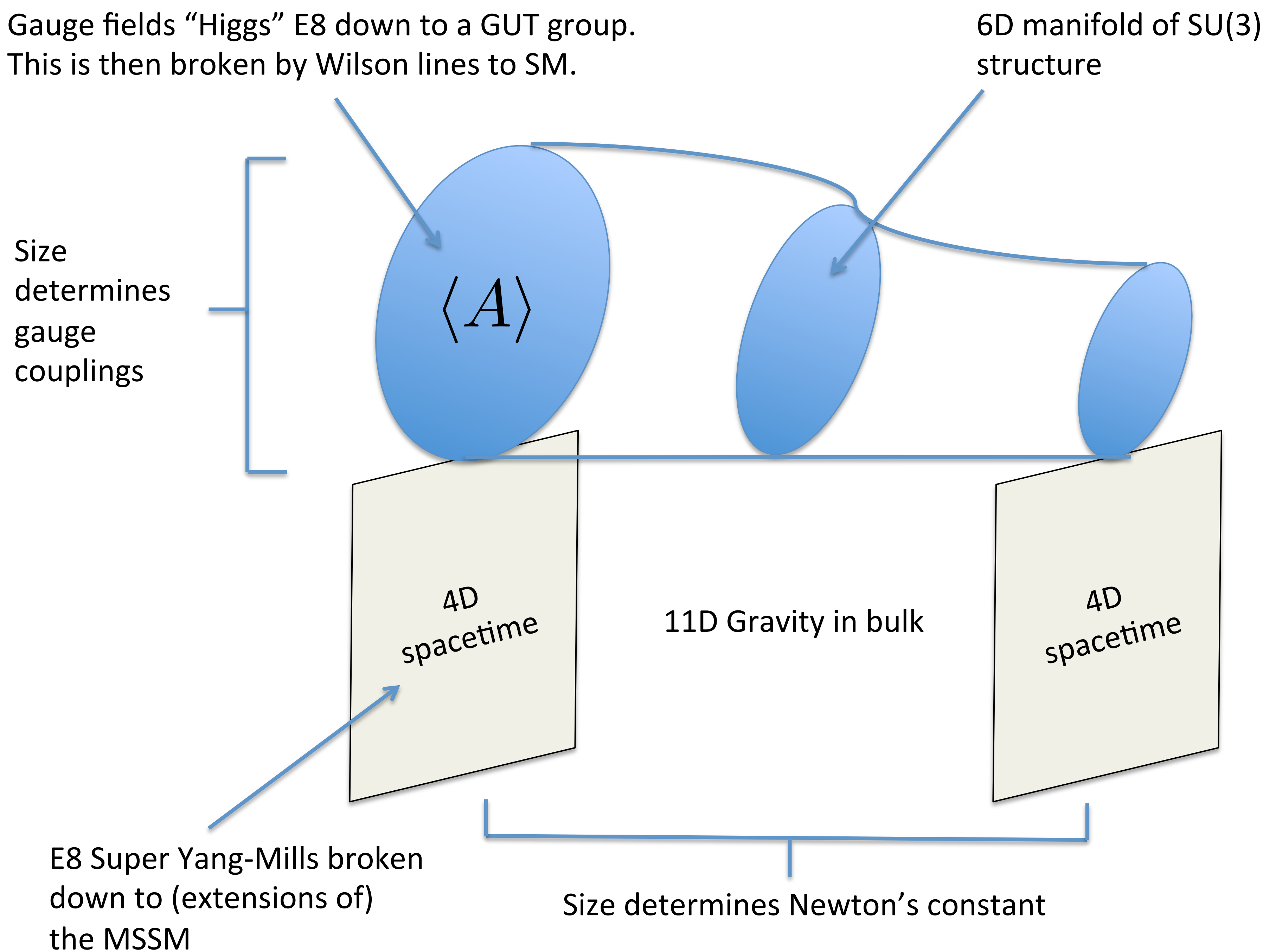
Advances in Smooth Heterotic String Theory

