advocated this idea consistently during many years, on the basis of far less evidence than we have today. It seemed obvious to me, but the response I got was frustrating. Therefore I was delighted that finally someone was stating this point of view loud and clear. As Susskind correctly points out, the idea that the standard model might not be the unique outcome of String Theory seemed unacceptable to most people. In seminars he gave on the subject that statement

translation of a speech I gave in 1998 [2], in Dutch, on the occasion of my inauguration at

Some quotations from the translated 1998 speech:

"Our planet is not the center of the solar system, our sun is just one of many stars and not even a very special one, and the same is true for our galaxy. It seems natural to assume that also our universe, including the quarks, leptons and interactions we observe is just one out of many possibilities."

„At this moment it is not clear what will be left of this enormous number of ground states once we understand String Theory properly. At first sight it may seem attractive that only one should survive, but if you think about it for a moment it becomes clear that this would really be an undesirable end to the story."

Our entire existence depends on a series of subtle processes that occurred during the evolution of the universe. These processes have finally led to a planet where, for example, the crucial element Carbon occurs with sufficient abundance. Various steps in this process depend critically on the parameters of the Standard Model, such as the masses of particles and the strength of interactions. It seems often easy to demonstrate that even small changes of certain parameters would obstruct the entire process.

As far as I am concerned the anthropic principle only makes sense if our universe it not the only possible one. Furthermore it only makes sense within a completely consistent theory.

In the paper of 2006, Bert was also remarking:

My own thoughts in this direction started around 1987. The year before I had pub- lished a paper with Wolfgang Lerche and Dieter Lu¨st [7]. Like other authors at the time, we found large numbers of four-dimensional chiral string theories, but much more than others we made a point of strongly emphasizing the non-uniqueness of the result. In the following year we began to understand that this was perhaps a bit premature. There were moduli to be fixed, and supersymmetry had to broken, and of course that could drastically change the conclusion. But it seemed to me that it was wishful thinking to assume that all these problems would be solvable for just one ground state, the one corresponding to the standard model.

CHIRAL FOUR-DIMENSIONAL HETEROTIC STRINGS FROM SELF-DUAL LATTICES

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Received 24 November 1986

It is shown how our previous work on lattice constructions of ten-dimensional heterotic strings can be applied to four dimensions. The construction is based on an extension of Narain's lattices by including the bosonized world-sheet fermions and ghosts, and uses conformal field theory as its starting point. A natural embedding of all these theories in the bosonic string is automatically provided. Large numbers of chiral string theories with and without $N = 1$ supersymmetry can be constructed. Many features of their spectra have a simple interpretation in terms of properties of even self-dual lattices. In particular we find an intriguing relation between extended supersymmetry and exceptional groups.

1. Introduction

In the early days of string theory it was considered a major embarrassment when

In this paper we do not claim that there is a real landscape of string vacua, but we note that the number of possible string solutions is very huge:

Huge but finite number of four-dimensional strings:

$$N_{sol} \simeq 10^{1500}$$

So we concluded:

„It seems that not much is left of the once celebrated uniqueness of string theory.“

During the early 2000's the string landscape & the multiverse became popular:

- Bousso, Polchinski (2000):

  Quantization of four form fluxes and dynamical neutralisation of the cosmological constant

- Susskind (2003):

  The Anthropic landscape of string theory

- Kachru, Kallosh, Linde, Trivedi - KKLT (2003):

  De Sitter vacua in string theory

- Douglas (2003):

  The Statistics of string / M-theory vacua

$\Rightarrow \; 10^{500}$ flux vacua

There is already earlier work about cosmology, inflation and the multiverse:

- Linde (1983, 1986):

  Chaotic inflation

  Eternally Existing Selfreproducing Chaotic Inflationary Universe

- Vilenkin (1983, 1984):

  The Birth of Inflationary Universes

  Quantum Creation of Universe

Anthropic principle:

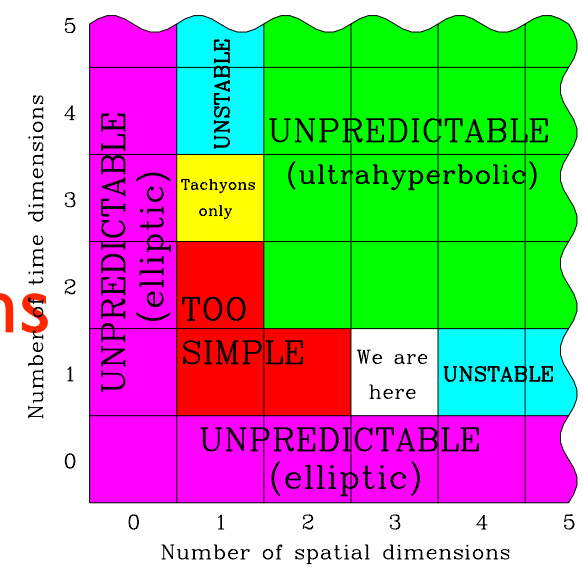
Our universe is not special!

Observed parameters take their observed values for the simple reason that they allow for intelligent life.

