A Brief History of String Phenomenology/Cosmology*

Fernando Quevedo
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50 years of Veneziano Amplitude
May 2018

* A personal perspective

General Subjects

- Compactifications and Model Building
- Effective Lagrangians
- Moduli Stabilisation
- Supersymmetry Breaking
- Stringy cosmology
- Inflation in string compactifications
- Post-Inflation in string compactifications
- Model independent results
- Spin-offs (theoretical and phenomenological)

Outline

- 1985-1994 Heterotic Phenomenology
- 1995-2009 Type I, II, F-theory Phenomenology (+Heterotic)
- 2010-2018 A chronicle (not history)

Heterotic Phenomenology

1984<t<1994

Calabi-Yau Manifolds

Nuclear Physics B258 (1985) 46–74

VACUUM CONFIGURATIONS FOR SUPERSTRINGS

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Received 2 January 1985

We study candidate vacuum configurations in ten-dimensional O(32) and $E_8 \times E_8$ supergravity and superstring theory that have unbroken $N = 1$ supersymmetry in four dimensions. This condition permits only a few possibilities, all of which have vanishing cosmological constant. In the $E_8 \times E_8$ case, one of these possibilities leads to a model that in four dimensions has an E_6 gauge group with four standard generations of fermions.

Dimensional Reduction

Volume 155B, number 3 PHYSICS LETTERS 23 May 1985

DIMENSIONAL REDUCTION OF SUPERSTRING MODELS ☆

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Received 5 February 1985; revised manuscript received 5 March 1985

Compactification of ten-dimensional supergravity on Calabi–Yau manifolds (as recently proposed by Candelas, Horowitz, Strominger, and the author) gives $n=1$ supergravity theories in four dimensions. This paper is devoted to working out the Kähler potential and superpotential which arise.

$$S = e^{3\sigma}\phi^{-3/4} + 3i\sqrt{2}\,D\,,$$

$$T = e^{\sigma}\phi^{3/4} - i\sqrt{2}a + C_x^* C^x$$

$$K = -\ln(S + S^*) - 3\ln(T + T^* - 2C^* C)\,,$$

Supersymmetry Breaking

Gaugino condensation + no-scale

Volume 155B, number 1,2 PHYSICS LETTERS 16 May 1985

ON THE LOW ENERGY $d = 4$, $N = 1$ SUPERGRAVITY THEORY EXTRACTED FROM THE $d = 10$, $N = 1$ SUPERSTRING ☆

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and

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Received 8 March 1985

We extract some general features of the $N = 1$ supergravity, $d = 4$ theory which could be obtained as a low energy limit of the recently proposed anomaly-free superstring theories One finds that after the breaking of the residual $d = 4$ supersymmetry the gravitino and gaugino masses are equal. Soft scalar couplings are also obtained, including trilinear terms as well as common scalar masses $m \sim m_{3/2}$ It is argued that a possible source of supersymmetry breaking may be the condensation of fermions in the Yang–Mills sector and we discuss this possibility in the context of the $E_8 \times E_8$ model Finally, we discuss some implications for the low energy supersymmetric spectrum, particularly squark and gluino masses.

Volume 156B, number 1,2 PHYSICS LETTERS 13 June 1985

GLUINO CONDENSATION IN SUPERSTRING MODELS

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Received 18 March 1985

Gluino condensation in the second E_8 provides a natural mechanism for supersymmetry breaking in $E_8 \times E_8$ superstring theory. Under certain assumptions, the vacuum energy is naturally zero in the leading approximation. The effective four-dimensional theory is similar to the "no-scale" supergravity theories.

$$W = Ae^{-aS} + B$$

Racetrack SUSY Breaking

Volume 193, number 1 PHYSICS LETTERS B 9 July 1987

ON SUPERSYMMETRY BREAKING IN SUPERSTRING THEORIES

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Received 25 March 1987

We show that non-zero gaugino condensates of several non-abelian gauge groups $G_1 \otimes ... \otimes G_k \subset E_8$ in low-energy $d=4$ superstring $E_8 \otimes E_6$ gauge theory can lead to the exponentially small (compared to the Planck scale) supersymmetry breaking scale. The Hosotani mechanism can provide the $E_8 \to G_1 \otimes ... \otimes G_k$ breaking.

$$\Delta W = \sum_l h_{N_l} \exp(-3s/2b_{N_l}) \exp(2\pi i k_l/N_l)$$

Preliminary Model Building

Nuclear Physics B259 (1985) 549–571

SUPERSTRING MODEL BUILDING

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Received 20 March 1985

We consider constraints on superstring theories compactified on Calabi-Yau manifolds arising from the proton lifetime, neutrino masses, $\sin^2\theta_w$, and the requirement of perturbative unification. All possible low-energy gauge groups are studied with variable number of generations. Several three-generation models pose no immediate problem. Four-generation models need an intermediate scale. We suggest a natural mechanism to generate it.

Nuclear Physics B258 (1985) 75–100

SYMMETRY BREAKING PATTERNS IN SUPERSTRING MODELS*

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Received 14 March 1985

It was recently proposed (by Candelas, Horowitz, Strominger and the author) that compact manifolds of SU(3) holonomy are an interesting starting point for superstring phenomenology. Some aspects of such models are explored in this paper. Possible low-energy gauge groups are classified. It is shown that these theories have a mechanism to produce extra massless Higgs doublets unaccompanied by light color triplets. The $SU(3)\times SU(2)\times U(1)$ couplings obey the standard relations after E_6 breaking, so the standard computation of $\sin^2\theta$ is valid. These models lead typically to discrete global symmetries, but a model in which these symmetries forbid all baryon-violating dimension-four operators may be hard to find. An alternative possibility (involving O(6) holonomy) is discussed in the last section.

Quasi-Realistic CY models

Nuclear Physics B278 (1986) 667–693
North-Holland, Amsterdam

A THREE-GENERATION SUPERSTRING MODEL
(I). Compactification and discrete symmetries

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Received 24 March 1986

We present the preliminary analysis of a three-generation heterotic superstring-inspired model. A detailed mathematical description of the manifold of compactification is given, along with a determination of its Hodge numbers and of the associated light supermultiplet structure. For a particular choice of vacuum moduli we derive this manifold's symmetry and groups, and determine their action on the massless fields in the theory. These transformation properties shall be shown, in a companion paper, to give rise to a model with interesting phenomenological properties.

A THREE-GENERATION SUPERSTRING MODEL
(II). Symmetry breaking and the low-energy theory

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Received 26 January 1987

We discuss low-energy phenomenology for a three-generation model, based upon compactification on a specific Calabi-Yau manifold, with an underlying $E_8 \otimes E_8$ symmetry following from the heterotic superstring. It is shown how a combination of breaking by flux loops and Higgs scalar vevs can lead to just the standard model at low energy. The discrete symmetries following from the compactification manifold give rise to a matter parity in the low energy theory which forbids dimension four baryon and lepton number violation. They also ensure a light pair of Higgs bosons and constrain the form of the light fermion mass matrix. The Kobayashi-Maskawa mixing matrix and light fermion masses are determined, and a relation is obtained between the mixing angles. The only light states additional to those of the supersymmetric standard model are a charged lepton and three neutral leptons. Neutrinos are massive but their mass is expected to be very small ($\leqslant O(10^{-1}$ eV)).

Orbifolds

Nuclear Physics B261 (1985) 678-686

STRINGS ON ORBIFOLDS*

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Received 26 June 1985

String propagation on the quotient of a flat torus by a discrete group is considered We obtain an exactly soluble and more or less realistic method of string compactification

Nuclear Physics B274 (1986) 285–314
North-Holland, Amsterdam

STRINGS ON ORBIFOLDS (II)

L. DIXON,[1†] J. HARVEY,[2†] C. VAFA[3] and E. WITTEN[2†]

Received 12 March 1986

A general framework for analyzing string propagation on the quotient of a manifold by a discrete group is presented. The conditions necessary for modular invariance and absence of tachyons are discussed. Models with four or fewer generations which correspond to the standard embedding of the spin connection in the gauge group are analyzed. We all discuss some generalizations which may lead to more phenomenologically promising models.

First explicit string compactifications exact CFTs with chiral matter! (some singular limit of CY)

Narain Compactifications

Volume 169B, number 1 PHYSICS LETTERS 20 March 1986

Nuclear Physics B279 (1987) 369–379
North-Holland, Amsterdam

NEW HETEROTIC STRING THEORIES IN UNCOMPACTIFIED DIMENSIONS < 10

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Received 6 December 1985

It is shown that infinitely many heterotic string theories exist in uncompactified dimensions less than 10, that are one-loop finite (for massless external legs). Tachyons are removed by compactifying into tori $(10-d)$ and $(26-d)$ dimensions of the right-moving superstring and left-moving bosonic string sectors, respectively. The condition for modular invariance is shown to be equivalent to self-duality condition on even lorentzian lattices with $(10-d)$ and $(26-d)$ timelike and spacelike directions, respectively. The construction results in a $(10-d)(26-d)$ parameter family of one-loop finite string theories. The zero mass sector of these theories for $d=4$ and 6 correspond to $N=4$ and 2 supergravity coupled to super Yang–Mills with many possible groups, some of which cannot be obtained by compactifying $d=10$ heterotic string theory.

