String Theory Phenomenology

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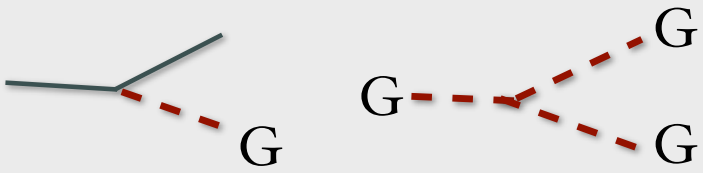
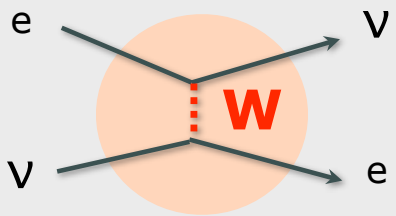
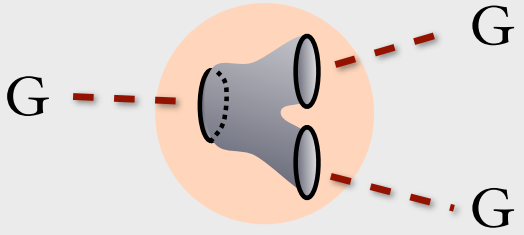
String theory

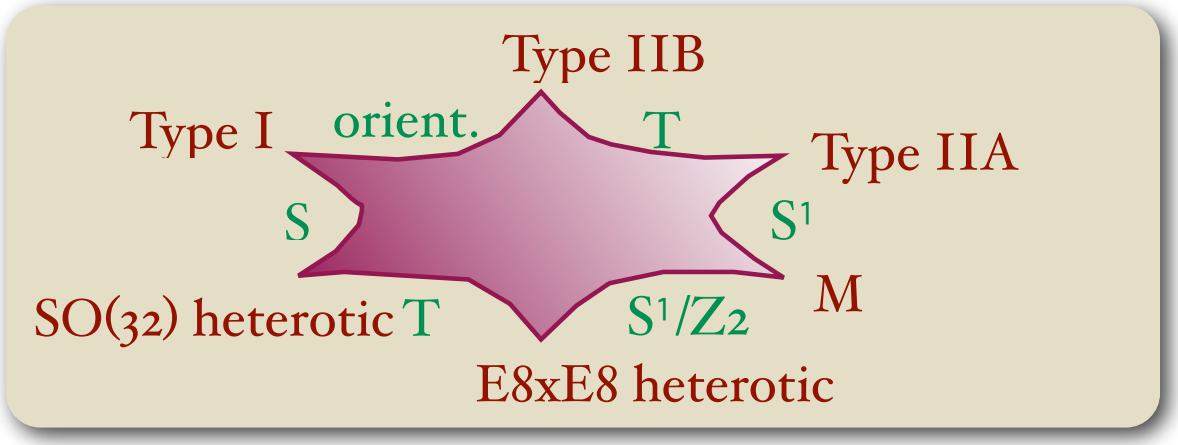
- Reconcile gravity with rules of Quantum Mechanics.
- General Relativity as effective field theory, UV completed by string theory

Analogy:	Fermi theory	General Relativity
- Vertex		
- Coupling	G_F	G_N
- Cutoff	$L_F \approx (100\ \text{GeV})^{-1}$	$L_F \approx (10^{19}\ \text{GeV})^{-1}$
- UV compl.	 Electroweak theory	 String theory