- Distance earth-sun

- Fine structure and strong coupling constants: nucleo-synthesis

- Ehrenfest: number of spatial dimensions



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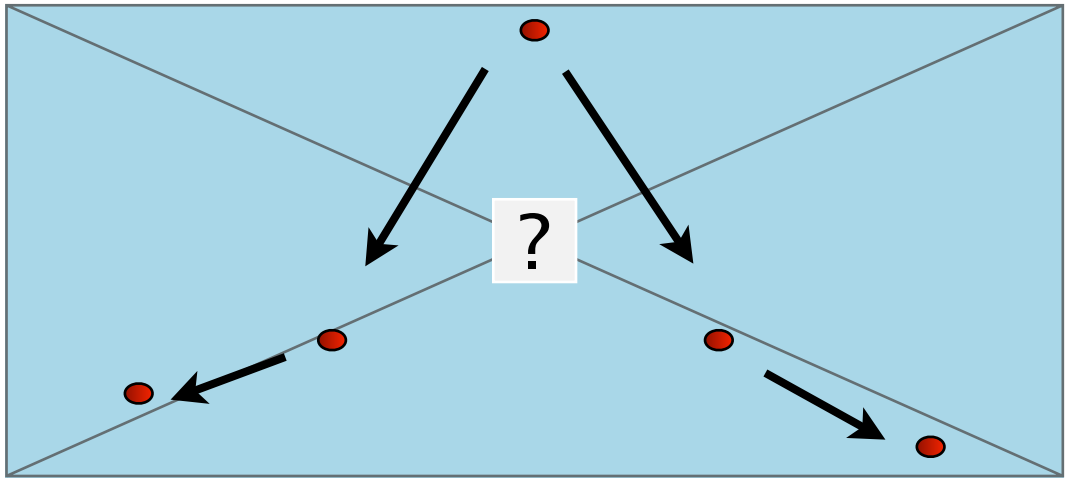
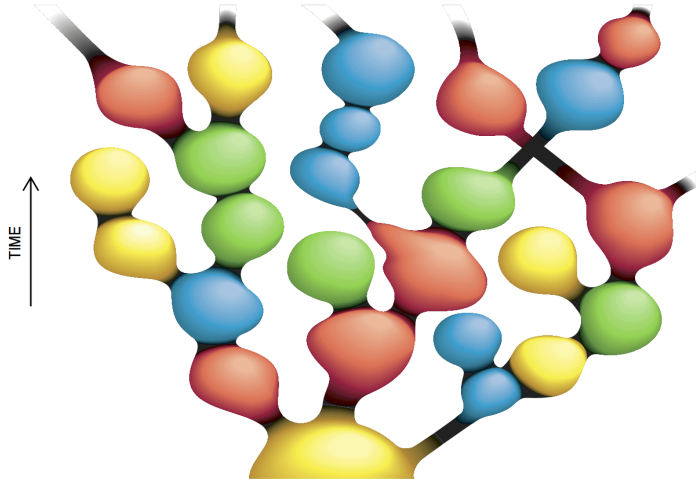
Multiverse picture:

Transition amplitudes between different universes



⇨ Eternal, self-producing universe:



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String theory:

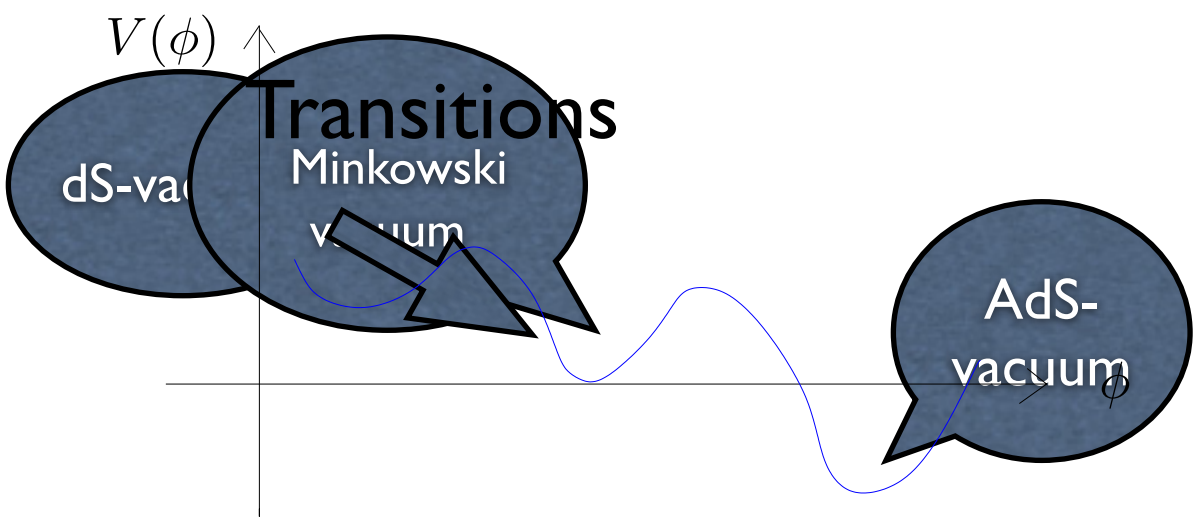
Unique in 10 dimensions, but many solutions (vacua) in lower (e.g. four) dimensions.