Direct 4D constructions + interpretation in terms of background fields g_{MN}, A_M^I, B_{MN}

A NOTE ON TOROIDAL COMPACTIFICATION OF HETEROTIC STRING THEORY

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Received 9 June 1986
(Revised 4 July 1986)

The connection of recently constructed lower dimensional heterotic strings with conventional toroidal compactification is clarified.

General Orbifold Models

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ORBIFOLDS AND WILSON LINES

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Received 12 December 1986

We study the consequences of the presence of gauge background fields on the torus underlying orbifold compactification of the heterotic string. It is pointed out that such Wilson lines provide us with a mechanism for controlling the number of chiral matter states both from twisted and untwisted sectors, as well as breaking the symmetry group. Starting from the Z orbifold, we can construct a variety of four-dimensional string models with three families of quarks and leptons and different gauge groups such as E_6, $SU(3)^3$, $SU(6)\times U(1)$ or $SU(5)\times[SU(2)\times U(1)]^2$.

Physics B288 (1987) 551–577
North-Holland, Amsterdam

ASYMMETRIC ORBIFOLDS

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Received 3 February 1987

We describe string theories in which the left-moving and right-moving degrees of freedom live on different orbifolds.

Quasi-Realistic Orbifold Models

Volume 191, number 3 PHYSICS LETTERS B 11 June 1987

ORBIFOLD COMPACTIFICATIONS WITH THREE FAMILIES OF $SU(3)\times SU(2)\times U(1)^n$

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Received 10 March 1987

We construct several $N=1$ supersymmetric three-generation models with $SU(3)\times SU(2)\times U(1)^n$ gauge symmetry, obtained from orbifold compactification of the heterotic string in the presence of constant gauge-background fields. This Wilson-line mechanism also allows us to eliminate extra colour triplets which could mediate fast proton decay.

Volume 210, number 1,2 PHYSICS LETTERS B 18 August 1988

Volume 214, number 1 PHYSICS LETTERS B 10 November 1988

THREE GENERATION $SU(3)\times SU(2)\times U(1)_Y$ MODELS FROM ORBIFOLDS

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Received 2 May 1988

Explicit $SU(3)\times SU(2)\times U(1)_Y$ four-dimensional string models are obtained from compactification of the heterotic string on the Z_3 orbifold. The presence of a Fayet–Iliopoulos term, associated with an "anomalous" U(1), plays a crucial role in the symmetry breaking process. In the example presented here the spectrum of light particles is remarkably close to that of the standard model. It contains three generations of the standard particles, with the correct representations under $SU(3)\times SU(2)\times U(1)_Y$, and all the extra colour triplets, which could mediate fast proton decay, become naturally massive. Finally, there is a true (not mixed) hidden sector. Despite these attractive facts the model still has some problems (related to renormalization group equations and fermion masses), which may be cured in other examples.

YUKAWA COUPLINGS IN DEGENERATE ORBIFOLDS: TOWARDS A REALISTIC $SU(3)\times SU(2)\times U(1)$ SUPERSTRING

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Received 19 May 1988

We discuss the construction of $SU(3)\times SU(2)\times U(1)$ three-generation superstrings through the "degenerate orbifolds" recently described by the authors. These are lower rank models continuously connected to rank-sixteen or twenty-two models through flat directions in the potential of the scalar fields. The structure of Yukawa couplings is carefully investigated and special attention is paid to nonrenormalizable interactions in determining the flat directions and the induced cubic couplings that are forbidden in the original model. The importance of twisted oscillator modes and moduli to this effect is explained. One specific example is presented in detail and its phenomenological consequences such as quark and lepton masses, proton stability and neutrino masses are discussed. In this example there are built-in "stringy" symmetries that protect Higgs doublets from getting large tree-level masses.

Fermionic and Bosonic Strings

Construction of Four-Dimensional Fermionic String Models

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(Received 23 June 1986)

We present a simple set of rules for constructing ultraviolet-finite closed-fermionic-string models. In particular, the method easily gives four-dimensional models which possess $N = 1$ supersymmetry, chiral fermions, and phenomenologically interesting gauge groups.

PACS numbers: 11.17.+y, 12.10.Gq

Nuclear Physics B287 (1987) 477–507
North-Holland, Amsterdam

ar Physics B289 (1987) 87–108
-Holland, Amsterdam

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.

FOUR-DIMENSIONAL SUPERSTRINGS

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Received 30 December 1986

We solve completely the constraints of factorization and multiloop modular invariance for closed string theories in which all internal quantum numbers of the string are carried by free periodic and antiperiodic world-sheet fermions. We derive a simple set of necessary and sufficient rules, and illustrate how they can be used to find the spectrum, one-loop amplitudes and low-energy lagrangian of many realistic four-dimensional chiral models. We prove that modular invariance and factorization ensure the presence of a massless graviton and the correct connection between spin and statistics. We also prove that the existence of a massless spin-$\frac{3}{2}$ state ensures the absence of tachyons and the vanishing of the one-loop cosmological constant.

Quasi-Realistic Fermionic Models

Volume 231, number 1,2 PHYSICS LETTERS B 2 November 1989

THE FLIPPED SU(5)×U(1) STRING MODEL REVAMPED

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Received 21 July 1989

We present a refined version of our three-generation flipped SU(5)×U(1) string model with the following properties.
- The complete massless spectrum is derived and shown to be free of all gauge and mixed anomalies apart from a single anomalous U(1).
- The imaginary part of the dilaton supermultiplet is eaten by the anomalous U(1) gauge boson, and the corresponding D-term is cancelled by large VEVs for singlet fields that break surplus U(1) gauge factors, leaving a supersymmetric vacuum with an SU(5)×U(1) visible gauge group and an SO(10)×SO(6) hidden gauge group.
- There are sufficient Higgs multiplets to break the visible gauge symmetry down to the standard model in an essentially unique way.
- All trilinear superpotential couplings have been calculated and there are in particular some giving m_t, m_b, $m_\tau \neq 0$.
- A renormalization group analysis shows that $m_t < 190$ GeV and $m_b \simeq 3m_\tau$.
- Light Higgs doublets are split automatically from heavy Higgs triplets, leaving no residual dimension-five operators for baryon decay, and the baryon lifetime $\tau_B \sim 2\times 10^{34\pm 2}$ yr.
- There are no tree-level flavour-changing neutral currents, but $\mu \to e\gamma$ may occur at a detectable level: $B(\mu \to e\gamma) \sim 10^{-11}$–$10^{-14}$.

Volume 205, number 4 PHYSICS LETTERS B 5 May 1988

GUT MODEL-BUILDING WITH FERMIONIC FOUR-DIMENSIONAL STRINGS ★

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Received 7 January 1988

We report a first attempt at model-building using the fermionic formulation of string theories directly in four dimensions. An example is presented of a supersymmetric flipped SU(5)×U(1) model with three generations and an adjustable hidden sector gauge group. The simplest version of the model contains most of the Yukawa couplings required by phenomenology, but not all those needed to give masses to quarks or conjugate neutrinos. These defects may be remedied in a more general version of the model.

Physics Letters B 278 (1992) 131–139
North-Holland

PHYSICS LETTERS B

A new standard-like model in the four dimensional free fermionic string formulation

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Received 22 October 1991

I present a new three generation superstring standard-like model in the free fermionic formulation with the following properties. The complete massless spectrum is derived and shown to be anomaly free apart from a single anomalous U(1). The Dine–Seiberg–Witten mechanism is applied to cancel the anomaly, leaving a supersymmetric vacuum. I show that the resulting observable gauge symmetry is SU(3)×SU(2)×U(1)^n where $n=1$ or 2. All trilinear superpotential couplings have been calculated. I show that of the standard model quarks and leptons, only $+\frac{2}{3}$ charged quarks obtain a non vanishing trilevel coupling, which suggests a possible explanation for the heaviness of the top quark relative to the lighter quarks and leptons. The additional, generation independent, U(1) symmetry may remain unbroken down to low energies and prevents fast proton decay.