- Elementary particles are oscillation modes of strings

String theory

- Formulated in 10d, string theory is a remarkably unique theory

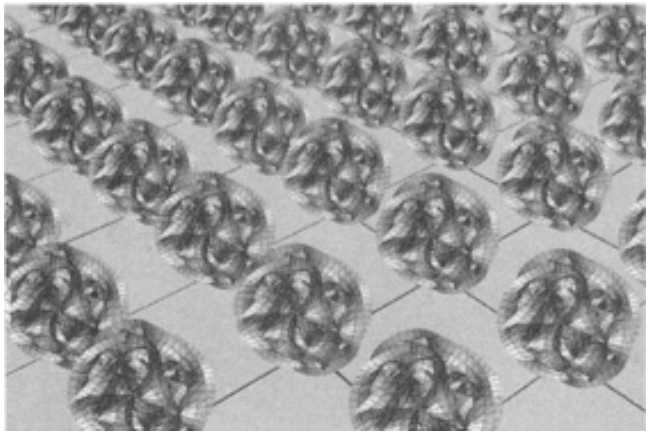


- But need to 'compactify' 6 dimensions in small finite size geometry

  Spacetime $M_4 \times X_6$

- Far from unique, and each choice of 'compactification' space leads to different 4d physics

Analogy with General Relativity:
Unique set of equations, but many solutions



String Phenomenology

- String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level

- If string theory is realized in Nature, it should be able to describe a very specific gauge sector: Standard Model

- Aim of String Phenomenology:

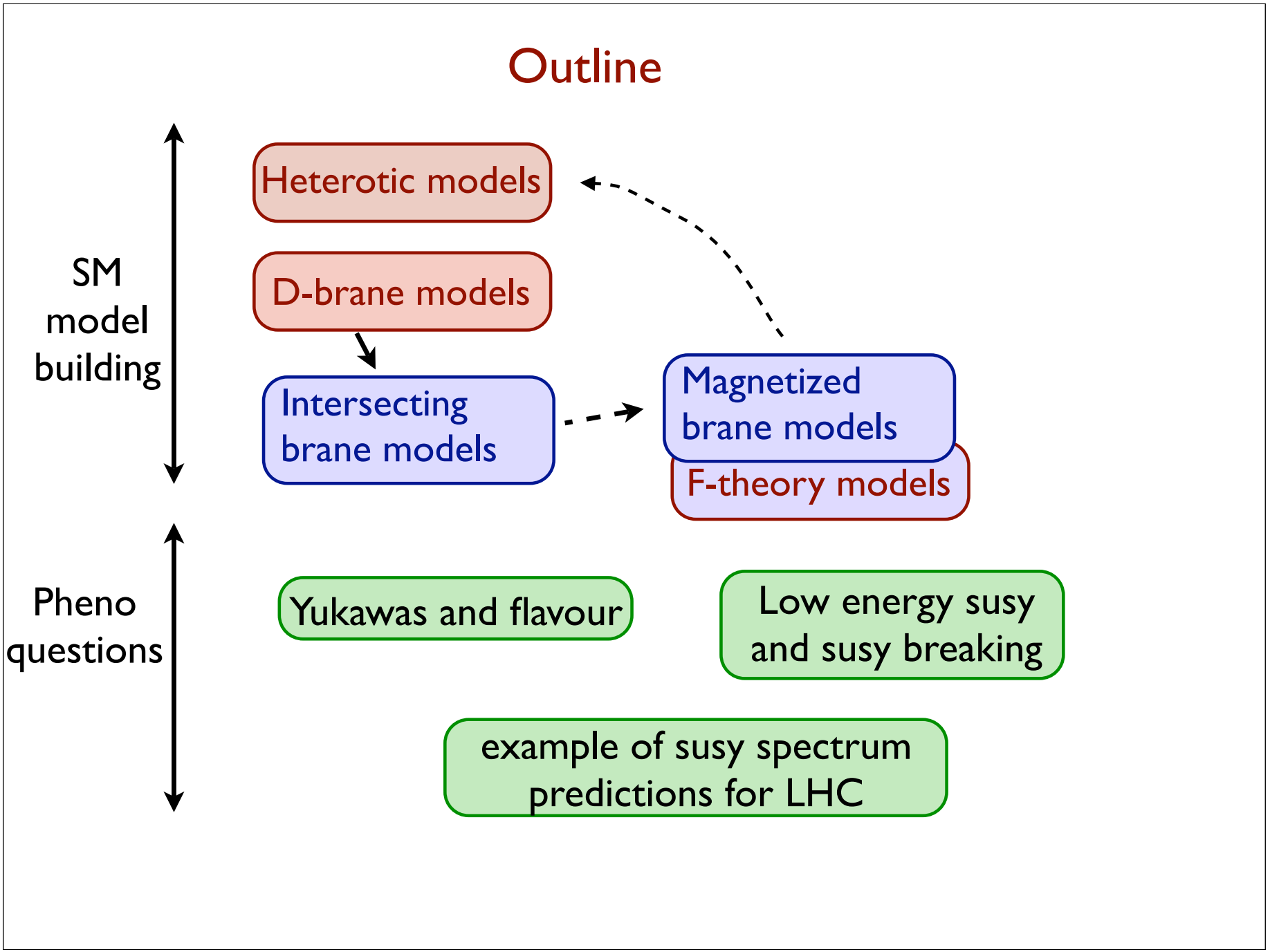
  - Determine classes of constructions with a chance to lead to SM
    Non abelian gauge interactions, replicated charged fermions, Higgs scalars with appropriate Yukawa couplings, ...

  - Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the high energy regime of SM in string theory

- Old program, yet continuous progress
  Moduli stabilization, non-perturbative effects, ...

- Huge field: For this talk, follow a particular path...

Outline


SM
model
building
Heterotic models
D-brane models
Intersecting
brane models
Magnetized
brane models
F-theory models
Pheno
questions
Yukawas and flavour
Low energy susy
and susy breaking
example of susy spectrum
predictions for LHC

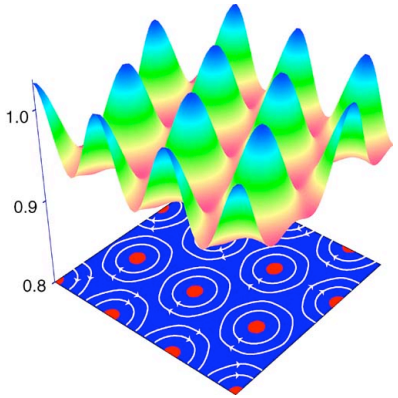
Heterotic string models

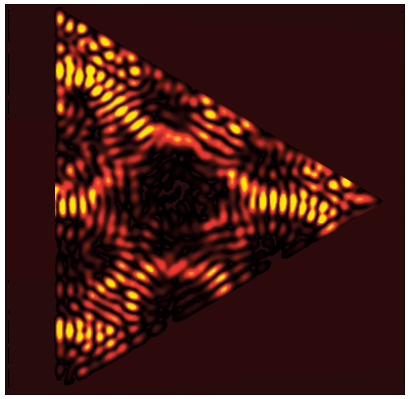
[Candelas, Horowitz, Strominger, Witten '85; Ovrut et al '00-'07

- In 10d, huge gauge group E8(xE8) and huge set of charged fermions (248)
- Turn on magnetic fields in extra dimensions, to break gauge group

  for instance $E8 \rightarrow SU(5) \times U(1)^4$ or $SU(3) \times SU(2) \times U(1)_Y \times U(1)^4$
- 10 charged matter become 4d GUT or SM charged fermions & Higgs

  $248 \supset 24\,, 10\,, 5, \bar{5}$
- In extra dims, SM particles behave as charged particles in magnetic field





- Multiple Landau groundstates ⇒ multiple copies of each fermion

Number of SM families given by number of Landau groundstates

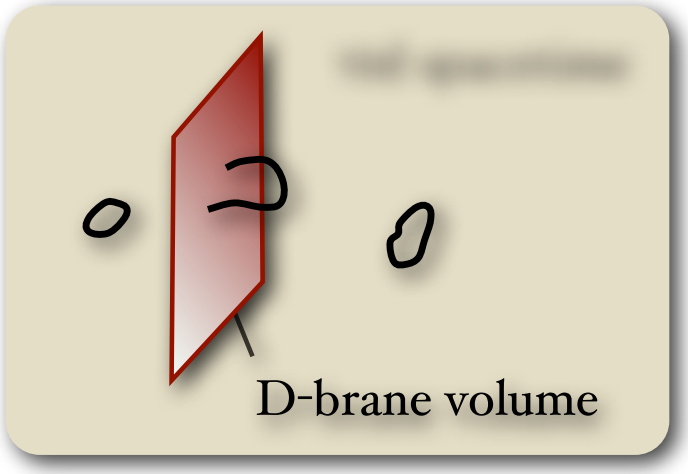
D-branes

[Polchinski '95]

