String Phenomenology - Search for the Vacuum

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Why are we interested in Strings?

Despite unprecedented triumph of the Standard Model in empirical description of low-energy particle physics: inacceptable shortcomings/inconsistencies of point particle QFT at fundamental level

- Ultra-violet divergences indicate breakdown/incompleteness of theory at high energies. Renormalizability does not cure this.
  Aim: UV-finite theory which does not need regularization
- No incorporation of gravitational effects into conventional QFT possible

Why are we interested in Strings?

- (MS)SM lagrangian is empirically well-motivated ansatz, but no explanation of messy details of observed physics from first principles
  In fact, it contains (infinitely) many more free parameters than just $19 + x$ mass/interaction terms:
  Why gauge principle in the first place?
  Why $SU(3) \times SU(2) \times U(1)_Y$?
  Particle content?
  Why not any other renormalizable theory?

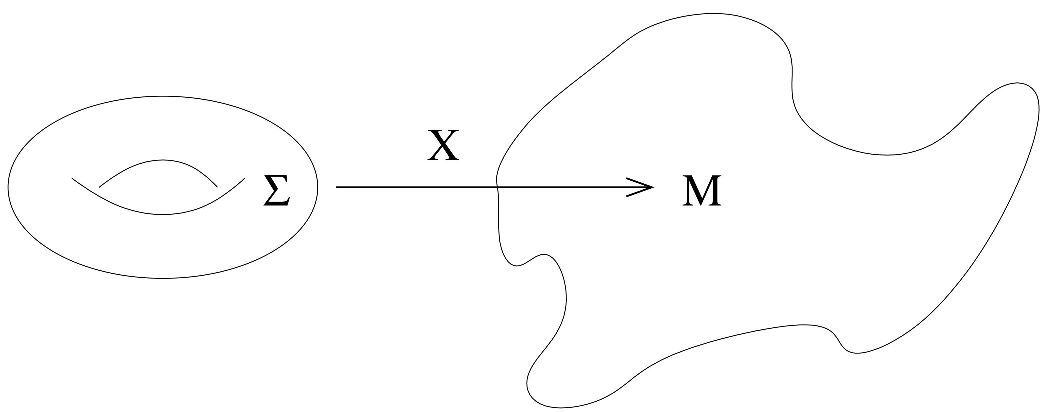
Can one do better?

General features of String Theory

General idea: Describe fundamental entities not as point particles, but as one-dimensional objects
$\rightsquigarrow$ Dynamics governed by embedding of $1+1$-dimensional worldsheet into target space using the kinematical framework of

- general covariance
- canonical quantization/path integral quantization

$\rightsquigarrow$ two-dimensional non-linear σ-model



General features of String Theory

$$S = -\frac{1}{4\pi\alpha'} \int_\Sigma d\tau\, d\sigma\, g^{ab}(\tau,\sigma)\, \partial_a X^\mu(\tau,\sigma)\, \partial_b X^\nu(\tau,\sigma)\, h_{\mu\nu}(X(\tau,\sigma))$$

+fermionic terms

- (τ, σ) parameterize 2-dimensional worldsheet
- $g^{ab}(\tau, \sigma)$ is the 2-dim metric
- $h_{\mu\nu}(X(\tau, \sigma))$ is the metric on the target space background manifold
- $\ell_s = 2\pi\sqrt{\alpha'}$ string length: fundamental length scale of theory

basically perturbative approach, today only some non-perturbative aspects (D-branes...) understood