Non-renormalisation of W under α' corrections

Nuclear Physics B268 (1986) 79–112

NEW ISSUES IN MANIFOLDS OF SU(3) HOLONOMY

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Received 25 November 1985

It is shown that in compactification of superstrings on manifolds of SU(3) holonomy, the superpotential receives no string theoretic corrections from the form it takes in the field theoretic limit, at least to all finite orders in sigma model perturbation theory. Modulo nonperturbative effects, this implies that those manifolds do indeed obey the exact classical equations of superstring theory, as has been argued on other grounds. Also, it is pointed out that the superpotential – even in the field theory limit – contains terms coupling charged fields to E_6 singlets as well as self-couplings of the charged fields. A slightly tentative argument is given that on certain manifolds of SU(3) holonomy – though not all – it is possible to find conformally invariant sigma models that, while keeping unbroken supersymmetry, break E_8 to SO(10) or SU(5) rather than E_6. Including the effects of Wilson lines this would mean that E_8 could be broken precisely to $SU(3) \times SU(2) \times U(1)$ while keeping unbroken supersymmetry. These facts may open avenues for solving the problems associated with neutrino masses, proton decay, and renormalization group calculations of coupling constants. They also may lead to models with fewer unknown parameters than have been present in previous quasi-realistic models.

Anomalous U(1)s and F-I Terms

Nuclear Physics B289 (1987) 589–598
North-Holland, Amsterdam

FAYET-ILIOPOULOS TERMS IN STRING THEORY

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For vacua of string theory which leave unbroken $N = 1$ supersymmetry in the leading approximation, non-renormalization theorems guarantee that higher order (string or sigma model) perturbative corrections do not modify the space-time superpotential. If the low energy gauge group contains U(1) factors, this is not enough to ensure that the low energy physics is perturbatively stable. It is still possible to generate a Fayet-Iliopoulos D-term. We show that under certain conditions such a term is generated, and destabilizes the vacuum. This is a counterexample to various claims about the universal absence of quantum tadpoles when expanding around a classical solution with unbroken supersymmetry. Whether, in a given model, the generation of a D-term will destabilize the vacuum (or merely change the pattern of symmetry breaking) can be determined from properties of the low energy effective action.

Stringy Calculations of EFT

Nuclear Physics B329 (1990) 27–82
North-Holland

ON EFFECTIVE FIELD THEORIES DESCRIBING (2, 2) VACUA OF THE HETEROTIC STRING*

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Received 29 May 1989

Classical vacua of the heterotic string corresponding to $c = 9$, $N = (2, 2)$ superconformal theories on the world sheet yield low-energy effective field theories with $N = 1$ space-time supersymmetry in four dimensions, gauge group $E_6 \otimes E_8$, several families of **27** and $\overline{\mathbf{27}}$ matter fields, and moduli fields. String theory relates matter fields to moduli; in this article we relate the kinetic terms in the effective lagrangian for both moduli and matter fields to the $\mathbf{27}^3$ and $\overline{\mathbf{27}}^3$ Yukawa couplings. Geometrically, we recover the result (obtained previously via the type II superstring and $N = 2$ supergravity) that moduli space is a direct product of two Kähler manifolds of restricted type, spanned by the moduli related respectively to the **27** and $\overline{\mathbf{27}}$ matter fields. The holomorphic functions of the moduli generating the two restricted Kähler metrics also determine the Yukawa couplings of the matter fields. We derive explicit formulae for the metric for the matter fields in terms of the metric for the corresponding moduli; the two metrics are not identical to each other. The precise relation between moduli and matter metrics takes a slightly different form on subspaces of the moduli space where the unbroken gauge symmetry is enhanced beyond $E_6 \otimes E_8$; this phenomenon is illustrated using the examples of (2, 2) orbifolds and tensor products of minimal $N = 2$ theories.

Nuclear Physics B307 (1988) 145–156
North-Holland, Amsterdam

ONE-LOOP THRESHOLD EFFECTS IN STRING UNIFICATION*

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Received 22 March 1988

Like grand unification of old, string unification predicts simple tree-level relations between the couplings of all unbroken gauge groups such as $SU(3)_C$ or $SU(2)_W$. I show here how to compute one-loop corrections to these relations for any four-dimensional model based on a classical vacuum of the heterotic string. The result can be used to calculate both $\sin^2\theta_W$ and Λ_{QCD} in terms of [illegible]

Nuclear Physics B355 (1991) 649–688
North-Holland

MODULI DEPENDENCE OF STRING LOOP CORRECTIONS TO GAUGE COUPLING CONSTANTS*

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Received 25 June 1990

We consider one-loop corrections Δ_a to inverse gauge couplings g_a^{-2} in supersymmetric vacua of the heterotic string. The form of these corrections plays an important role in scenarios for dynamical supersymmetry breaking in string theory. Specifically, we calculate the exact functional dependence of $\Delta_a(U)$ on any untwisted modulus field U of an orbifold vacuum: it has the universal form $\Delta_a(U, \bar{U}) = A_a \cdot \log|\eta(U)|^4 \cdot \mathrm{Im}\, U) + \text{const.}$, where A_a are easily computable rational constants. The dependence is nontrivial ($A_a \neq 0$) only if some sectors of the orbifold Hilbert space have precisely $N = 2$ space-time supersymmetry. The expression for Δ_a has an expected invariance under modular transformations of U, since these are symmetries of the orbifold vacuum state. However, Δ_a is not the real part of a holomorphic function, in seeming contradiction with the existence of a supersymmetric effective lagrangian. The apparent paradox is an infrared problem, and can occur not just in string theory but in renormalizable supersymmetric field theories as well. We show how the paradox is resolved in the field theory case and argue that the same resolution applies also to the string theory case.

The Dine-Seiberg Problem

Volume 162B, number 4,5,6 PHYSICS LETTERS 14 November 1985

IS THE SUPERSTRING WEAKLY COUPLED?

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Received 1 July 1985

We argue that if the superstring is to describe our world, it is probably strongly coupled. Several other (unlikely) possibilities are discussed.

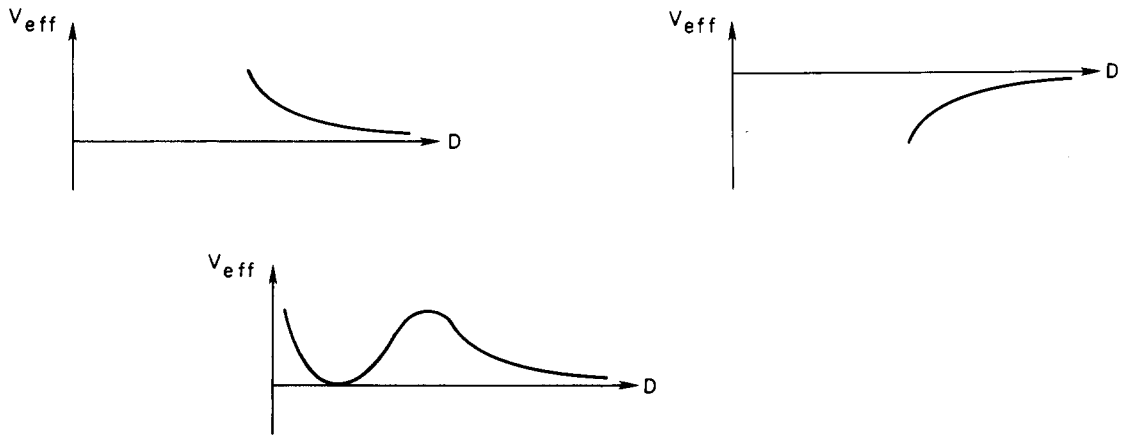

Fig. 2. A possible strongly coupled vacuum.

No Global Symmetries

Nuclear Physics B307 (1988) 93–108
North-Holland, Amsterdam

CONSTRAINTS ON STRING VACUA WITH SPACETIME SUPERSYMMETRY

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We examine the consequences of extended spacetime supersymmetry for classical superstring vacua with four dimensions uncompactified $N = 2$ spacetime supersymmetry implies that the "internal" $N = 1$ superconformal algebra with central charge $\hat{c} = 6$ splits into a piece with $\hat{c} = 4$ which has $N = 4$ superconformal invariance, and a piece with $\hat{c} = 2$ which is constructed from two free dimension $\frac{1}{2}$ superfields $N = 4$ spacetime supersymmetry requires that the entire $\hat{c} = 6$ algebra be represented by six free superfields Using the world-sheet properties of $N = 1$ spacetime supersymmetric classical vacua, we show that spacetime supersymmetry cannot be continuously broken within a family of classical vacua Finally, we argue that the effective field theories for classical vacua of superstring theories (whether spacetime supersymmetric or not) have no continuous *global* symmetries – all continuous symmetries are gauged

No-go theorem for type II

ON FOUR-DIMENSIONAL GAUGE THEORIES FROM TYPE II SUPERSTRINGS

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We study the four-dimensional gauge theories which are associated with classical vacua of the type II superstring, i.e. which correspond to a superconformal field theory on the world sheet. Using the fact that gauge symmetry arises from a supersymmetric affine Kac-Moody algebra, and demanding unitarity of the underlying world-sheet field theory, we show that no such vacua can yield the particle spectrum of the standard model. Of the gauge theories which are permitted by unitarity, we find that many can be constructed explicitly as orbifolds which twist the left- and right-moving degrees of freedom of the string asymmetrically; among these are three $N = 4$ supersymmetric models – which have previously been constructed in a quite different fashion – and two $N = 1$ supersymmetric models with chiral gauge representations for the massless fermions.