Some of most successful setups to realize the SM is based on D-branes

High-dim. planes on which open strings end

- Brane world:
  - Closed strings: gravity in 10d
  - Open strings: gauge+matter on brane



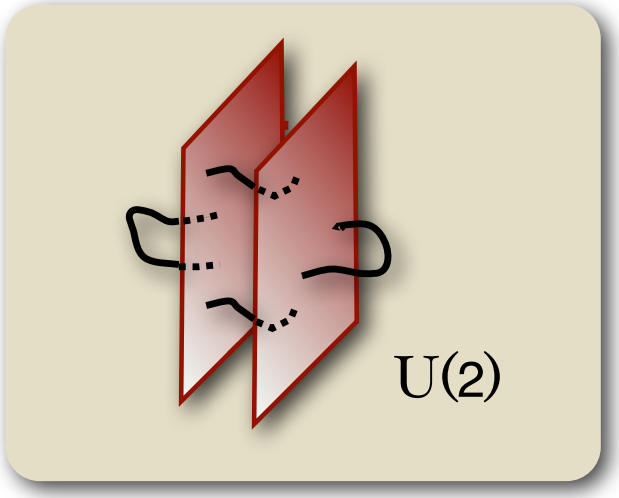
- Allows large extra dimensions

$$M_P^2\, g_{SM}^2 = \frac{M_s^{11-p}\, V_\perp}{g_s}$$

[Antoniadis, Arkani-Hamed, Dimopoulos, Dvali '98]

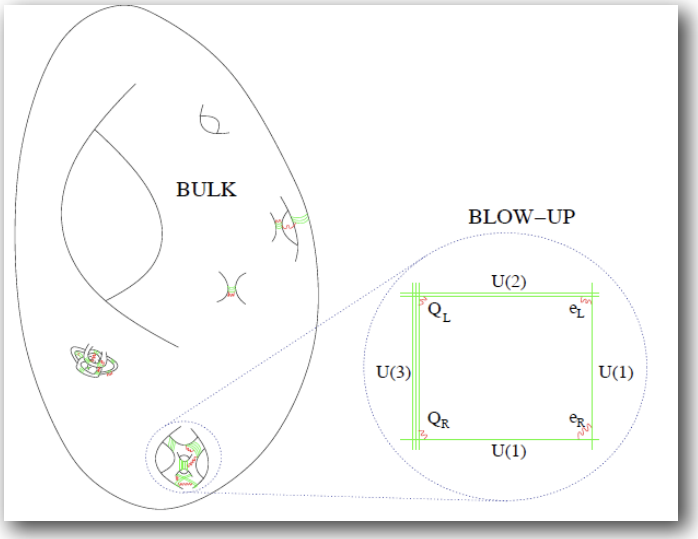
- Geometrization of SM features

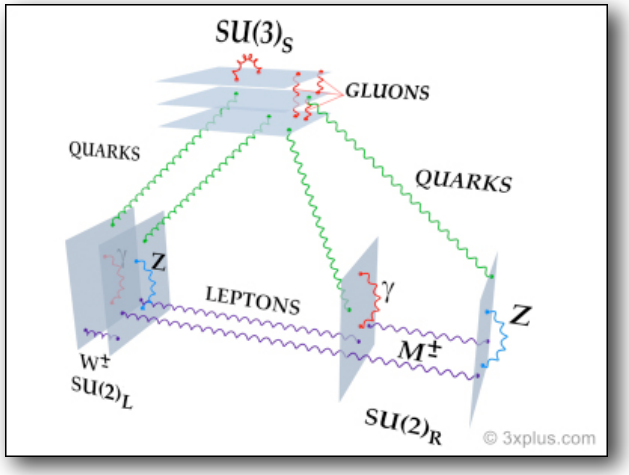
Non-abelian gauge interactions on volume of coincident D-branes