Many possibilities for different particle physics models!

Many possibilities for different cosmological models!

Different string vacua correspond to different lower-dimensional „universes“

Energy landscape of string vacua:



$V(\phi)$: vacuum energy (cosmological constant)

Another nice paper by Bert from the year 2008 with more remarks on the landscape and the anthropic principle:

NIKHEF/2008-011
July 2008
hep-th/yymmnnn

The Emperor's Last Clothes?

Overlooking the String Theory Landscape[1]

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Instituto de Física Fundamental, CSIC, Madrid

Abstract

We are in the middle of a remarkable paradigm shift in particle physics, a shift of opinion that occurred so slowly that some even try to deny that they changed their minds at all. It concerns a very basic question: can we expect to derive the laws of particle physics from a fundamental theory? The Standard Model of particle physics as well as the 1984 string theory revolution provided ample food for thought about this. The reason this was ignored for so long can be traced back to an old fallacy: a misguided idea about our own importance.

Hans Christian Andersen: Emperor's New Clothes:

„The inspiration for the title of this paper is the well-known fairy tale about the emperor and his new clothes, advertised to be invisible only to stupid and incompetent people. Since nobody wanted to belong to that category, all claimed to be able to see the clothes, until a small child said "but he is not wearing anything". Then suddenly everyone claimed to have noticed this already."

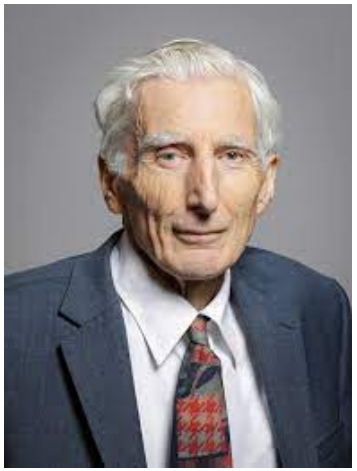
Debate:

Steven Weinberg (particle physicist):

``Now we may be at a new turning point, a radical change in what we accept as a legitimate foundation for a physical theory. The current excitement is is of course a consequence of the discovery of a vast number of solutions of string theory.''

Lord Rees (cosmologist):

``The universe in which we've emerged belongs to the unusual subset that permits complexity and consciousness to develop. Once we accept this, various apparently special features of our universe -- those that some theologians once adduced as evidence for Providence or design -- occasion no surprise.''



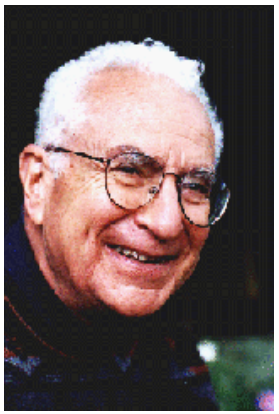
David Gross (string theorist):

``The landscape idea? I hate it ”

“Never, never, never, never give up!”

Murray Gell-Mann (particle physicist):

``If we really live in a multiverse, Physics will have been reduced to an environmental science like Botany.”



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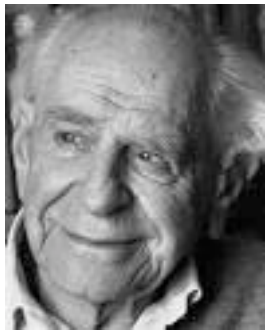
Criticism - philosophy debate :



Karl Popper: A theory must be falsifiable.

Does string theory make any predictions?

Is string theory falsifiable?

Almost anything goes ➤

How to make any prediction in string theory, i.e. how to determine the correct string vacuum state?

How to deal with the string landscape?

Two strategies to find something interesting:

- Do not look randomly - look for green (promising) spots in the landscape ➠ model building, bottom up approach.

There exist many explicit (semi)realistic string models:

SM like features with SUSY broken at low energies

string inflation, cosmological constant, ...

- Explore all mathematically consistent possibilities.

⇨ Top down approach:

String statistics:

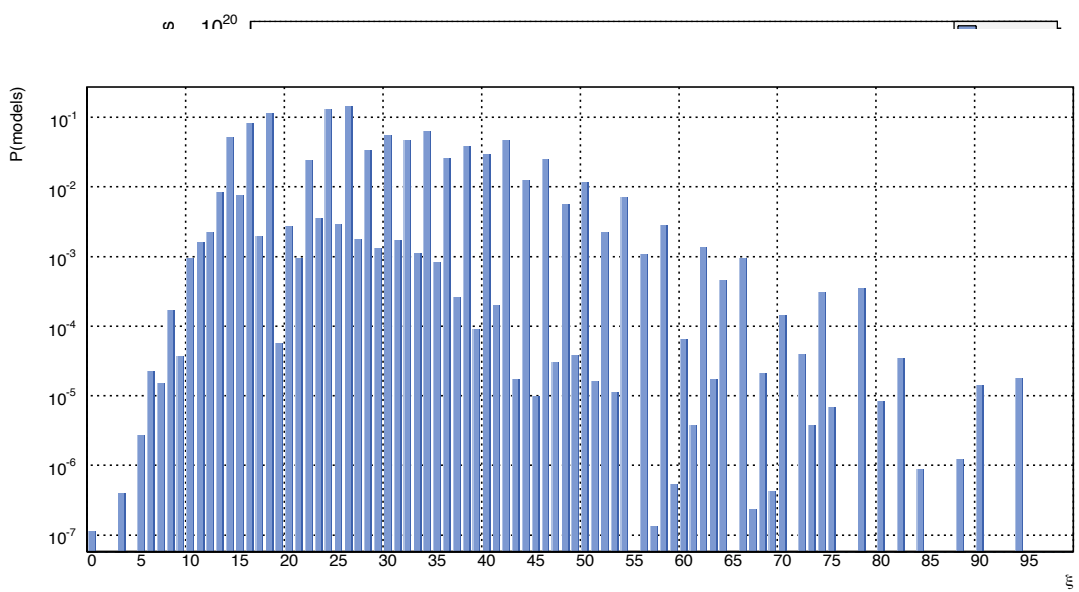
Investigation of the statistical properties of (4D) string vacua and their observables (gauge group, no. of families, ...).

(Blumenhagen, Gmeiner, Honecker, Weigand, D.L. (2004-2007))

Statistics of type II intersecting D-brane compactifications:

Millions of standard models!

Gmeiner, Hor
arXiv:0806.3(



SM gauge group, 3 generations with # of chiral exotics

SM gauge group with # of generations

Supersymmetric Standard Model Spectra from RCFT orientifolds

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Abstract

We present supersymmetric, tadpole-free $d = 4, N = 1$ orientifold vacua with a three family chiral fermion spectrum that is identical to that of the Standard Model. Starting with all simple current orientifolds of all Gepner models we perform a systematic search for such spectra. We consider several variations of the standard four-stack intersecting brane realization of the standard model, with all quarks and leptons realized as bifundamentals and perturbatively exact baryon and lepton number symmetries, and with a $U(1)_Y$ vector boson that does not acquire a mass from Green-Schwarz terms. The number of supersymmetric Higgs pairs $H_1 + H_2$ is left free. In order to cancel all tadpoles, we allow a "hidden" gauge group, which must be chirally decoupled from the standard model. We also allow for non-chiral mirror-pairs of quarks and leptons, non-chiral exotics and (possibly chiral) hidden, standard model singlet matter, as well as a massless B-L vector boson. All of these less desirable features are absent in some cases, although not simultaneously. In particular, we found cases with massless Chan-Paton gauge bosons generating nothing more than $SU(3) \times SU(2) \times U(1)$. We obtain almost 180000 rationally distinct solutions (not counting hidden sector degrees of freedom), and present distributions of various quantities. We analyse the tree level gauge couplings, and find a large range of values, remarkably centered around the unification point.

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NIKHEF/2006-003

Orientifolds, hypercharge embeddings and the Standard Model

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[5] *IMAPP, Radboud Universiteit Nijmegen, The Netherlands*

`http://www.cpht.polytechnique.fr/cpth/kiritsis/`

Abstract: The embedding of the SM hypercharge into an orientifold gauge group is studied. Possible embeddings are classified, and a systematic construction of bottom-up configurations and top-down orientifold vacua is achieved, solving the tadpole conditions in the context of Gepner orientifolds. Some hypercharge embeddings are strongly preferred compared to others. Configurations with chiral antisymmetric tensors are suppressed. We find among others, genuine examples of supersymmetric SU(5), flipped SU(5), Pati-Salam and trinification vacua with no chiral exotics.

Testable signatures of string theory:

(i) Measurement of heavy string excitations.

This is possible if the fundamental string scale is low,

i.e. if $M_{\rm string}/M_{\rm Planck} << 1$

- Perturbative quantum gravity states:
  string Regge excitations.

(String Hunters' Companion: Concrete calculations of cross sections: Model independent results, i.e. true for a large class of string compactifiactions
S. Stieberger, T. Taylor, D. L.: 2008/2009)

$$LHC: \qquad M_{\rm string} \geq \mathcal{O}(7TeV)$$

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(ii) Stringy large extra dimensions:

(Arkani-Hamed, Antioniadis, Dimopoulos, Dvali, 1998)

- Kaluza-Klein states from compact internal geometry

$\Rightarrow$ Deviation from Newtonian gravity

$$R_{\text{compact.}} \leq \mathcal{O}(\mu\,\text{meter})$$

(iii) „Exotic“ light string states:

- E.g. Light Z’ gauge bosons

Restrictions on the landscape: the cosmological constant

Observed Dark energy - simplest explanation:

Cosmological constant $\Lambda \simeq 10^{-122} M_{\rm Planck}^2$

Still big puzzle in physics !

Is there a natural explanation for the smallness of the cosmological constant ?

The smallness of Λ can be nicely explained by the anthropic principle. (Weinberg, 1987)

$\Rightarrow$ Need at least 10^{120} de Sitter string vacua with a positive cosmological string constant!

The KKLT scenario:

Type IIB Calabi-Yau compactifications with fluxes and branes

Two step procedure:

- Lots of deformations of compactifications that correspond to massless scalar fields.