T-Duality (spin-off)

Volume 149B, number 4,5 PHYSICS LETTERS 20 December 1984

CASIMIR EFFECTS IN SUPERSTRING THEORIES

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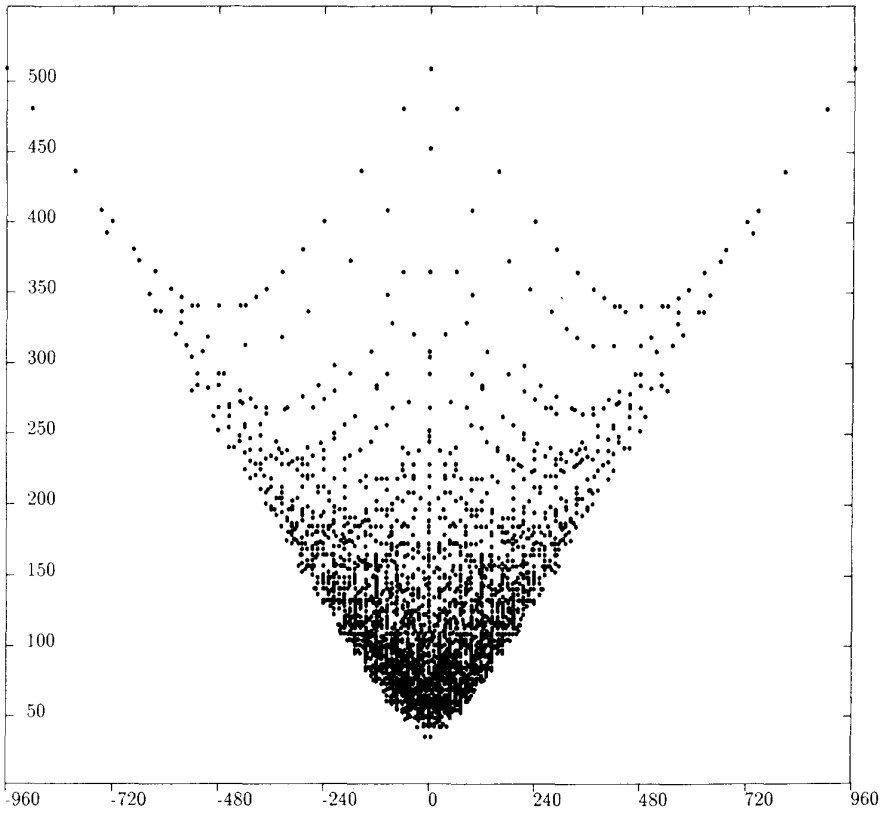
Compactification of the space in superstring theories is studied by calculating the one-loop effective potential provided that the supersymmetry is softly broken by some mechanism. The Casimir energy of closed string modes is shown to compactify the ten-dimensional Minkowski space M_{10} into a stable $M_d \times T_{10-d}$ $(1 \leqslant d < 10)$ with $a_i = \sqrt{\alpha'}/R_i = 1$, where α' and R_i are the Regge slope and the ith radius of the torus T_{10-d}, respectively. In the SST-I model, although the closed string (gravity) sector decouples from the open string (Yang–Mills) sector in $\alpha' \to 0$ limit, the former functions as an initiator as well as a stabilizer of the compactification.

$$a_i \to a_i^{-1}$$

‘Experimental’ Mirror symmetry



Nuclear Physics B341 (1990) 383–402
North-Holland

CALABI–YAU MANIFOLDS IN WEIGHTED $\mathbb{P}_4$*

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Received 10 November 1989
(Revised 12 February 1990)

It has recently been recognized that the relation between exactly solvable conformal field theory compactifications of the Heterotic String and Calabi–Yau manifolds necessarily involves the discussion of embeddings in weighted projective space. We therefore study this class of manifolds more closely. We have constructed a subclass of these spaces and find that this class features a surprising symmetry under $\chi \to -\chi$. Furthermore, we show that this class is potentially of much greater interest with regard to phenomenologically viable models, as there are 25 three-generation models among these manifolds.

Also: Greene+Plesser; Dixon; Lerche-Vafa-Warner

T-Duality and SUSY Breaking

Volume 245, number 3, 4 PHYSICS LETTERS B 16 August 1990

Supersymmetry breaking from duality invariant gaugino condensation

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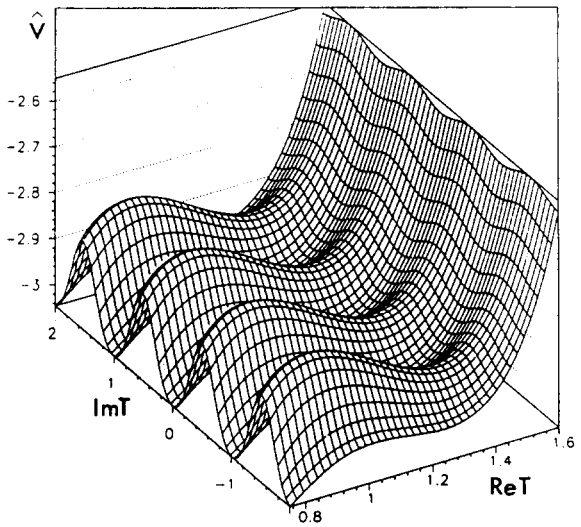
It is known that the formation of gaugino condensates can be a source of supersymmetry breaking in string theory. We study the constraints imposed by target space modular invariance on the formation of such condensates. We find that the dependence of the vacuum energy on the moduli of the internal variety is such that the theory is forced to be compactified. The radius of compactification is of the order of the string scale and in the process target space duality is spontaneously broken.

First concrete efforts to stabilise both the S and T fields using gaugino condensation and modular dependent gauge couplings



Duality and supersymmetry breaking in string theory

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Target-space duality is incorporated in previously proposed effective actions describing non-perturbative supersymmetry breaking in string theory via gaugino condensation. Duality-preserving vacua with broken supersymmetry and fixed unified coupling constant do generically occur. The question of the vanishing of the cosmological constant is also briefly addressed.

General Expression for Soft-Terms

ELSEVIER

Nuclear Physics B422 (1994) 125–171

NUCLEAR PHYSICS B

Towards a theory of soft terms for the supersymmetric standard model

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Abstract

We perform a systematic analysis of the soft supersymmetry-breaking terms arising in some large classes of four-dimensional strings. The analysis does not assume any specific supersymmetry-breaking mechanism but provides a means of parametrizing our ignorance in a way consistent with some known properties of these four-dimensional strings. We introduce a *goldstino angle* parameter θ which says where the source of supersymmetry-breaking resides, either predominantly in the dilaton sector ($\sin\theta = 1$ limit) or in the rest of the chiral fields, notably the moduli ($\sin\theta = 0$ limit). All formulae for soft parameters take particularly simple forms when written in terms of this angle. The $\sin\theta = 1$ limit is (up to small corrections) universal. As $\sin\theta$ decreases, the model dependence increases and the resulting soft terms may or may not be universal, depending on the model. General expressions for the soft terms as functions of θ for generic four-dimensional strings are provided. For each *given* string model, one trades the four soft parameters (M, m, A, B) of the minimal supersymmetric standard model by the two parameters $m_{3/2}$ (gravitino mass) and $\sin\theta$. The role of complex phases and the associated constraints from limits on the electric dipole moment of the neutron are discussed. Also emphasized is the importance of treating the problem of the cosmological constant in a self-consistent manner. Three prototype string scenarios are discussed and their low-energy implications are studied by imposing appropriate radiative $SU(2)_L \times U(1)$ breaking. The supersymmetric particle spectra present definite patterns which may be experimentally tested at future colliders.