Intersecting D-branes [Berkooz, Douglas, Leigh, '96;]

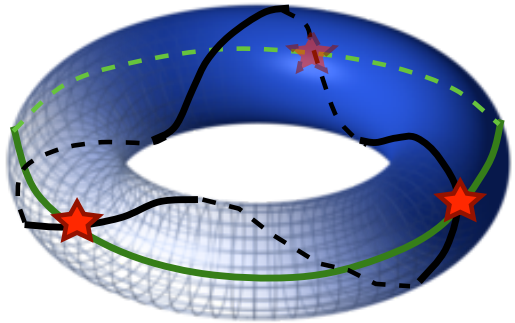
- Charged matter arises from open strings among stack of D-branes intersecting in the extra dimensions





- Multiple intersections ⇒ multiple copies of each fermion

Number of SM families given by number of geometric intersections

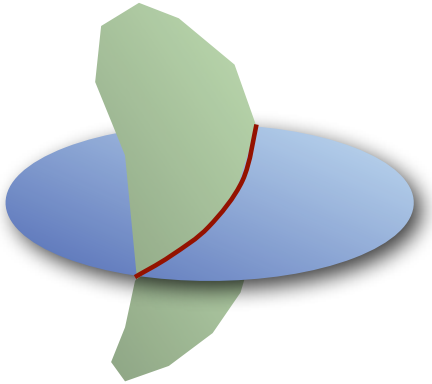


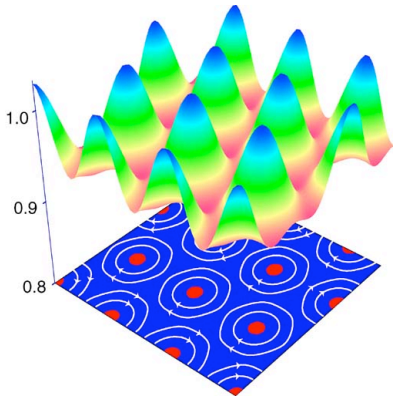
[Blumehagen, Gorlich, Kors, Lust '00;
Aldazabal, Franco, Ibanez, Rabadan, AU '01
Ibanez, Marchesano, Rabadan '02]

Magnetized brane models

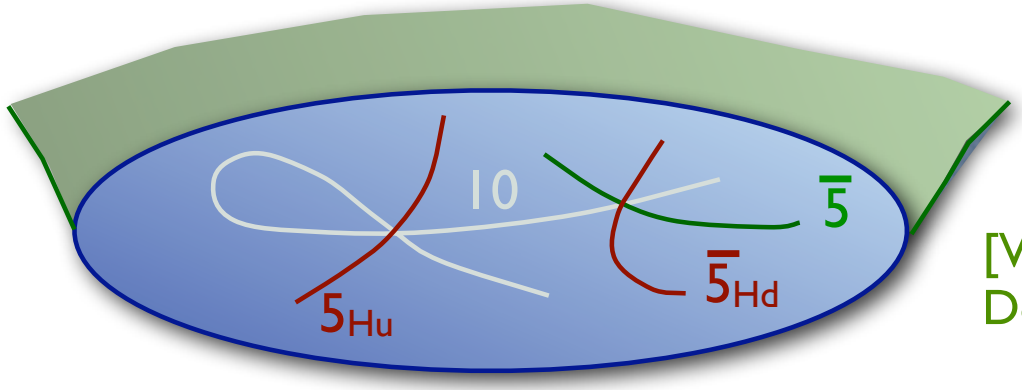
[Bachas '95; Angelantonj, Antoniadis, Dudas, Sagnotti, '00]

- In a ' dual' equivalent description, matter at intersection localized as electric particles in magnetic fields





- Number of SM families given by number of Landau groundstates
- Similar to heterotic, but can start smaller group: 5 branes → SU(5)
- Successful GUT models of SU(5) →SU(3) x SU(2) x $U(1)_Y$



'F-theory'

[Vafa, Heckman; Donagi, Wijnholt; ...'08]