Problem of moduli stabilization.

- Add fluxes (and other non-perturbative effects)

$\longrightarrow$ Moduli get massive, i.e. stabilised

$\Rightarrow AdS_4$ string vacua with $\Lambda_{AdS} < 0$

- Tune $|\Lambda_{AdS}|$ to be very small

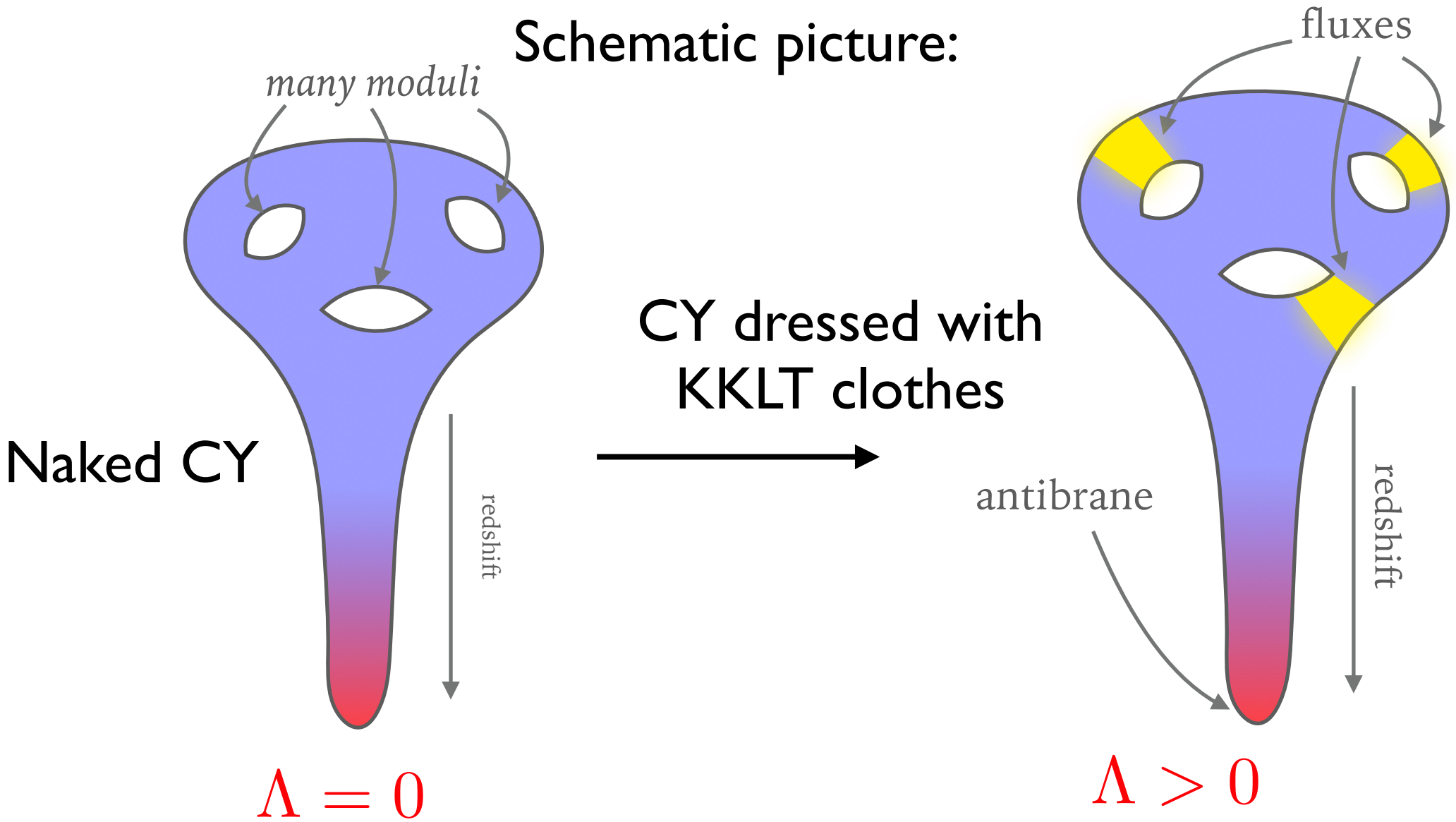
- Need „uplift“ to dS_4 vacua with small positive cosmological constant.

- Add anti-brane that contributes a positive vacuum energy

Compactification needs exponentially large red-shift

$\longrightarrow$ Calabi-Yau spaces with a large throat

Schematic picture:



Does this lead to 10^{120} de Sitter string vacua with positive (small) cosmological constant ?

There are some subtle stability questions concerning the anti-brane uplift.

[I. Bena, M. Grana, N. Halmagyi (2009);
I. Bena, E. Dudas, M. Grana, S. Lüst (2018)]

In addition there are two questions already for step-one:

(i) Tadpole conjecture

[I. Bena, J. Blabäck, S. Lüst, M. Grana (2021)]

Flux number $$Q_{flux} \leq \frac{\chi}{24} \simeq \frac{1}{4} N_{moduli}$$

But $Q_{flux} \simeq \alpha N_{moduli}$ with $\alpha \sim \mathcal{O}(1)$

For Calabi-Yau spaces with a large number of moduli, not all moduli can be stabilised.