Physics Letters B 306 (1993) 269–275
North-Holland

PHYSICS LETTERS B

Model-independent analysis of soft terms in effective supergravity and in string theory

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We discuss supersymmetry breakdown in effective supergravities such as emerge in the low-energy limit of superstring theory. Without specifying the precise trigger of the breakdown, we analyse the soft parameters in the Lagrangian of the supersymmetrized Standard Model.

$$\mathcal{L}_{\not S\mathrm{USY}} = \underbrace{m_0^2\,\varphi^*\varphi}_{\text{scalar masses}} + \left(\underbrace{M_\lambda\,\lambda\lambda}_{\text{gaugino masses}} + h.c.\right) + (A\,\varphi^3 + h.c.)$$

$$M_{1/2} = \frac{1}{f+f^*}F^I\partial_I f$$

$$A_{\alpha\beta\gamma} = F^I K_I + F^I\partial_I \log Y_{\alpha\beta\gamma} - F^I\partial_I \log\left(Z_\alpha Z_\beta Z_\gamma\right)$$

$$m_0^2 = V_0 + m_{3/2}^2 - F^I F^J \partial_I\partial_J \log Z$$

Introducing S-Duality

Strong–weak coupling duality and non-perturbative effects in string theory

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We conjecture the existence of a new discrete symmetry of the modular type relating weak and strong coupling in string theory. The existence of this symmetry would strongly constrain the non-perturbative behaviour in string partition functions and introduces the notion of a maximal (minimal) coupling constant. An effective lagrangian analysis suggests that the dilaton vacuum expectation value is dynamically fixed to be of order one In supersymmetric heterotic strings, supersymmetry (as well as this modular symmetry itself) is generically spontaneously broken

the membrane include those of the string together with a duality transformation for the dilaton field. (Type II A strings, however, are not selfdual but "dual" to type II B strings [22,23]). Of course, there is at the moment no idea about how a ten-dimensional heterotic string could be obtained from any eleven-dimensional extended structure, but that is certainly an open possibility. If this was the case, duality in both T and S would be expected.

The S-duality we are discussing includes an invariance under the transformation of the string coupling constant $g \to 1/g$. Montonen and Olive [24] conjectured some time ago that this type of duality invariance does in fact occur in field theory models of the Georgi–Glashow type (and for any other gauge group with adjoint scalars). They argued that both the spectrum of elementary particles and solitonic states should be dual to each other. Then it is natural to conjecture that the complete theory, the one which describes simultaneously elementary and solitonic states, should present a modular symmetry of the type described in refs. [2,1]. Thus we conjecture that the Montonen–Olive type duality of the heterotic strings will lead to a modular invariance symmetry as in eq. (2).

The effective lagrangian should be explicitly duality invariant, as happens with the $R \to 1/R$ duality. The analogy is quite complete. For small g (big R) the "elementary" strings dominate and the "dual" particles (winding modes in T-duality) are very massive. For big g the opposite occurs. Thus a duality $g \to 1/g$ in the effective four-dimensional field theory

Moduli as Inflatons?

PHYSICAL REVIEW D VOLUME 34, NUMBER 10 15 NOVEMBER 1986

Candidates for the inflaton field in superstring models

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(Received 1 July 1986)

We consider the flat directions of the potential that play a crucial role in the four-dimensional supersymmetric models that are believed to emerge from the compactification of superstring theories and study the possibility that they give rise to an inflationary scenario. None of the scalar fields present in these models—in particular the dilaton field connected with supersymmetry breaking and the SU(5)-singlet scalars in the matter sector—seem, however, to be good candidates for the inflaton, the scalar field whose cosmological evolution leads to an inflationary expansion of the Universe.

T-Duality, Cosmology and 2+2=4

Nuclear Physics B316 (1989) 391–410
North-Holland, Amsterdam

SUPERSTRINGS IN THE EARLY UNIVERSE

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We investigate some aspects of thermodynamics and cosmology for superstrings. By a rather delicate computation using the microcanonical ensemble we show that the thermodynamic description of strings is sound (specific heat is positive at large energies) only for strings propagating in spaces where all the spatial directions are compact. Using this result and by considering a simple model, we show how strings resolve the initial singularity of the Big Bang. We also discuss a cosmological scenario which has the potential of explaining the space-time dimensionality.

Pre-Big-Bang Cosmology

Astroparticle Physics 1 (1993) 317–339
North-Holland

Astroparticle Physics

Pre-big-bang in string cosmology

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Received 14 October 1992

The duality-type symmetries of string cosmology naturally lead us to expect a pre-big-bang phase of accelerated evolution as the dual counterpart of the decelerating expansion era of standard cosmology. Several properties of this scenario are discussed, including the possibility that it avoids the initial singularity and that it provides a large amount of inflation. We also discuss how possible tracks of the pre-big-bang era may be looked for directly in the spectral and "squeezing" properties of relic gravitons and, indirectly, in the distorsion they induce on the cosmic microwave background.

Cosmological Moduli Problem

Physics Letters B 318 (1993) 447–456
North-Holland

PHYSICS LETTERS B

Model-independent properties and cosmological implications of the dilaton and moduli sectors of 4D strings

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Editor: R. Gatto

We show that if there is a realistic 4D string, the dilaton and moduli supermultiplets will generically acquire a small mass $\sim O(m_{3/2})$, providing the only vacuum-independent evidence of low-energy physics in string theory beyond the supersymmetric standard model. The only assumptions behind this result are (i) softly broken supersymmetry at low energies with zero cosmological constant, (ii) these particles interact with gravitational strength and the scalar components have a flat potential in perturbation theory, which are well-known properties of string theories. (iii) They acquire a VEV of the order of the Planck scale (as required for the correct value of the gauge coupling constants and the expected compactification scale) after supersymmetry gets broken. We explore the cosmological implications of these particles. Similar to the gravitino, the fermionic states may overclose the Universe if they are stable or destroy nucleosynthesis if they decay unless their masses belong to a certain range or inflation dilutes them. For the scalar states it is known that the problem cannot be entirely solved by inflation, since oscillations around the minimum of the potential, rather than thermal production, are the main source for their energy and can lead to a huge entropy generation at late times. We discuss some possible ways to alleviate this entropy problem, that favour low-temperature baryogenesis, and also comment on the possible role of these particles as dark matter candidates or as sources of the baryon asymmetry through their decay.

Cosmological Implications of Dynamical Supersymmetry Breaking*

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Abstract

We provide a taxonomy of dynamical supersymmetry breaking theories, and discus the cosmological implications of the various types of models. Models in which supersymme try breaking is produced by chiral superfields which only have interactions of gravitation strength (*e.g.* string theory moduli) are inconsistent with standard big bang nucleosyn thesis unless the gravitino mass is greater than $\mathcal{O}(3) \times 10^4$ GeV. This problem cannot b solved by inflation. Models in which supersymmetry is dynamically broken by renormali able interactions in flat space have no such cosmological problems. Supersymmetry can b broken either in a hidden or the visible sector. However hidden sector models suffer fro several naturalness problems and have difficulties in producing an acceptably large gluin mass.

String Phenomenology After Dualities and D-Branes

(t> 1994)

Horava-Witten

ELSEVIER

Nuclear Physics B 475 (1996) 94–114

NUCLEAR PHYSICS B

Eleven-dimensional supergravity on a manifold with boundary

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Abstract

In this paper, we present a systematic analysis of eleven-dimensional supergravity on a manifold with boundary, which is believed to be relevant to the strong coupling limit of the $E_8 \times E_8$ heterotic string. Gauge and gravitational anomalies enter at a very early stage, and require a refinement of the standard Green-Schwarz mechanism for their cancellation. This uniquely determines the gauge group to be a copy of E_8 for each boundary component, fixes the gauge coupling constant in terms of the gravitational constant, and leads to several striking new tests of the hypothesis that there is a consistent quantum M-theory with eleven-dimensional supergravity as its low-energy limit.

ELSEVIER

NUCLEAR PHYSICS B

Nuclear Physics B 471 (1996) 135–158

Strong coupling expansion of Calabi-Yau compactification

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Abstract

In a certain strong coupling limit, compactification of the $E_8 \times E_8$ heterotic string on a Calabi-Yau manifold X can be described by an eleven-dimensional theory compactified on $X \times \mathbf{S}^1/\mathbb{Z}_2$. In this limit, the usual relations among low-energy gauge couplings hold, but the usual (problematic) prediction for Newton's constant does not. In this paper, the equations for unbroken supersymmetry are expanded to the first non-trivial order, near this limit, verifying the consistency of the description and showing how, in some cases, if one tries to make Newton's constant too small, strong coupling develops in one of the two E_8's. The lower bound on Newton's constant (beyond which strong coupling develops) is estimated and is relatively close to the actual value.

TeV Strings (Brane World)

FERMILAB-PUB-96/070-T
hep-th/9603133

Weak Scale Superstrings

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Recent developments in string duality suggest that the string scale may not be irrevocably tied to the Planck scale. Two explicit but unrealistic examples are described where the ratio of the string scale to the Planck scale is arbitrarily small. Solutions which are more realistic may exist in the intermediate coupling or "truly strong coupling" region of the heterotic string. Weak scale superstrings have dramatic experimental consequences for both collider physics and cosmology.