Some phenomenological properties

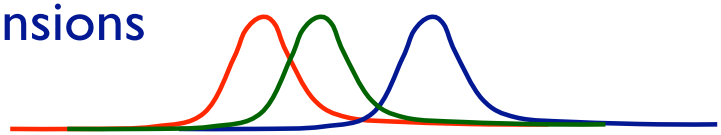
[Aldazabal, Franco, Ibanez, Rabadan, AU '01]

- Gauge coupling unification

  Unified higher-dimensional gauge group, broken by magnetic field

- Yukawa couplings

  Overlap of wavefunctions in extra dimensions



$$Y_{jk} \simeq e^{-A_{Hjk}+i\phi_{jk}}$$

Realistic textures for masses and mixings in particular models

- String scale

  - Susy models, can have large string scale [later for susy breaking]

  - Non-susy models: large extra dimensions [ADD'98] or warping [later]

- Proton decay

In SM models, forbidden by $U(1)_a$ baryon number (Z' boson)

In GUT models, possible but suppressed just above experimental bound

- Interesting pattern of Z' bosons beyond SM

Flux compactifications

[Dasgupta, Rajesh, Sethi '99; Giddings, Kachru, Polchinski '01]

What fixes geometry of compactification space?

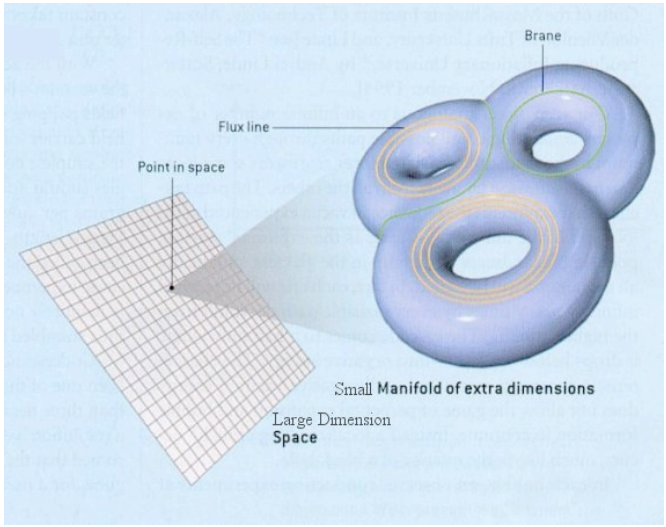
- Free parameters in the compact geometry are massless fields in 4d (moduli')

  Phenomenological disaster!

  5th forces, cosmological problems,...

- Turn on magnetic fluxes also in bulk

Generalized gauge potentials in gravity sector



- Interesting effects:

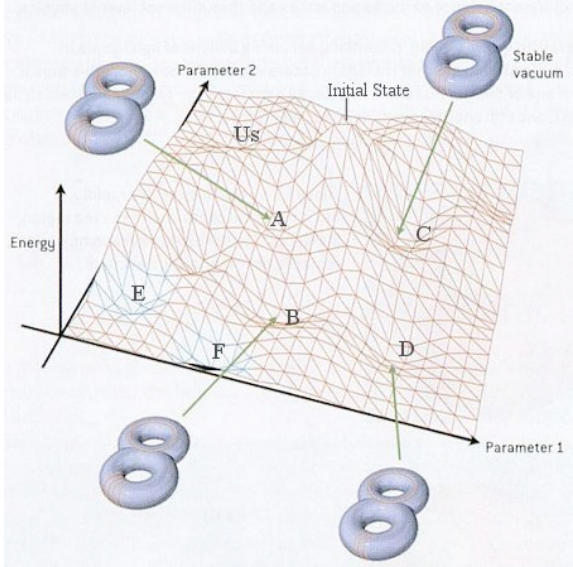
  - Flux energy depends on geometry:

    Stabilization by energy minimization

  - Fluxes gravitate: warped dimensions

    [Randall, Sundrum '99]

  - Supersymmetry breaking fluxes, inducing soft terms in susy branes



What at LHC?

