Prospects in String Phenomenology

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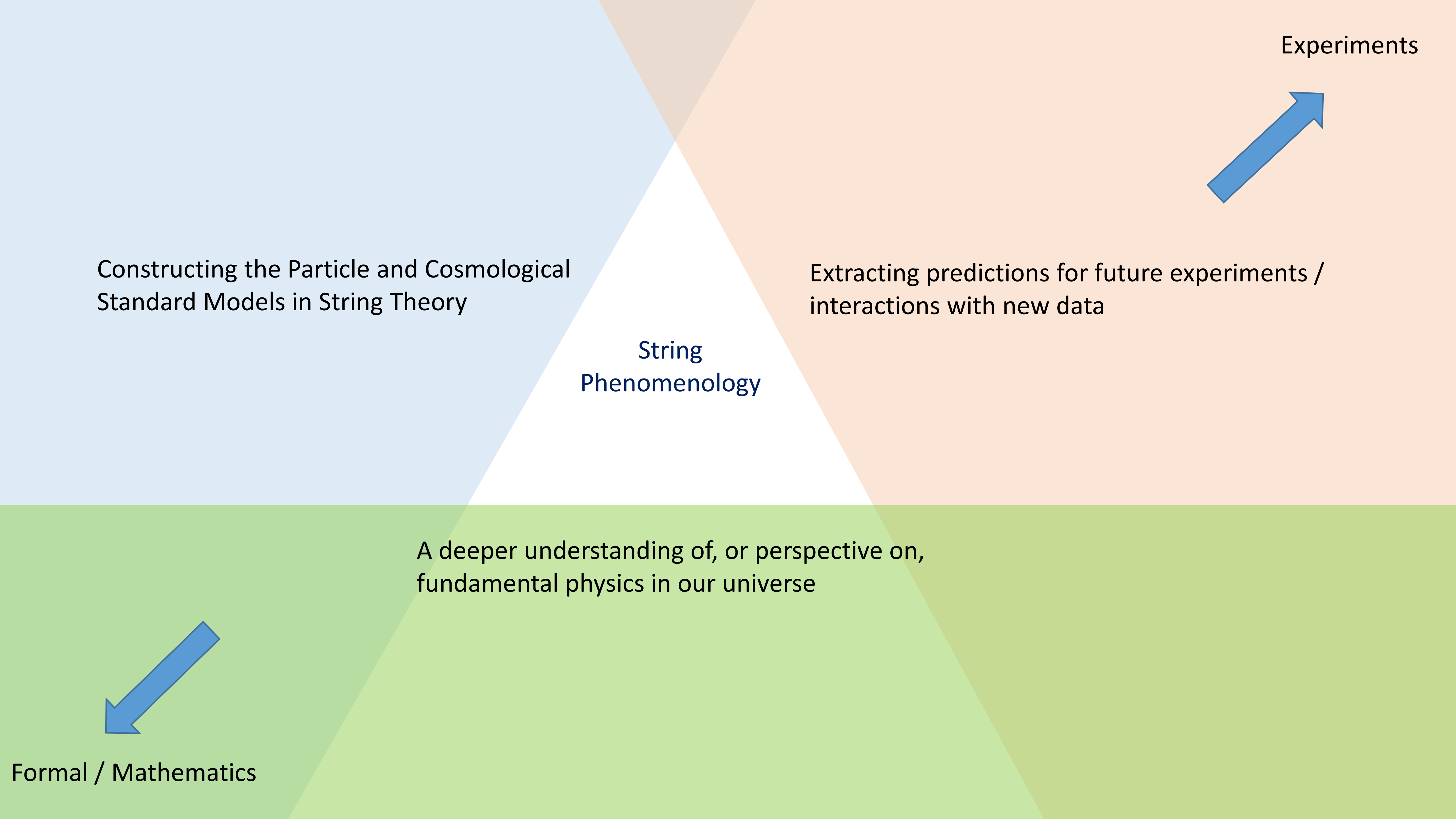
Bad Honnef 2015


Experiments
Constructing the Particle and Cosmological Standard Models in String Theory
Extracting predictions for future experiments / interactions with new data
String Phenomenology
A deeper understanding of, or perspective on, fundamental physics in our universe
Formal / Mathematics

Interactions with LHC results

- Supersymmetry just around the corner
- Susy partners at 10-30 TeV
- Susy partners at $10^{8\text{-}11}$ TeV
- Susy partners at $10^{13\text{-}16}$ TeV
- Z’ Detected
- Strings at the LHC

Supersymmetry around the corner

- How is supersymmetry breaking mediated to the Standard Model?