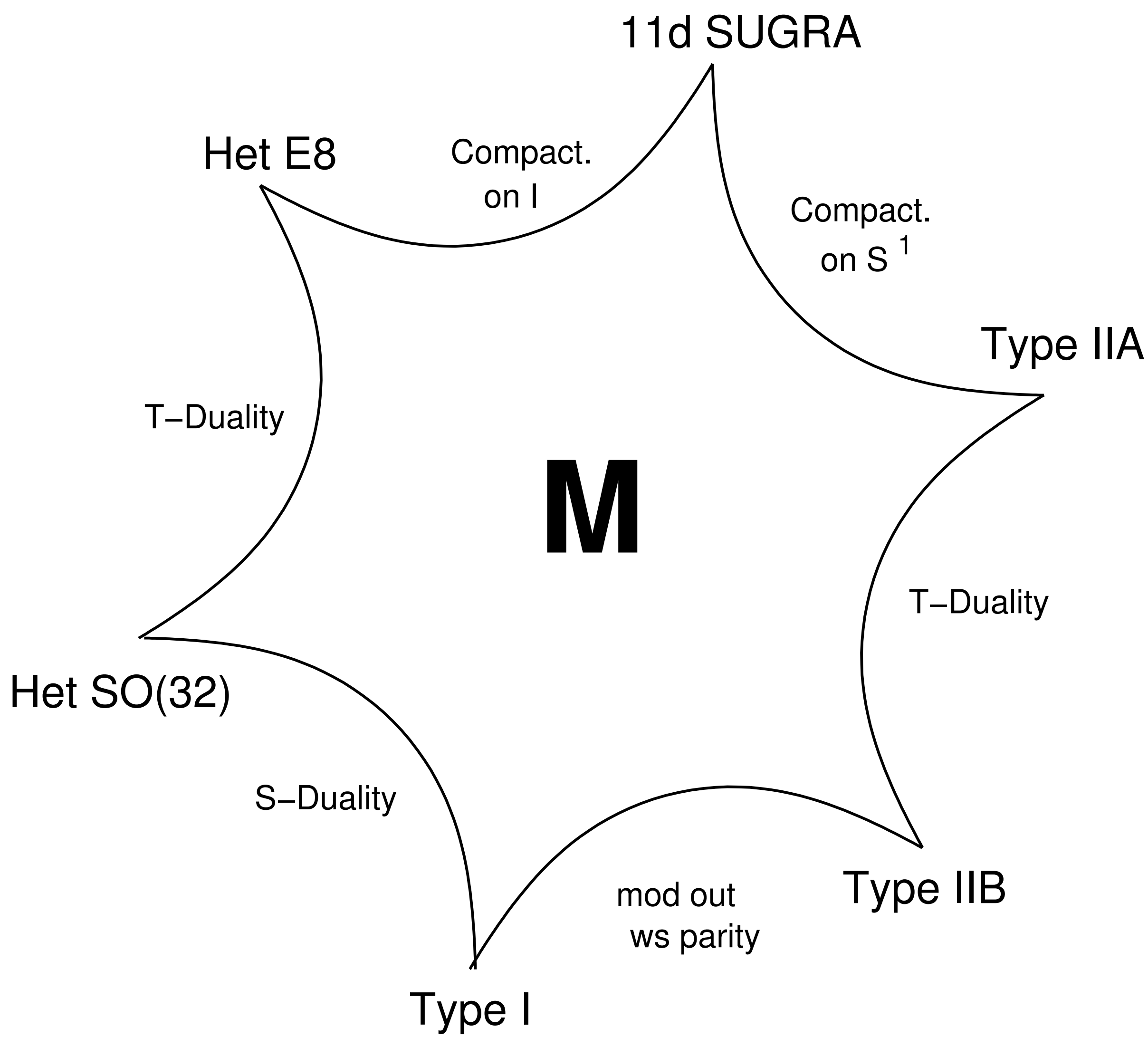
General features of String Theory

Target space effective theory determined (perturbatively) by

- quantum consistency of σ-model
  $\leadsto$ dimension of spacetime $= 10$ for absence of ghosts (unitarity)
  $\leadsto$ SUSY at string scale from modular invariance of torus amplitude
- string scattering amplitudes
  $\leadsto$ compute perturbative interactions of 10-dim. effective theory

In 10 D - depending on details of fermionic action - this gives precisely 5 different types of string theories which are all related by duality

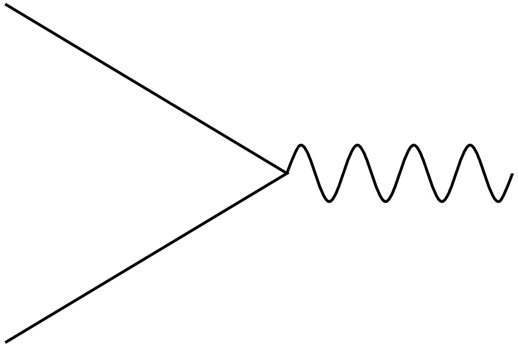
General features of String Theory



General features of String Theory

Does this solve some of the fundamental problems of point-particle theories?