James Gray – Virginia Tech


Gauge fields "Higgs" E8 down to a GUT group.
This is then broken by Wilson lines to SM.
6D manifold of SU(3)
structure
Size
determines
gauge
couplings
$\langle A \rangle$
4D
spacetime
11D Gravity in bulk
4D
spacetime
E8 Super Yang-Mills broken
down to (extensions of)
the MSSM
Size determines Newton's constant

- For a perturbative N=1 SUSY vacuum, six manifold must admit SU(3) structure with:

$$\mathcal{W}_1 = \mathcal{W}_2 = 0 \qquad \mathcal{W}_4 = \frac{1}{2}\mathcal{W}_5 = d\phi$$

$$\mathcal{W}_3 = \text{anything}$$

Strominger, Hull '86
Lopes et al hep-th/0211118

- More general cases with no perturbative SUSY vacuum are known but I will ignore these today.

(Lukas et al: hep-th/1005.5302, Gray et al: hep-th/1205.6208, Angus et al: to appear.)

- Calabi-Yau case: huge number of explicit examples to work with (algebraic geometry can be used).
- Non-Calabi-Yau case: very few interesting examples.

Model Building

- Calabi-Yau case: Huge number of models with exact MSSM charged spectrum known.

Single models:

Bouchard and Donagi: hep-th/0512149
and Bouchard, Cvetic and Donagi: hep-th/0602096
Braun, He, Ovrut and Pantev: hep-th/0501070
Anderson, Gray, He and Lukas: hep-th/0911.1569
Braun, Candelas, Davies and Donagi: hep-th/1112.1097

Data set of 100's of models:

Anderson, Gray, Lukas and Palti: arXiv: 1106.4804
arXiv:1202.1757

- We can compute superpotential couplings and some other phenomenological details as well.
  Missing: matter field K, reliable susy breaking vacua.

- Non-Calabi-Yau case: No exact standard models are known.

  Some work towards this goal:

  Becker, Becker, Fu, Tseng and Yau: hep-th/0604137
  Fu and Yau: hep-th/0604063
  Goldstein and Prokushkin: hep-th/0212307
  Klaput, Lukas and Matti: arXiv:1107.3573
  Chatzistavrakidis and Zoupanos: arXiv:0905.2398
  Chatzistavrakidis, Manousselis and Zoupanos: arXiv:0811.2182

  The problem is a paucity of examples due to the fact that we can't directly use algebraic geometry in this case.

  In fact some of the above cases are not Strominger system examples…

Moduli Stabilization

- We have to remove the uncharged massless scalar fields, moduli, which appear in the four dimensional theory.

  This remains the weakest point of heterotic string phenomenology.

- Calabi-Yau case: Requires an interplay of perturbative and non-perturbative effects, especially to stabilize overall volume – no convincing stable vacuum yet. Pieces of the 4d theory still being understood.

- Non-Calabi-Yau case: More promising, especially with regard to overall volume. Superpotential gains extra terms for example:

$$W \propto \int_X (H + idJ) \wedge \Omega = \int_X (H + i\mathcal{W}_3) \wedge \Omega$$

- Hard to stabilize the moduli such that internal volumes are large enough to give the correct gravitational/gauge couplings so far (excepted from paucity of examples):

This year only!:
Lukas, Lalak and Svanes: arXiv:1504.06978
(links to:
Klaput, Lukas, Matti and Svanes: arXiv: 1210.5933)

Two Recent Pieces of Work

Hypercharge flux in heterotic

- Instead of breaking the GUT group to the standard model with a Wilson line – use non-vanishing field strength!

No unification:

Blumenhagen, Moster and Weigand: hep-th/0603015
Blumenhagen, Moster, Reinbacher and Weigand: hep-th/0612039

Unification:

Blumenhagen, Honecker and Weigand: hep-th/0504232
Anderson, Constantin, Lee and Lukas: hep-th/1411.0034

- Group theory:

$$
\begin{aligned}
E_8 &\supset SU(3) \times SU(2) \times SU(6) \\
&\supset SU(3) \times SU(2) \times S(U(n_1) \times \ldots U(n_m))
\end{aligned}
$$

- Commutant of an $S(U(n_1) \times \ldots U(n_m))$ structure group is (low energy gauge group):

$$SU(3) \times SU(2) \times U(1)^{m-1}$$

- Generically the U(1)s will be Green-Schwarz massive.
- Can you:
  - Keep only one massless and have it be hypercharge
  - Keep gauge unification (say to within 5%)
  - Get the charged matter spectrum of the MSSM
- From group theory alone – yes!
- In actual Calabi-Yau reductions – no! (charged exotics)