- Parameterise supersymmetry breaking by an F-term for some spurion field X

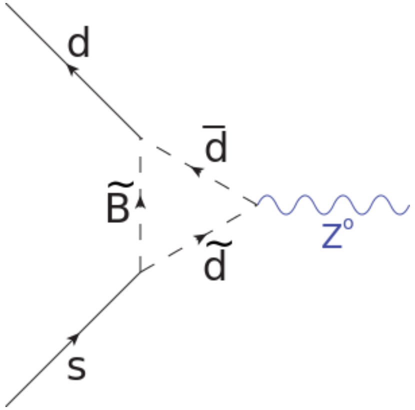
$$\langle F_X \rangle \neq 0, \quad \langle X \rangle = 0.$$

- Soft term masses for the scalar superpartners $\Delta \mathcal{L} = \int d^4\theta \left[\frac{(z_Q)^i_j}{M_P^2} X^\dagger X Q_i^\dagger Q^j + \cdots \right.$

- Tev Masses are given by $m_{\text{susy}} \sim \frac{\langle F_X \rangle}{M_P}. \quad \langle F_X \rangle \sim M_P m_{\text{susy}} \sim (10^{11}\ GeV)^2.$

- But $(z_Q)^i_j$ do not see flavour physics *generically,* since they are gravitationally induced

- Need to understand non-genericness of gravitational physics to explain the absence of Flavour Changing Neutral Currents



Susy partners at 10-30 TeV

- Can avoid constraints from gravity mediated flavour changing neutral currents
- A generic expectation in string theory?
- String theory typically has many moduli fields which couple only gravitationally
- At very high energies they are expected to have String/Planck scale vevs
- The energy stored by such a field is $\rho = \frac{1}{2} m_\sigma^2 \langle \sigma \rangle^2$
- The equation of motion for a scalar field in an expanding universe is $$\frac{\partial^2 \sigma}{\partial t^2} + 3H \frac{\partial \sigma}{\partial t} + \frac{\partial V}{\partial \sigma} = 0$$
- The coupling of the field is gravitational so it has a decay rate $$\Gamma_\sigma = \frac{c}{2\pi} \frac{m_\sigma^3}{\Lambda^2},$$
- It will oscillate and decay to light degrees of freedom at time $t_{\mathrm{decay}} \sim H^{-1} \sim \Gamma_\sigma^{-1}$

Susy partners at 10-30 TeV

- When it decay such a modulus will reheat the universe to a temperature

$$T_{\rm r} = c^{1/2} \left(\frac{10.75}{g_*} \right)^{1/4} \left(\frac{m_\sigma}{50\,\mathrm{TeV}} \right)^{3/2} T_{\rm BBN} \, ,$$

- This must be above the temperature of Big Bang Nucleosynthesis which turns into a bound on the mass of the moduli of around 30-50 TeV

- In many string constructions the masses of the moduli are tied to the scale of supersymmetry breaking

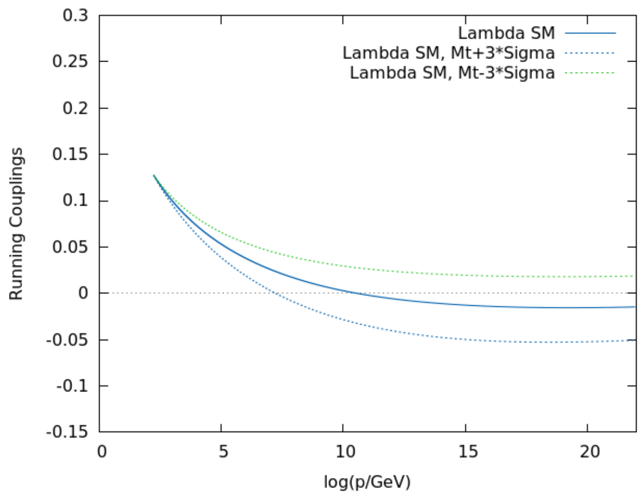
- If SUSY is lower scale how do we avoid the cosmological moduli problem?