- UV-finiteness by smoothing out interaction point: replace



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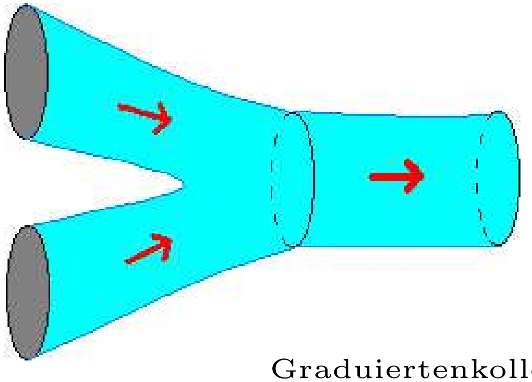


General features of String Theory

- Incorporation of perturbative quantum gravity:
  2 conceivable topologies of 1-dim. string
  - open strings $\rightsquigarrow$ quantization yields massless spin 1 states carrying gauge degrees of freedom = gauge bosons
  - closed strings $\rightsquigarrow$ massless spin 2 states coupling to energy momentum tensor = graviton

  Consequece: Every Yang-Mills theory necessarily has to couple to gravity!
  Direct derivation of Einstein gravity plus perturbative series of higher derivative corrections from consistency of string worldsheet theory
  Two fundamental pillars of observed low-energy dynamics - Yang-Mills theory and Einstein gravity - provided by string theory for free

General features of String Theory

- Natural explanation of details of (MS)SM?
  $\rightsquigarrow$ goal of string phenomenology

In principle: Every (meta-)stable solution of the string e.o.m yields an acceptable vacuum
$\rightsquigarrow$ string vacuum $=$ consistent configuration of background values for massless string fields around which we perturb
includes choice of background metric, of VEV for dilaton ϕ ($=$massles scalar) and various antisymmetric abelian tensor fields
Important: These are not arbitrary effective Lagrangians one postulates, but particular solutions of a fundamental theory!
Each of these vacua gives an eff. theory with a stringy UV-completion consistent with gravity!

String Phenomenology

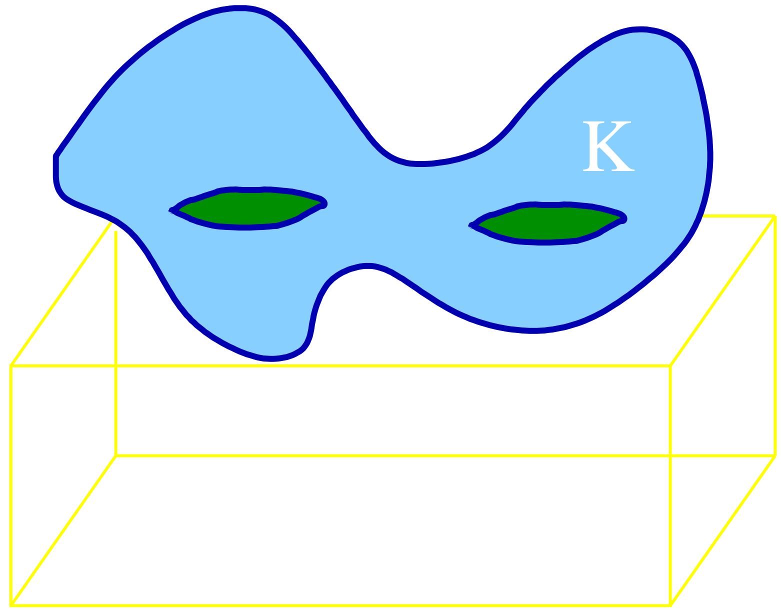
Current estimates suggest up to order 10^{500} stable (i.e. SUSY) 4-dimensional vacua (string landscape).
These are quite a few! - Still: reduction of number of possible theories from ∞ to a large, but finite number!
Conceptual problems:

- Is there a (non-perturbative) dynamical vacuum selection principle on moduli space of solutions?
- Is there a stringy notion of naturalness on the landscape?
- Are all stable vacua realized (baby universes, multiverse...)?