Apparently the (AdS4) flux landscape is much smaller than originally believed !!

(ii) Problem of scale separation for flux vacua with small $|\Lambda_{AdS}|$

Typically there will be a very large number of additional light (KK) states at the AdS mass scale.

[D. Tsimpis (2012); F. Gautason, M. Scholl, T. Van Riet, M. Williams (2015)]

There is no valid and controllable AdS_4 effective field theory description.

Dual holographic picture of AdS_4 vacua provides further support for the scale separation problem.

[T. Collins, D. Jafferis, C. Vafa, K. Xu, S. Yau (2022);
S. Lüst, C. Vafa, M. Wiesner, K. Xu (2022)]

The KKLL scenario was thought to be a big supporter for the anthropic principle and the multiverse picture, but there are some unsolved issues.

General no-theorems for de Sitter vacua:

[Maldacena, Nunez (2000)]

- De Sitter conjecture for the potential: [Obied, Ooguri, Spodyneiko, Vafa (2018)]

$$V' \geq c\,V \quad \text{and} \quad c > 0$$

This forbids dS - vacua with $V' = 0 \text{ and } V > 0$

- General arguments that de Sitter is not possible in quantum gravity. [Dvali, Gomez (2014)]

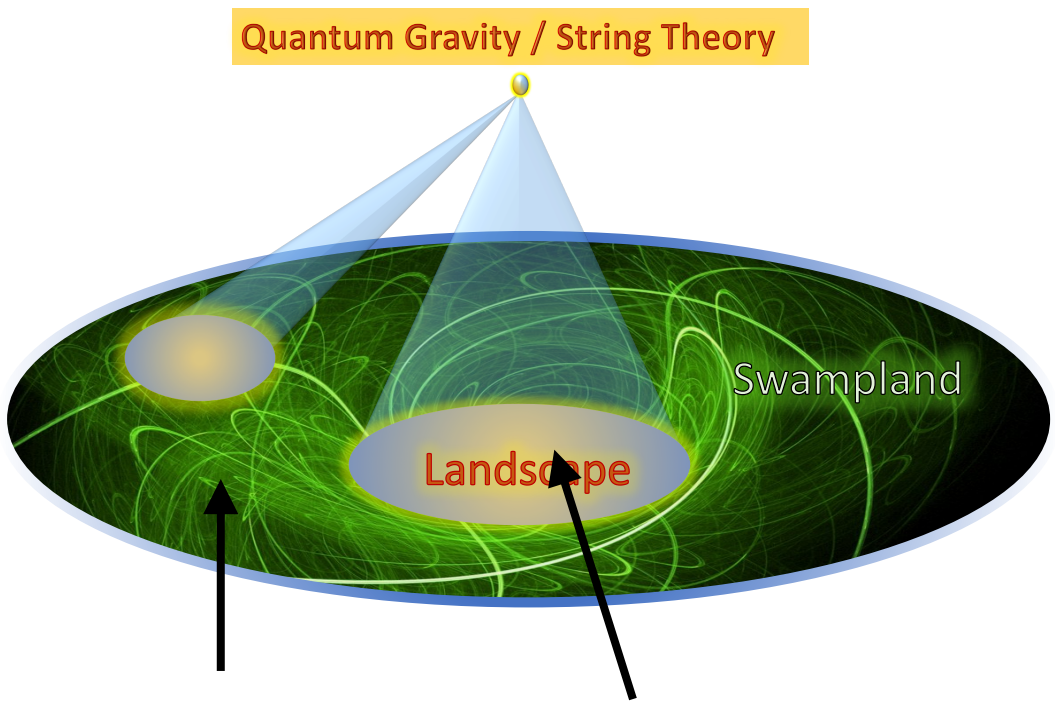
It is conceivable that the anthropic explanation of the cosmological constant does not work !

Multiverse picture would somehow collapse, if there are no de Sitter vacua in string theory. !

New clothes for the emperor - the swampland

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?

[C.Vafa (2005)]



