Heterotic String Phenomenology.

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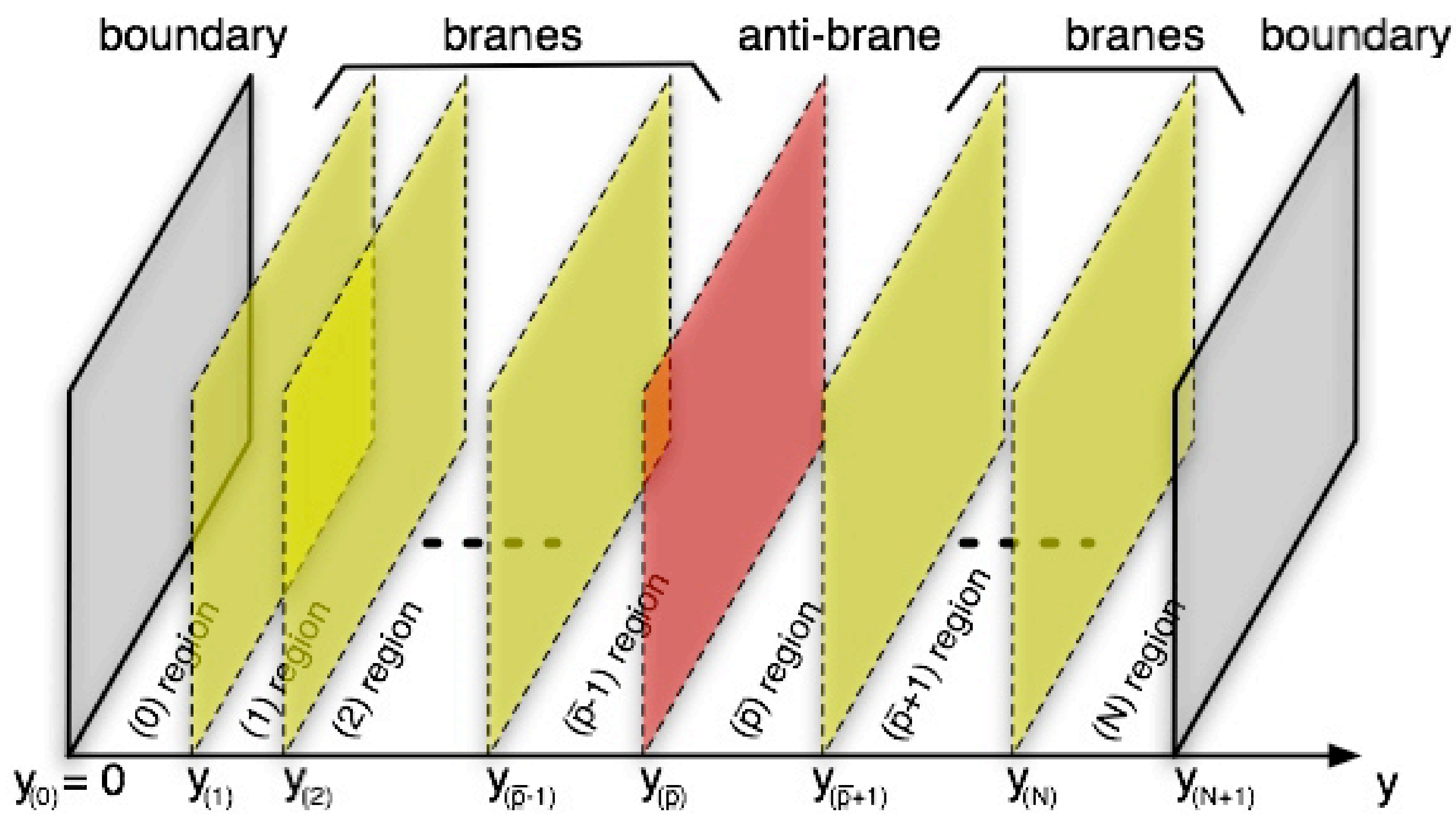
Introduction to Heterotic M-theory

Horava Witten - the strongly coupled limit of heterotic string



- Bulk is eleven dimensional supergravity.
- Boundaries support ten dimensional E8 SYM.
- M5 world volume actions for central branes.

- One dimension out of eleven is already compact. So that gets us down to ten dimensions.
- In order to get an $\mathcal{N}=1$ supersymmetric 4D theory we compactify the remaining six on a manifold of SU(3) structure.
- Often we specialize to cases with a perturbative, Minkowski supersymmetric ground state (i.e a nice supersymmetric vacuum). This leads us to a Calabi-Yau threefold.