Master question: Identify the/ a/ all (?) realistic vacuum/a with all measured properties of the SM and test its "beyond the SM"-physics

4D String Model Building

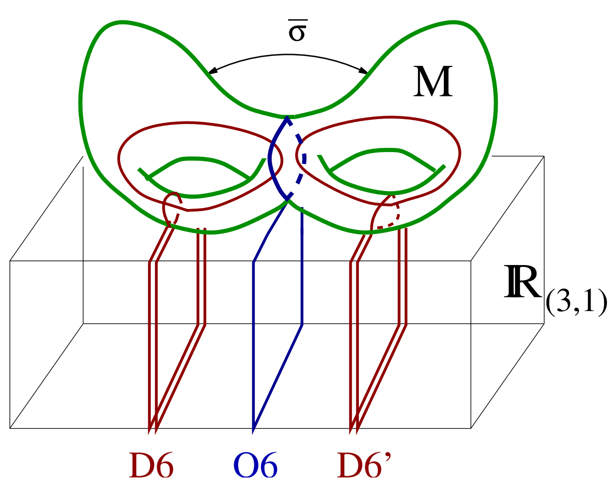
Compactification ansatz: $\mathcal{M}_{1,9} = \mathcal{M}_{1,3} \times K_6$
geometry of internal K_6 severely restricted by background values of bosonic fields and amount of 4D SUSY
easiest case: K_6 is Calabi-Yau ,i.e. of $SU(3)$-holonomy
$\rightsquigarrow \mathcal{N} = 1$ SUSY
geometry of K_6 uniquely determines field content/ interactions in 4D



Intersecting Brane Worlds

Include Dp-branes (($p+1$)-dim. hyperplanes on which open strings end) to engineer gauge sector
p-branes fill spacetime and wrap $(p-3)$-cycle on K_6
Highly non-trivial consistency conditions:

- Stability (SUSY): cycle must be calibrated (volume minimizing) representative of its homology class
- p-branes carry various charges $\rightsquigarrow$ insist on charge cancellation, e.g. by inclusion of O-planes



Intersecting Brane Worlds

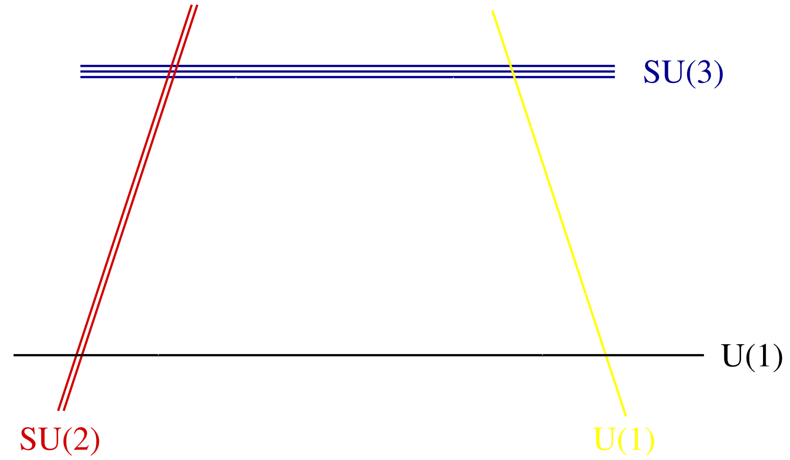
Stack of N_a coincident branes $\rightarrow$ gauge factor $SU(N_a) \times U(1)_a$

At intersection of two different stacks $\rightarrow$ chiral fermions from open strings stretching between them

$\rightsquigarrow$ chiral matter in bifundamental (N_a, N_b)

number of generations $=$ topological intersection number of cycles

model building: realize MSSM gauge group $+$ matter in concrete setups



Intersecting Brane Worlds

Mathematical details very involved
$\rightsquigarrow$ Explicit string solutions only for $K_6 = T^6/\mathcal{Z}_N \times \mathcal{Z}_M$
(SUSY cycles known)

In this very constrained framework basic SM features can be reproduced, but no completely satisfying model so far

Statistical approach: Aim at overview over generic properties on vacuum space/distributions of observables