Moduli and Spectra of Non-Calabi-Yau cases

- Calabi-Yau case: Light states (moduli and matter) naively given in terms of quasi-topological properties:

$$H^1(\mathcal{TX}) \ , \ H^1(\mathcal{TX}^\vee) \ , \ H^1(\mathcal{V}) \ \ldots$$

- Can we obtain as similar a result as possible for Non-Calabi-Yau cases?

Anderson, Gray and Sharpe: arXiv:1402.1532
De la Ossa and Svanes: arXiv:1402.1725

- "Massless" degrees of freedom can be found by perturbing equations of motion so…

Hull, Strominger: 86

- The most general $\mathcal{N}=1$ heterotic compactification with maximally symmetric 4d space:
  - Complex manifold

$$F_{ab} = F_{\overline{a}\overline{b}} = 0 \qquad H = i/2(\overline{\partial} - \partial)J$$

$$dH = -\frac{1}{30}\alpha' \mathrm{tr} F \wedge F + \alpha' \mathrm{tr} R \wedge R$$

$$g^{a\overline{b}} F_{a\overline{b}} = 0 \qquad H_{\overline{b}c\overline{a}} g^{\overline{b}c} = -6\overline{\partial}_{\overline{a}}\phi$$

Gillard, Papadopoulos and Tsimpis
hep-th/0304126

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- Perturb all of the fields:

$$\mathcal{J} = \mathcal{J}^{(0)} + \delta\mathcal{J} \quad A = A^{(0)} + \delta A$$

$$J = J^{(0)} + \delta J$$

$$H = H^{(0)} + \delta H^{\text{closed}} - \frac{1}{30}\alpha'\delta\omega_3^{\text{YM}} + \alpha'\delta\omega_3^{\text{L}}$$

- And look at what the first order perturbation to the supersymmetry relations looks like…

Restrict attention to manifolds obeying the $\partial\bar{\partial}$-lemma

Lemma: Let X be a compact Kähler manifold. For A a d-closed (p,q) form, the following statements are equivalent.

$$A = \overline{\partial} C \Leftrightarrow A = \partial C' \Leftrightarrow A = dC''$$

$$\Leftrightarrow A = \partial\overline{\partial}\tilde{C} \Leftrightarrow A = \partial\hat{C} + \overline{\partial}\check{C}$$

For some $C, C', C'', \tilde{C}$ and $\check{C}$.

- Perturb all of the equations to get a mess.
- Then repackage in terms of something which is easier to comprehend…

$$H^1(\mathcal{H}) = \begin{cases} \ker\left(\ker\{H^1(TX) \xrightarrow{[F],[R]} H^2(\mathrm{End}_0(V)) \oplus H^2(\mathrm{End}_0(TX))\} \xrightarrow{M} H^2(TX^\vee)\right) \\ \oplus \\ \ker\left(H^1(\mathrm{End}_0(V)) \xrightarrow{-\frac{4}{30}\alpha'[F]} H^2(TX^\vee)\right) \oplus \ker\left(H^1(\mathrm{End}_0(TX)) \xrightarrow{4\alpha'[R]} H^2(TX^\vee)\right) \\ \oplus \\ H^1(TX^\vee)\ . \end{cases}$$

- This is a subspace of

$$H^1(\mathcal{TX}^\vee) \oplus H^1(\mathcal{TX}) \oplus H^1(\mathrm{End}_0(\mathcal{V})) \oplus H^1(\mathrm{End}_0(\mathcal{TX}))$$

  defined by maps determined by the supergravity data (matter is included!).
- All maps are well defined, as are associated extensions.
- This precisely matches the supergravity computation.

Conclusions

- Calabi-Yau Case:
  - Huge number of examples/amount of calculation control.
  - Model building reasonably far along.
  - Moduli Stabilization/SUSY breaking still a problem.

- Non-Calabi-Yau Case:
  - More promising from point of view of moduli stabilization.
  - Paucity of examples is really hindering progress.