- If SUSY is broken at around 30 TeV can we save some form of naturalness?

Susy partners at $10^{8\text{-}11}$ TeV

- A solution to the naturalness problem?

- Interesting scale because in the Standard Model the Higgs quartic coupling vanishes at around that scale



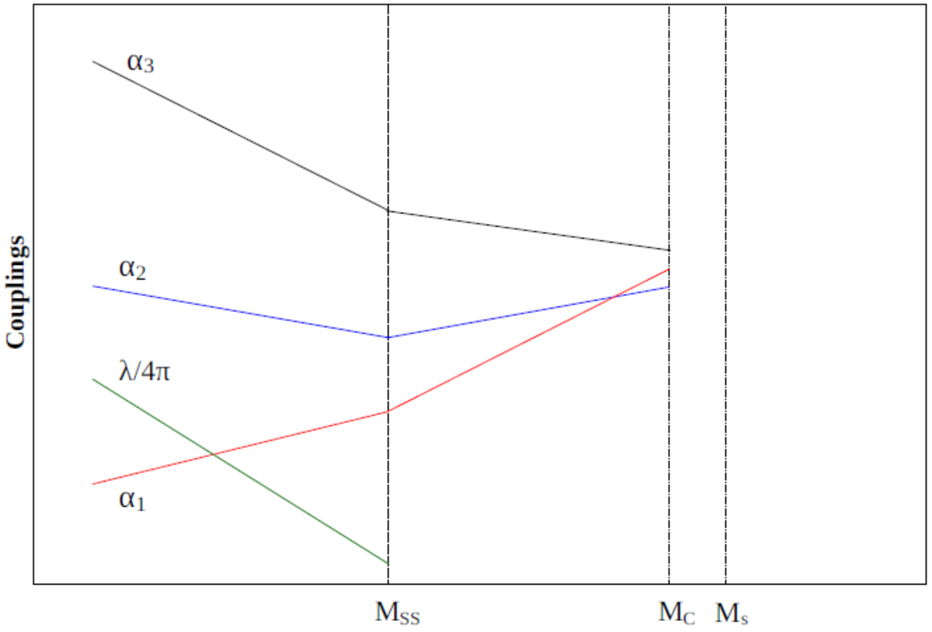
- String theoretic explanation for the vanishing of the quartic coupling?

- String theoretic explanation for why SUSY breaking at that scale?

[Ibanez,Marchesano,Regalado,Valenzuela ‘12] [Hebecker,Knochel,Weigand ‘12]

Susy partners at 10^{8-11} TeV

- Interaction with Grand Unification?
- No precise unification of the gauge couplings



- Can the mis-unification be attributed to string scale effects?

[Ibanez,Marchesano,Regalado,Valenzuela ‘12] [Hebecker,Unwin ‘12]

Susy partners at $10^{13\text{-}16}$ TeV

- Stability of string scale supersymmetry breaking?

- Very little known about the vacuum structure of the theory: manifolds which do not preserve supersymmetry are less constrained

- Einstein's equations are second order while supersymmetry equations are first order

- Recent work on string scale supersymmetry breaking in string theory

[Blaszczyk,Groot Nibbelink,Loukas,Ramos-Sanchez '15] [Abel,Dienes,Mavroudi '15]

- Possible to find some stable configurations but not clear if they survive at higher loops and the non-perturbative level