ELSEVIER

24 September 1998

PHYSICS LETTERS B

Physics Letters B 436 (1998) 257–263

New dimensions at a millimeter to a fermi and superstrings at a TeV

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Editor: H. Georgi

Abstract

Recently, a new framework for solving the hierarchy problem has been proposed which does not rely on low energy supersymmetry or technicolor. The gravitational and gauge interactions unite at the electroweak scale, and the observed weakness of gravity at long distances is due the existence of large new spatial dimensions. In this letter, we show that this framework can be embedded in string theory. These models have a perturbative description in the context of type I string theory. The gravitational sector consists of closed strings propagating in the higher-dimensional bulk, while ordinary matter consists of open strings living on D3-branes. This scenario raises the exciting possibility that the LHC and NLC will experimentally study ordinary aspects of string physics such as the production of narrow Regge-excitations of all standard model particles, as well more exotic phenomena involving strong gravity such as the production of black holes. The new dimensions can be probed by events with large missing energy carried off by gravitons escaping into the bulk. We finally discuss some important issues of model building, such as proton stability, gauge coupling unification and supersymmetry breaking.

Branes at Singularities

JHEP HYPER VERSION

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D-branes at singularities: a bottom-up approach to the string embedding of the standard model

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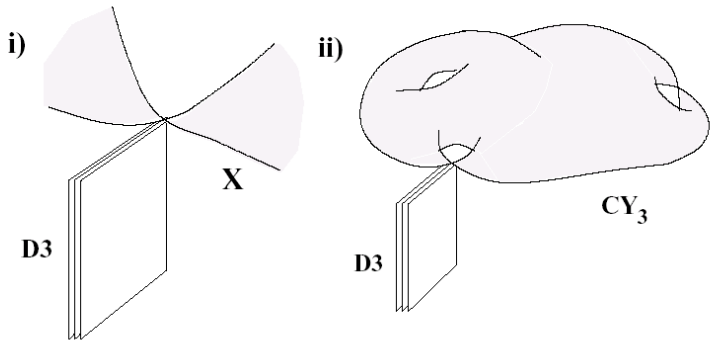
Abstract: We propose a bottom-up approach to particle physics model building from string theory. We start this program by using configurations of type-IIB D3- and D7-branes located at singularities, combined appropriately to reproduce phenomenologically desirable features. We study in detail $\mathbb{Z}_N$ $\mathcal{N}=1,0$ orbifold singularities leading to SM or LR symmetric gauge group. The unique $\mathcal{N}=1$ supersymmetric twist leading to three generations is $\mathbb{Z}_3$, predicting $\sin^2\theta_W = 3/14 = 0.21$, and yielding the simplest semirealistic string models ever built. In the non-supersymmetric case, each $\mathbb{Z}_N$, $N>4$, leads to three-generation models, but the Weinberg angle is in general too small. One can obtain a large class of $D=4$ compact models by embedding the above structure into a Calabi Yau compactification. We construct explicit examples using $T^6\mathbb{Z}_3$ orbifolds and orientifolds, with additional antibrane hidden sectors, leading to gravity mediated supersymmetry breaking. We construct an explicit F-theory compactification with unbroken $\mathcal{N}=1$ supersymmetry,with a three-family LR sector.

Local vs Global Models



Intersecting Brane Models

JHEP HYPER VERSION

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Getting just the standard model at intersecting branes

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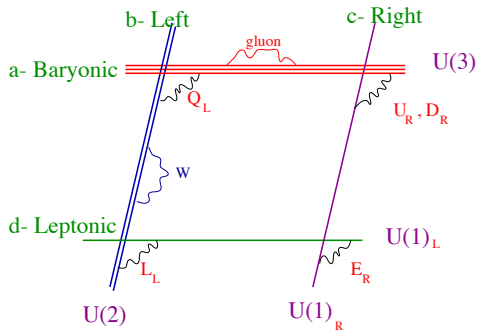
Abstract: We present what we believe are the first specific string (D-brane) constructions whose low-energy limit yields just a three generation $SU(3)\times SU(2)\times U(1)$ standard model with no extra fermions nor U(1)'s (without any further effective field theory assumption). In these constructions the number of generations is given by the number of colours. The Baryon, Lepton and Peccei-Quinn symmetries are necessarily gauged and their anomalies cancelled by a generalized Green-Schwarz mechanism. The corresponding gauge bosons become massive but their presence guarantees automatically proton stability. There are necessarily three right-handed neutrinos and neutrino masses can only be of Dirac type. They are naturally small as a consequence of a PQ-like symmetry. There is a Higgs sector which is somewhat similar to that of the MSSM and the scalar potential parameters have a geometric interpretation in terms of brane distances and intersection angles. Some other physical implications of these constructions are discussed.



ELSEVIER

Nuclear Physics B 615 (2001) 3–32

NUCLEAR PHYSICS B

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Chiral four-dimensional $N = 1$ supersymmetric type IIA orientifolds from intersecting D6-branes

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Abstract

We construct $N = 1$ supersymmetric four-dimensional orientifolds of type IIA on $\mathbf{T}^6/(\mathbf{Z}_2 \times \mathbf{Z}_2)$ with D6-branes intersecting at angles. The use of D6-branes not fully aligned with the O6-planes in the model allows for a construction of many supersymmetric models with chiral matter, including those with the Standard Model and grand unified gauge groups. We perform a search for realistic gauge sectors, and construct the first example of a supersymmetric type II orientifold with $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and three quark–lepton families. In addition to the supersymmetric Standard Model content, the model contains right-handed neutrinos, a (chiral but anomaly-free) set of exotic multiplets, and diverse vector-like multiplets. The general class of these constructions are related to familiar type II orientifolds by small instanton transitions, which in some cases change the number of generations, as discussed in specific models. These constructions are supersymmetric only for special choices of untwisted moduli. We briefly discuss the supersymmetry breaking effects away from that point. The M-theory lift of this general class of supersymmetric orientifold models should correspond to purely geometrical backgrounds admitting a singular G_2 holonomy metric and leading to four-dimensional M-theory vacua with chiral fermions.

Instantons and W

ELSEVIER

Nuclear Physics B 474 (1996) 343–360

NUCLEAR PHYSICS B

Non-perturbative superpotentials in string theory

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Received 8 May 1996; accepted 22 May 1996

Abstract

The non-perturbative superpotential can be effectively calculated in M-theory compactification to three dimensions on a Calabi-Yau four-fold X. For certain X, the superpotential is identically zero, while for other X, a non-perturbative superpotential is generated. Using F-theory, these results carry over to certain Type IIB and heterotic string compactifications to four dimensions with $N = 1$ supersymmetry. In the heterotic string case, the non-perturbative superpotential can be interpreted as coming from space-time and world-sheet instantons; in many simple cases contributions come only from finitely many values of the instanton numbers.

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NUCLEAR PHYSICS B

Spacetime instanton corrections in 4D string vacua: The seesaw mechanism for D-brane models

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Available online 6 March 2007

Abstract

We systematically investigate instanton corrections from wrapped Euclidean D-branes to the matter field superpotential of various classes of $N = 1$ supersymmetric D-brane models in four dimensions. Both gauge invariance and the counting of fermionic zero modes provide strong constraints on the allowed non-perturbative superpotential couplings. We outline how the complete instanton computation boils down to the computation of open string disc diagrams for boundary changing operators multiplied by a one-loop vacuum diagram. For concreteness we focus on E2-instanton effects in type IIA vacua with intersecting D6-branes, however the same structure emerges for type IIB and heterotic vacua. The instantons wrapping rigid cycles can potentially destabilise the vacuum or generate perturbatively absent matter couplings such as proton decay operators, μ-parameter or right-handed neutrino Majorana mass terms. The latter allow the realisation of the seesaw mechanism for MSSM like intersecting D-brane models.