Bianchi Identity in ten dimensions:

$$dH = -\frac{3\alpha'}{\sqrt{2}}\left(\mathrm{tr}F^{(1)} \wedge F^{(1)} + \mathrm{tr}F^{(2)} \wedge F^{(2)} - \mathrm{tr}R \wedge R\right)$$

integrate both sides over a non-trivial 4 cycle in the CY...

$$\int_{\mathcal{C}_4} \mathrm{tr} F^{(1)} \wedge F^{(1)} + \int_{\mathcal{C}_4} \mathrm{tr} F^{(2)} \wedge F^{(2)} = \int_{\mathcal{C}_4} \mathrm{tr} R \wedge R$$

- The right hand side of this expression is non zero for a Calabi-Yau manifold.
- We see that we must have non-trivial gauge field vevs in the internal dimensions in our vacuum
- We want to pick these gauge field vevs such that they too preserve $\mathcal{N} = 1$ supersymmetry in the 4D EFT.

The Calabi-Yau metric and gauge fields are not known explicitly

$\longrightarrow$ Use of algebraic geometry to describe the compactification

Matter in 4D theory:

- If gauge field vevs on standard model orbifold fixed plane are valued in a group G then 4D visible sector gauge group is commutant of G in E8.

Eg, G=SU(5) $\longrightarrow$ SU(5) GUT.

- Dimensional reduction of SYM fields gives 4D matter.
- No adjoint Higgs' are present to break the GUT.
- Therefore Wilson lines are used instead.

The goal: Find a Calabi-Yau and bundle (gauge field vevs) such that we get the standard model gauge group, matter content, Yukawa couplings, etc...

An example of model building: The Monad Program

- Approach: algorithmically scan large classes of Calabi-Yau and gauge bundles at a time, in their entirety.
  - Comprehensive - if you don't find the model you want then it doesn't exist in that class
  - Can search for whatever you want not just the MSSM
  - The class we start with are the so-called monad bundles over the favourable complete intersection Calabi-Yau threefolds.

- A few results for the *positive* monads - a well defined sub-class
  - This class of configurations is infinite
  - Imposing that we obtain an N=1 supersymmetric 4D theory restricts us to 7118 examples over 63 Calabi-Yau (started with ~4500 Calabi-Yau).
  - Possibility of a three family model restricts to 559 examples.
  - SU(5) GUT with 3 families before Wilson line breaking - one possible model.
  - We can then algorithmically determine the gauge group, complete particle spectrum, Yukawa couplings of the resulting theories.

Moduli in 4D theory:

(in a Calabi-Yau compactification)

- The size of the eleventh direction
- Energy preserving deformations of the Calabi-Yau
- Energy preserving deformations of the bundle (gauge field vevs)
- Positions of any additional branes ... etc...

All of these fields must be given a mass by some mechanism -- moduli stabilization.

This turns out to be hard in heterotic.

A simple illustration of the problem:

$$K = -\ln(S+\overline{S}) - 3\ln(T+\overline{T}) - 3\ln(Z+\overline{Z})$$

hard to stabilize everything
non-perturbatively, so add flux: $W_{\rm pert} = W(Z)$

Potential is given by usual $\mathcal{N}=1$ formula:

$$V = e^K \left[K^{I\overline{J}} F_I \overline{F}_{\overline{J}} - 3|W|^2\right] \quad \text{where} \quad F_I = \partial_I W + K_I W$$

so perturbatively:

$$F_S = -\frac{1}{S+\overline{S}} W \qquad F_T = -\frac{3}{T+\overline{T}} W$$

$$K_{S\overline{S}} = \frac{1}{(S+\overline{S})^2} \qquad K_{T\overline{T}} = \frac{3}{(T+\overline{T})^2}$$

Plugging this in:

$$V \to e^{K}\left[K^{Z\overline{Z}}F_{Z}\overline{F}_{\overline{Z}} + |W|^{2}\right] \sim \frac{1}{(S+\overline{S})(T+\overline{T})^{3}}$$

- Perturbative run away force on dilaton and Kahler moduli.
- Hard to counter with non-perturbative effects unless very small.
- So we need an (approximate) Minkowski vacuum.

For susy we require:

$$\partial_{Z}W = 0\ ,\ W = 0 \qquad \text{at least approximately.}$$

$$W = ia + bZ + icZ^2 + dZ^3$$

where a, b, c and d are quantized.

- $\partial_Z W = 0$ can be solved easily enough.
- The resulting Z can then be substituted back into W.
- Then attempt to choose a so as to make W small.
- But in heterotic a *is real*...

...so we can't make the perturbative runaway forces small.

- This can be made more rigorous and generalized to arbitrary Calabi-Yau in the large complex structure limit.
- Away from that limit I have not found any Susy Minkowski vacua in the examples where K and W are known.

There are lots of people working on ways to get around this:

- Lots of work on using more general manifolds of SU(3) structure than Calabi-Yau
- The (technical) problem with this is that then all of the known nice model building techniques no longer apply.

Conclusions

- Heterotic M-theory is still one of the most likely ways in which string theory can be linked to phenomenology.
- At the model building level the theory is very successful, in particular in incorporating desirable aspects of GUT physics.
- Moduli stabilization is more difficult in heterotic than in the type II superstring theories, certainly without loosing the model building technology that has been developed.