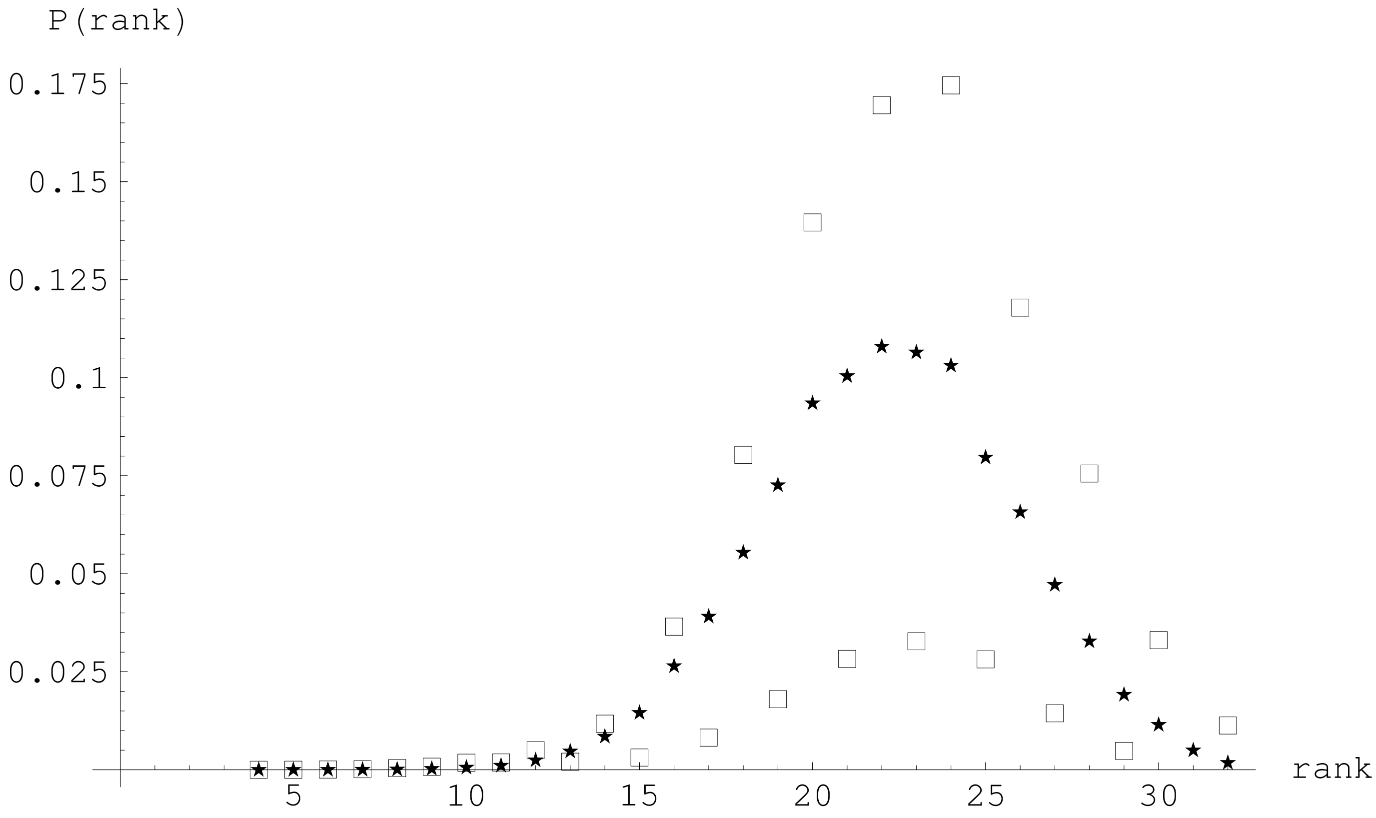
Example: IBW on $K_6 = T^6/\mathcal{Z}_2 \times \mathcal{Z}_2$: [Blumenhagen, Gmeiner, Honecker,Lüst, Weigand 04/05]

10^8 consistent solutions to string e.o.m

Consider correlations between observables, e.g. distribution of total rank among all models or number of generations of quarks and leptons in subset of models with MSSM gauge group