- A possible scenario:

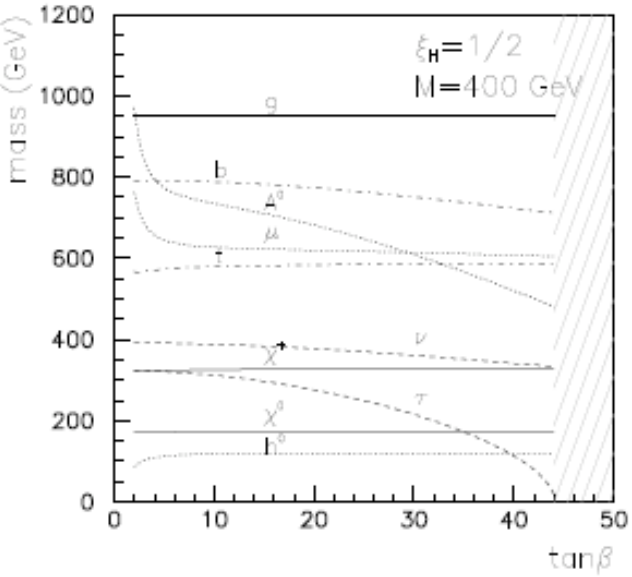
  Flux susy breaking with susy branes:

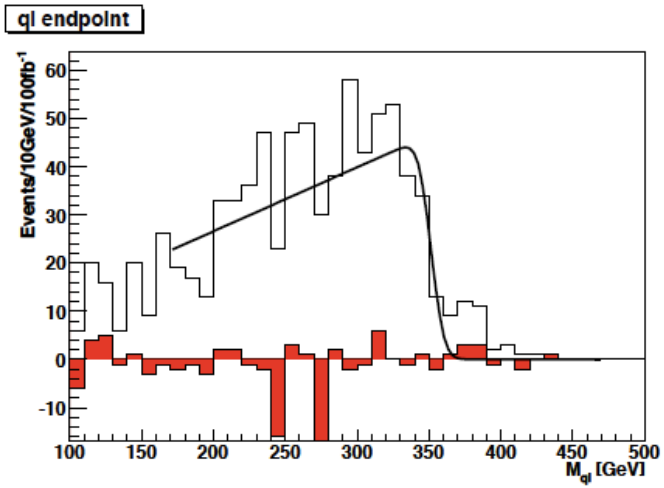
  ⇒ Low energy susy with soft terms from gravity mediation (≈ msugra)

- Stringy output: concrete models are predictive about sparticle spectrum

Ex: MSSM parameters Aparicio, Cerdeno, Ibanez '08

Figure 3: Low-energy supersymmetric spectrum as a function of $\tan\beta$ for $\xi_H = 1/2$, (left) and $\xi_H = 1$ (right) with $M = 400$ GeV and $\mu < 0$. From bottom to top, the solid lines represent the masses of the lightest neutralino, the lightest chargino, and the gluino. Dashed lines display the masses of the lightest stau and lightest sneutrino. Dot-dashed lines correspond to the stop and sbottom masses. Finally, the lightest Higgs mass, the pseudoscalar Higgs mass and the absolute value of the μ parameter are displayed by means of dotted lines. The ruled area for large $\tan\beta$ is excluded by the occurrence of tachyons in the slepton sector.





Ex: spectrum reconstruction from edges
Conlon, Kom, Suruliz, Allanach, Quevedo '07

Figure 15: Reconstructing the spectrum with a clear di-lepton edge from events passing cuts selection B and $M_{qll} < M_{qll}^{max}$: the M_{ql} edge. We expect an edge at 371 GeV from the spectrum. Standard Model background is shown in red.

What is it good for?

- Many realistic vacua: No unique testable prediction

Each particular consistent realistic model is probably wrong
But some general lessons may be right and key to the UV of SM

- New scenarios (in UV complete theory):
Extra dimensions, brane world, warping, ...

- Plausible patterns within each
e.g. Low energy susy and susy breaking soft terms

- Smoking guns for some scenarios (±contrived)
e.g. string resonances in TeV scale models

- Expect interesting impact of LHC results