No global symmetries conjecture

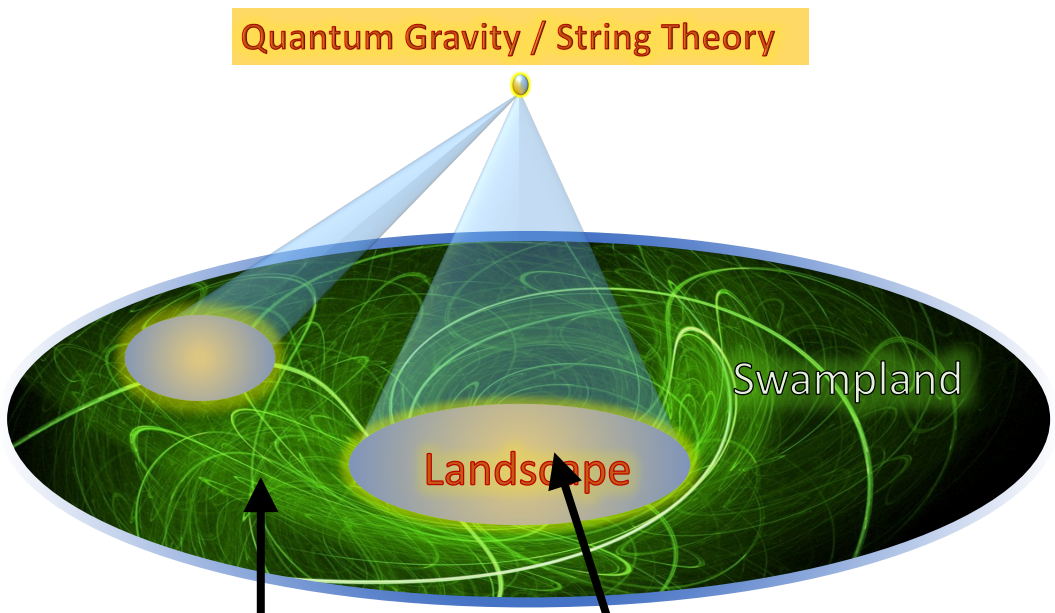
G_{global}

$\cancel{G_{global}}$

New clothes for the emperor - the swampland

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?

[C.Vafa (2005)]



No state with $q \geq m$

Exist state with $q \geq m$

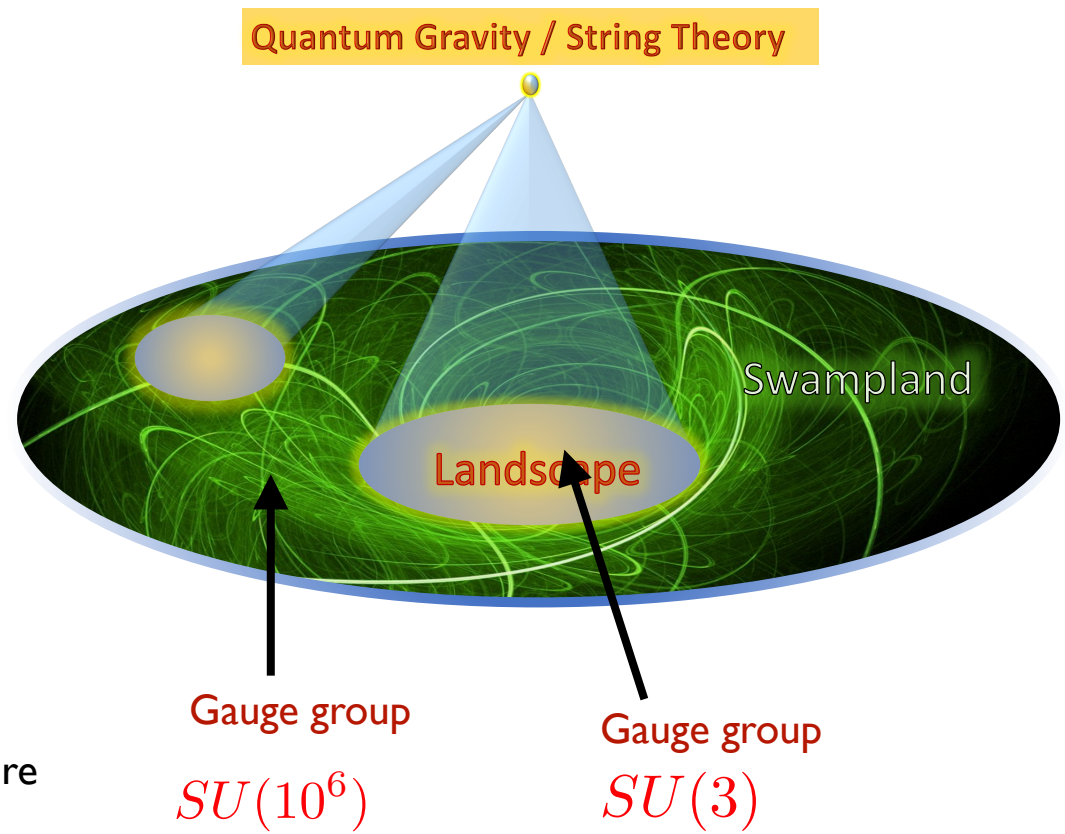
Weak gravity conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa (2006)]

New clothes for the emperor - the swampland

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?

[C.Vafa (2005)]



Finiteness conjecture

Swampland conjectures:

General conjectures in quantum gravity about the boarder line between the landscape and the swampland.

$\longrightarrow$ New restrictions on the landscape

- rigorous and also less rigorous
- less useful and useful in phenomenology
- often motivated from general black hole properties
- often tested in string theory

Swampland distance conjecture:

At large distance Δ directions in the parameter space of string vacua there must be an infinite tower of states with mass scale m.