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Neutrino Majorana masses from string theory instanton effects

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Abstract: Finding a plausible origin for right-handed neutrino Majorana masses in semirealistic compactifications of string theory remains one of the most difficult problems in string phenomenology. We argue that right-handed neutrino Majorana masses are induced by non-perturbative instanton effects in certain classes of string compactifications in which the $U(1)_{B-L}$ gauge boson has a Stückelberg mass. The induced operators are of the form $e^{-U}\nu_R\nu_R$ where U is a closed string modulus whose imaginary part transforms appropriately under $B - L$. This mass term may be quite large since this is not a gauge instanton and $Re\,U$ is not directly related to SM gauge couplings. Thus the size of the induced right-handed neutrino masses could be a few orders of magnitude below the string scale, as phenomenologically required. It is also argued that this origin for neutrino masses would predict the existence of R-parity in SUSY versions of the SM. Finally we comment

Brane Inflation

ELSEVIER

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PHYSICS LETTERS B

Physics Letters B 450 (1999) 72–82

Brane inflation

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Abstract

We present a novel inflationary scenario in theories with low scale (TeV) quantum gravity, in which the standard model particles are localized on the branes whereas gravity propagates in the bulk of large extra dimensions. This inflationary scenario is natural in the brane world picture. In the lowest energy state, a number of branes sit on top of each other (or at an orientifold plane), so the vacuum energy cancels out. In the cosmological setting, some of the branes ''start out'' relatively displaced in the extra dimensions and the resulting vacuum energy triggers the exponential growth of the 3 non-compact dimensions. The number of e-foldings can be very large due to the very weak brane-brane interaction at large distances. In the effective four-dimensional field theory, the brane motion is described by a slowly rolling scalar field with an extremely flat plateau potential. When branes approach each other to a critical distance, the potential becomes steep and inflation ends rapidly. Then the branes ''collide'' and oscillate about the equilibrium point, releasing energy mostly into radiation on the branes. In this scenario, it is even possible for the electroweak Higgs field to be the inflaton.

D-brane Inflation[1]

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Abstract

We discuss a calculable version of brane inflation, in which a set of parallel D-brane and anti-D-brane worlds, initially displaced in extra dimension, slowly attract each other. In the effective four-dimensional theory this slow motion of branes translates into a slow-roll of a scalar field (proportional to their separation) with a flat potential that drives inflation. The number of possible e-foldings is severely constrained. The scalar spectral index is found to be 0.97, while the effective compactification scale is of order 10^{12} GeV. Reheating of the Universe is provided by collision and subsequent annihilation of branes.

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The inflationary brane-antibrane universe

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ABSTRACT: We show how the motion through the extra dimensions of a gas of branes and antibranes can, under certain circumstances, produce an era of inflation as seen by observers trapped on a 3-brane, with the inflaton being the inter-brane separation. Although most of our discussion refers to arbitrary p-branes, when we need to be specific we assume that they are D-branes of type-II or type-I string theory. For realistic brane couplings, such as those arising in string theory, the inter-brane potentials are too steep to inflate the universe for acceptably long times. However, for special regions of the parameter space of brane-antibrane positions the brane motion is slow enough for there to be sufficient inflation. Inflation would be more generic in models where the inter-brane interactions are much weaker. The spectrum of primordial density fluctuations predicted has index n slightly less than 1, and an acceptable amplitude, provided that the extra dimensions have linear size $1/r \sim 10^{12}$ GeV. Reheating occurs as in hybrid inflation, with the tachyonic instability of the brane-antibrane system taking over for small separations. The tachyon field can induce a cascade mechanism within which higher-dimension branes annihilate into lower-dimension ones. We argue that such a cascade naturally stops with the production of 3-branes in 10-dimensional string theory.

String inspired: Ekpyrotic/ Cyclic Cosmology Scenario

The Ekpyrotic Universe: Colliding Branes and the Origin o

Hot Big Bang

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Abstract

We propose a cosmological scenario in which the hot big bang universe is produced by the collision of a brane in the bulk space with a bounding orbifold plane, beginning from an otherwise cold, vacuous, static universe. The model addresses the cosmological horizon, flatness and monopole problems and generates a nearly scale-invariant spectrum of density perturbations without invoking superluminal expansion (inflation). The scenario relies, instead, on physical phenomena that arise naturally in theories based on extra dimensions and branes. As an example, we present our scenario predominantly within the context of heterotic M-theory. A prediction that distinguishes this scenario from standard inflationary cosmology is a strongly blue gravitational wave spectrum, which has consequences for microwave background polarization experiments and gravitational wave detectors.

Fluxes and Moduli Stabilisation

hep-th/0105097

Hierarchies from Fluxes in String Compactifications

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Abstract

Warped compactifications with significant warping provide one of the few known mechanisms for naturally generating large hierarchies of physical scales. We demonstrate that this mechanism is realizable in string theory, and give examples involving orientifold compactifications of IIB string theory and F-theory compactifications on Calabi-Yau four-folds. In each case, the hierarchy of scales is fixed by a choice of RR and NS fluxes in the compact manifold. Our solutions involve compactifications of the Klebanov-Strassler gravity dual to a confining $\mathcal{N} = 1$ supersymmetric gauge theory, and the hierarchy reflects the small scale of chiral symmetry breaking in the dual gauge theory.

de Sitter, Kahler Moduli Stabilisation and the Landscape

de Sitter Vacua in String Theory

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We outline the construction of metastable de Sitter vacua of type IIB string theory. Our starting point is highly warped IIB compactifications with nontrivial NS and RR three-form fluxes. By incorporating known corrections to the superpotential from Euclidean D-brane instantons or gaugino condensation, one can make models with all moduli fixed, yielding a supersymmetric AdS vacuum. Inclusion of a small number of $\overline{D3}$ branes in the resulting warped geometry allows one to uplift the AdS minimum and make it a metastable de Sitter ground state. The lifetime of our metastable de Sitter vacua is much greater than the cosmological timescale of 10^{10} years. We also prove, under certain conditions, that the lifetime of dS space in string theory will always be shorter than the recurrence time.

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Large Volume Scenario

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Systematics of moduli stabilisation in Calabi-Yau flux compactifications

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Abstract: We study the large volume limit of the scalar potential in Calabi-Yau flux compactifications of type IIB string theory. Under general circumstances there exists a limit in which the potential approaches zero from below, with an associated non-supersymmetric AdS minimum at exponentially large volume. Both this and its de Sitter uplift are tachyon-free, thereby fixing all Kähler and complex structure moduli. Also, for the class of vacua described in this paper, the gravitino mass is independent of the flux discretuum, whereas the ratio of the string scale to the 4d Planck scale is hierarchically small but flux dependent. The inclusion of α' corrections plays a crucial role in the structure of the potential. We illustrate these ideas through explicit computations for a particular Calabi-Yau manifold.

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Large-volume flux compactifications: moduli spectrum and D3/D7 soft supersymmetry breaking

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Abstract: We present an explicit calculation of the spectrum of a general class of string models, corresponding to Calabi-Yau flux compactifications with $h_{1,2} > h_{1,1} > 1$ with leading perturbative and non-perturbative corrections, in which all geometric moduli are stabilised as in [14]. The volume is exponentially large, leading to a range of string scales from the Planck mass to the TeV scale, realising for the first time the large extra dimensions scenario in string theory. We provide a general analysis of the relevance of perturbative and non-perturbative effects and the regime of validity of the effective field theory. We compute the spectrum in the moduli sector finding a hierarchy of masses depending on inverse powers of the volume. We also compute soft supersymmetry breaking terms for particles living on D3 and D7 branes. We find a hierarchy of soft terms corresponding to 'volume dominated' F-term supersymmetry breaking. F-terms for Kähler moduli dominate both those for dilaton and complex structure moduli and D-terms or other de Sitter lifting terms. This is the first class of string models in which soft supersymmetry breaking terms are computed after fixing all geometric moduli. We outline several possible applications of our results, both for cosmology and phenomenology and point out the differences with the less generic KKLT vacua.

Brane Inflation and Moduli Stabilisation

hep-th/0308055
SLAC-PUB-9669
SU-ITP-03/18
TIFR/TH/03-06

Towards Inflation in String Theory

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We investigate the embedding of brane inflation into stable compactifications of string theory. At first sight a warped compactification geometry seems to produce a naturally flat inflaton potential, evading one well-known difficulty of brane-antibrane scenarios. Careful consideration of the closed string moduli reveals a further obstacle: superpotential stabilization of the compactification volume typically modifies the inflaton potential and renders it too steep for inflation. We discuss the non-generic conditions under which this problem does not arise. We conclude that brane inflation models can only work if restrictive assumptions about the method of volume stabilization, the warping of the internal space, and the source of inflationary energy are satisfied. We argue that this may not be a real problem, given the large range of available fluxes and background geometries in string theory.

Local F-Theory Models

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AEI-2007-174

arXiv:0802.3391

Model Building with F-Theory

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Abstract

Despite much recent progress in model building with D-branes, it has been problematic to find a completely convincing explanation of gauge coupling unification. We extend the class of models by considering F-theory compactifications, which may incorporate unification more naturally. We explain how to derive the charged chiral spectrum and Yukawa couplings in $N = 1$ compactifications of F-theory with G-flux. In a class of models which admit perturbative heterotic duals, we show that the F-theory and heterotic computations match.