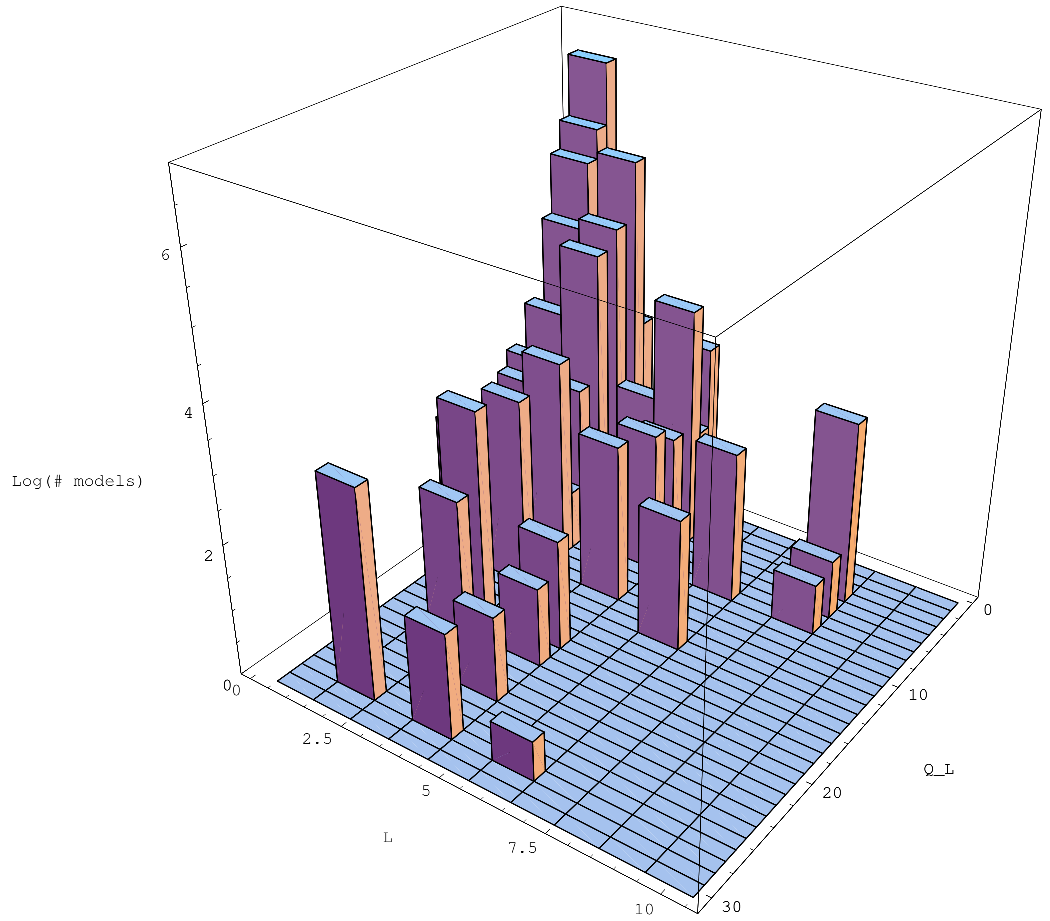
IBW-Statistics

Rank distribution among all models



IBW-Statistics

Number of generations of quarks and leptons in subset of models with MSSM gauge group



IBW-Statistics

Suppression factors for various constraints of Standard Model properties

Restriction	Factor
gauge factor $U(3)$	0.0816
gauge factor $U(2)/Sp(2)$	0.992
No symmetric representations	0.839
Massless $U(1)_Y$	0.423
Three generations of quarks	2.92×10^{-5}
Three generations of leptons	1.62×10^{-3}
Total	1.3×10^{-9}

$\rightsquigarrow$ overall suppression factor of $R \approx 1.3 \times 10^{-9}$

Conclusion

- String Theory gives the fundamental dynamical principles observed in nature for free.
- MSSM as one of many consistent solutions to string equations?
  MSSM seems to be nothing special from point of view landscape of $\rightsquigarrow$ Ultimate Copernican Revolution?
- We need to get to know the solution space much better (heterotic vacua, non-trivial backgrounds...)!
- What is non-perturbative String Theory?
- Is there a vacuum selection principle?