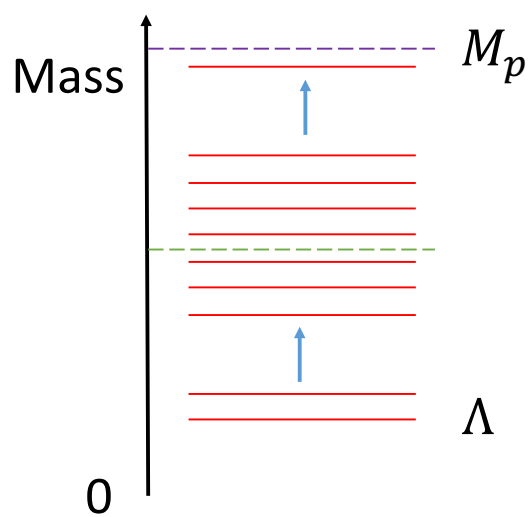
SDC:

$$m = M_P e^{-\Delta}$$

[H. Ooguri, C.Vafa (2006)]

EFT breaks down at $\Lambda_{sw} \equiv m$

$\Lambda_{sw} << M_P$ when $\Delta \to \infty$



Emergent string conjecture

[S. Lee, W. Lerche, T. Weigand (2019)]

At large distances there can be only two kind of towers:

(i) KK particles and winding strings:

$$m_{KK} = \frac{n}{R}$$

Related distance in the internal moduli space:

$$\Delta_R \simeq |\log R| \to \infty \quad \text{for} \quad R \to \infty, 0$$

(ii) Massive string excitations $\quad m_s = g_s \sqrt{n}$

$$\Delta_s \simeq |\log g_s| \to \infty \quad \text{for} \quad g_s \to 0, \infty$$

The AdS distance conjecture

Consider AdS_d vacua in quantum gravity with varying negative cosmological constant Λ_{cc} .

[D.L. , E. Palti, C.Vafa (2019)]

There exist an infinite tower of states with mass scale m, which behaves as

ADC:

$$m \sim |\Lambda_{cc}|^{\alpha} \quad \text{with} \quad \alpha \geq \frac{1}{2}$$

This is closely related to the scale separation problem.

AdS_d alone cannot exits alone as consistent background.

The conjecture is satisfied for many known backgrounds like $AdS_5 \times S^5$ via the tower of KK modes.

Gravitino mass conjecture

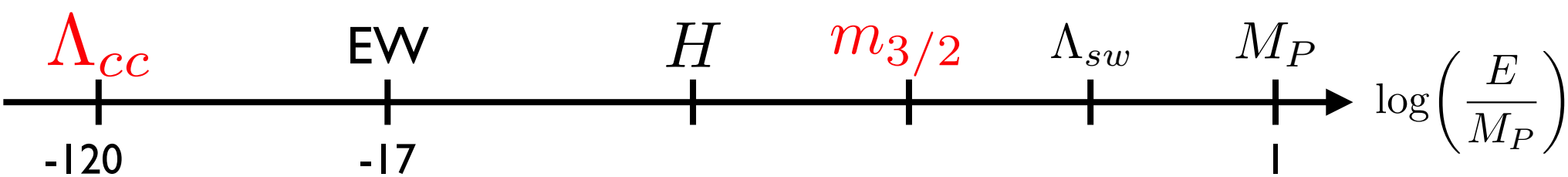
[N. Cribiori, M. Scalisi, D.L. ; A. Castellano, A. Font. A. Harraez, L. Ibanez (2021)]

In the limit of small gravitino mass there exist an infinite tower of states with mass scale m, which behaves as:

GMC:

$$m \sim (m_{3/2})^n \quad \text{with} \quad n > 0$$

Susy breaking scale is of order or higher than the Hubble scale H of inflation!



In the year 1989, Bert also wrote an early „swampland“ paper:

Volume 237, number 3,4 PHYSICS LETTERS B 22 March 1990

ELECTRIC CHARGE QUANTIZATION IN STRING THEORY

A.N. SCHELLEKENS
CERN, CH-1211 Geneva 23, Switzerland

Received 15 December 1989

The conditions for electric charge quantization in four-dimensional heterotic string theories are investigated in a model-independent way. We find that fractional charges can be avoided only by using higher level Kač–Moody algebras, or by allowing rather implausible values for $\sin^2\theta_w$ at the Planck scale.

Conclusion - back to uniqueness ?

Anthropic string landscape: almost anything goes

Swampland program: not anything goes anymore

shrinking of landscape:

$10^{500-1500} \rightarrow 10^{N}$ string vacua

In particular: $N < 120??$

Are the swampland constraints from string theory/ quantum gravity so strong that we end up with a unique ground state ?

It does not look like: there is still room for anthropic thinking, e.g. for the SM model parameters.

However there is an intense debate about the cosmological constant in string theory!

If there are no de Sitter vacua in string theory, then the anthropic explanation of Λ and the multiverse picture is challenged.

New clothes for the emperor !

Bert, besides being an early collaborator, and also Beatriz are very good friends.

At the end I like to show some pictures.

CERN Christmas Play 1990


THE-URIST

Wedding of Beatriz and Bert in August 1991

China, 2006

Munich, 2016

Munich, 2016

Madrid, 2021: Prize Spanish Royal Society of Physics

Many thanks to you Bert for your important contributions to theoretical physics, for the collaboration and your friendship !!