GUTs and Exceptional Branes in F-theory - I

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Abstract

Motivated by potential phenomenological applications, we develop the necessary tools for building GUT models in F-theory. This approach is quite flexible because the local geometrical properties of singularities in F-theory compactifications encode the physical content of the theory. In particular, we show how geometry determines the gauge group, matter content and Yukawa couplings of a given model. It turns out that these features are beautifully captured by a four-dimensional topologically twisted $\mathcal{N} = 4$ theory which has been coupled to a surface defect theory on which chiral matter can propagate. From the vantagepoint of the four-dimensional topological theory, these defects are surface operators. Specific intersection points of these defects lead to Yukawa couplings. We also find that the unfolding of the singularity in the F-theory geometry precisely matches to properties of the topological theory with a defect.

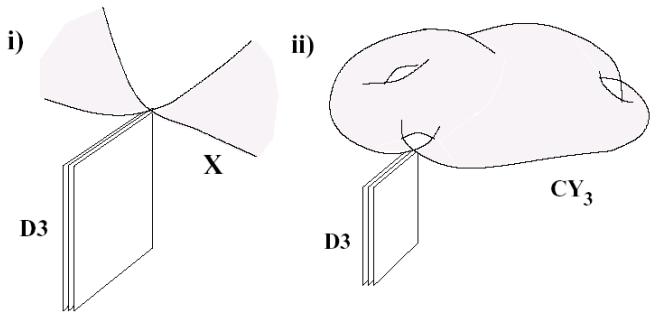
Summary

1985-1995

- Heterotic: Calabi-Yau x Flat 4D
- E6 'string inspired models'
- Simplest dimensional reduction
- Gaugino condensation
- 4d strings (orbifold, bosonic,fermionic, Gepner, KS) from CFT's.
- First quasi realisitic models (CY,orbifold,fermionic)
- Evidence and application of mirror symmetry !!!
- Anomalous U(1)'s, (field dependent) FI
- Gauge coupling unification from LEP
- Threshold corrections to gauge couplings
- T,S duality and attempts to moduli stabilisation
- The CMP
- Structure of Soft terms

1995-2005

- Duality revolution, 11D (Horava-Witten, G2)
- D-branes
- Instantons W
- Large extra dimensions + warping
- Type I,II model building,
  - Bottom up (local models)
  - intersecting branes
- Heterotic revamp (orbifolds, CY's, G2 holonomy ?)
- Fluxes + moduli stabilisation IIB, KKLT, LVS (Landscape)
- SUSY breaking
- Concrete inflation models + alternatives to inflation



2005-2015

- Concrete models of inflation
- Explicit EFTs and instanton calculations
- F-theory phenomenology
- Nonthermal dark matter
- Axiverse + cosmic axion background
- Quasi-Realistic models large data (heterotic)
- Discrete symmetries
- Global IIB models + moduli stabilisation
- Global F-theory models
- SUSY breaking and de Sitter uplift revamped

Some numbers

Summary of Soft terms

	KKLT	**LVS**
Soft term	D3	D3
$M_{1/2}$	$\pm\left(\frac{3}{2a\mathcal{V}^{2/3}}\right)\, m_{3/2}$	$\pm\left(\frac{3s^{3/2}\xi}{4\mathcal{V}}\right)\, m_{3/2}$
m_0^2	$\left(\frac{s^{3/2}\xi}{4\mathcal{V}}\right) m_{3/2}^2$	$\left(\frac{5s^{3/2}\xi}{8\mathcal{V}}\right)\, m_{3/2}^2$
A_{ijk}	$-(1-s\partial_s \log Y_{ijk})\, M_{1/2}$	$-(1-s\partial_s \log Y_{ijk})\, M_{1/2}$

	KKLT	**LVS**
Soft term	D7	D7
$M_{1/2}$	$\pm\left(\frac{1}{a\mathcal{V}^{2/3}}\right) m_{3/2}$	$\pm\left(\frac{3}{4a\tau_s}\right) m_{3/2}$
m_0^2	$(1-3\omega)\, m_{3/2}^2$	$\left(\frac{9(1-\lambda)}{16a^2\tau_s^2}\right)\, m_{3/2}^2$
A_{ijk}	$\frac{3}{2}(2\lambda-1-s\partial_s \log Y_{ijk})\, M_{1/2}$	$-3(1-\lambda)\, M_{1/2}$

String Scenario	n_s	r
D3/$\overline{\text{D3}}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
Racetrack Inflation	$0.95 \leq n_s \leq 0.96$	$r \leq 10^{-8}$
N − flation	$0.93 \leq n_s \leq 0.95$	$r \leq 10^{-3}$
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$
Poly − instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

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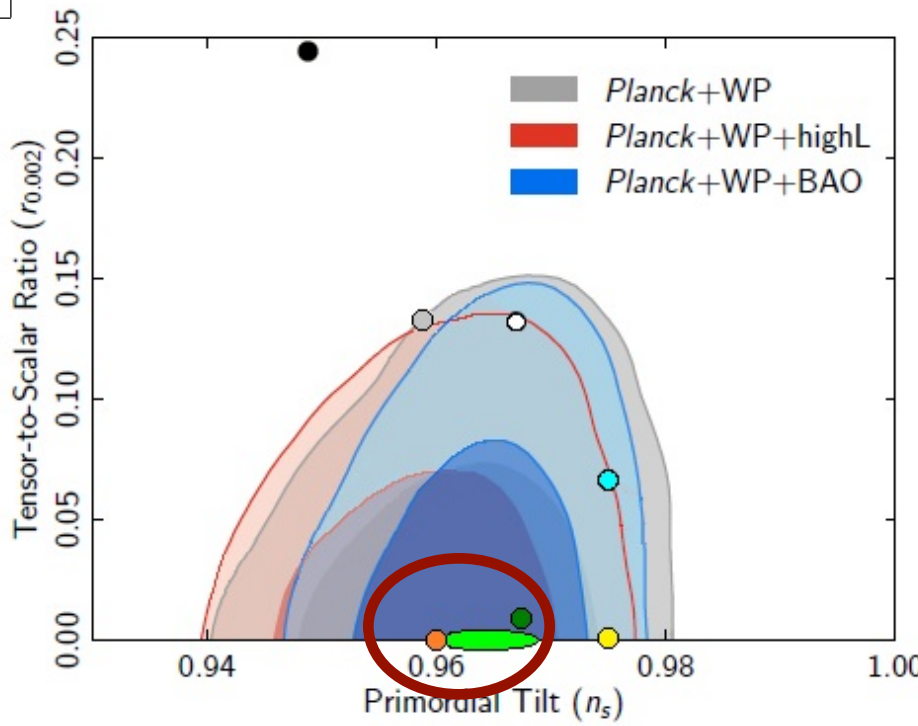
e.g. String Inflation models



In good shape after Planck 2013-2015,

(but most would have been RULED OUT if bicep2 were OK !)

No compelling model so far.

C. Burgess, M. Cicoli, FQ arXiv:1306.3512

Relevant Scales in LVS

String Scale

$$M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi \mathcal{V}}},$$

Kaluza Klein Scale

$$M_{KK} \simeq \frac{M_P}{\sqrt{4\pi}\mathcal{V}^{2/3}},$$

Gravitino mass

$$m_{3/2} \simeq \left(\frac{g_s^2}{2\sqrt{2\pi}}\right) \frac{W_0 M_P}{\mathcal{V}}.$$

Volume modulus mass

$$m_{\mathcal{V}} \simeq m_{3/2}/\sqrt{\mathcal{V}}.$$

Volume axion mass

$$m_a \sim M_P\, e^{-a\mathcal{V}^{2/3}}$$

Volume modulus star

$$M_{\mathcal{V}} \sim \frac{M_P^2}{m_{\mathcal{V}}} \sim M_P\, \mathcal{V}^{2/3}$$

Volume axion star

$$M_a \sim \frac{M_P^2}{m_a} = M_P\, e^{a\mathcal{V}^{2/3}}$$

Vacuum decay rates

$$\Gamma \sim e^{-\mathcal{V}^3}$$

Current Directions

- Global F-Theory Models
- Global brane models with moduli stabilisation
- Large scale inflation and Weak Gravity Conjecture
- Landscape vs Swampland
- Consistency of de Sitter uplift
- Post –inflation string cosmology (moduli domination, oscillons, moduli stars,...)
- Machine learning and the landscape

Recent Reviews

- Ibanez and Uranga book (CUP)
- T. Weigand, arXiv:1009.3497
- R. Blumenhagen et al hep-th/0610327
- F. Denef arXiv:0803.1194
- M. Douglas and S. Kachru hep-th/0610102
- A. Maharana and E. Palti arXiv:1212.0555
- L. Anderson, arXiv:1804.08792