[Antoniadis,Dudas,Sagnotti '99] …

Interactions with Cosmological results

- Detection of primordial tensor modes See talk by D. Baumann

- Dark radiation: non-SM relativistic degrees of freedom at recombination

$$\rho_{total} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right) .$$

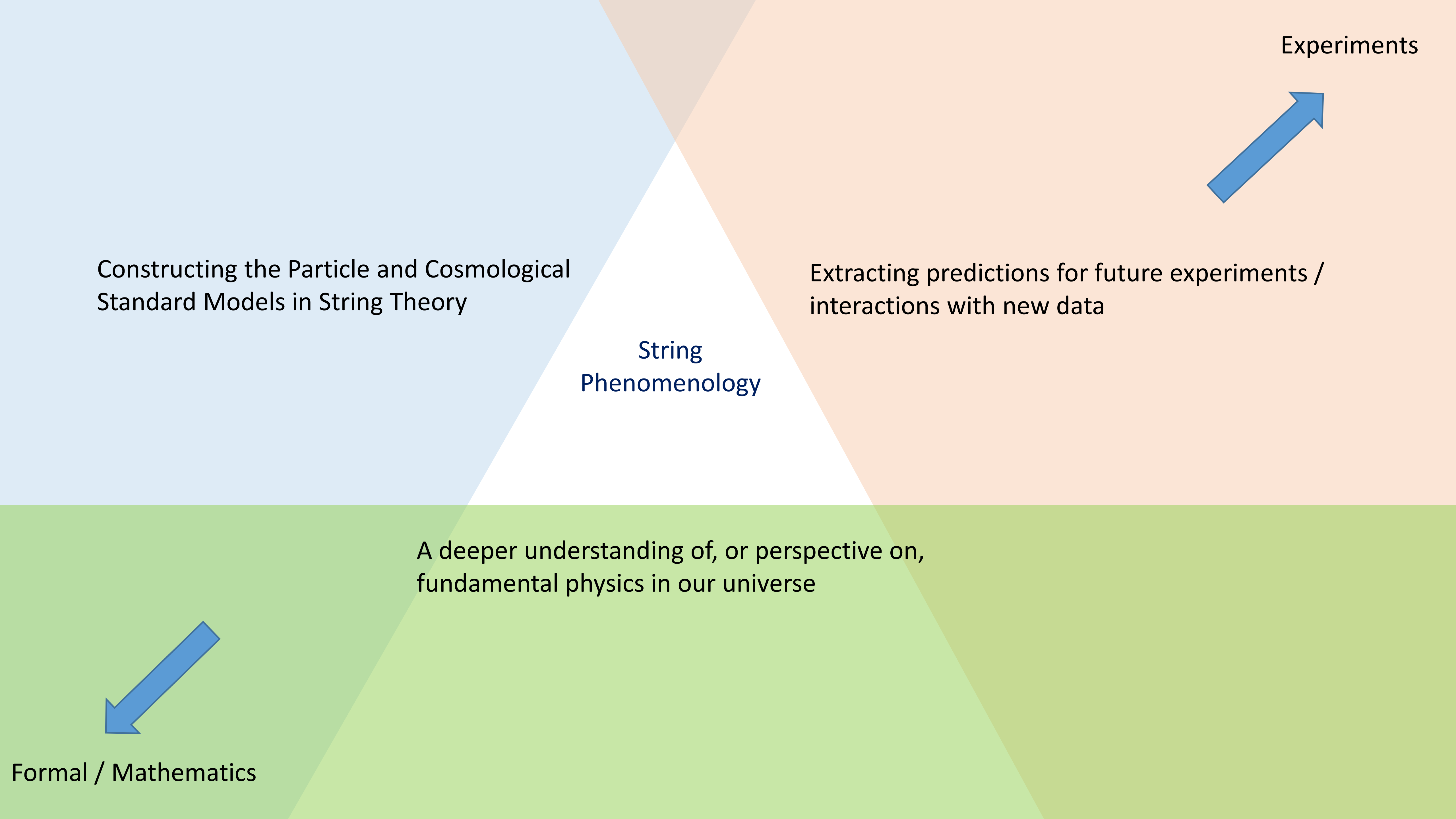
- Current experimental bounds around: Neff=3.28 ± 0.3 at 2 sigma (with HST data: 3.52 ± 0.48)

- This is determined in the UV theory from the branching fraction of the inflaton or last modulus to reheat

$$\Delta N_{eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{\frac{1}{3}} \frac{\rho_{DR}}{\rho_{SM}}\bigg|_{T=T_d} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{\frac{1}{3}} \frac{\Gamma_{\tau_b \to DR}}{\Gamma_{\tau_b \to SM}} ,$$

- Very strongly constrains string models

[Cicoli,Conlon,Quevedo ’12] [Angus,Conlon,Haisch,Powell ‘13] [Hebecker,Mangat, Rompineve,Witkowski ‘14] [Angus ‘14]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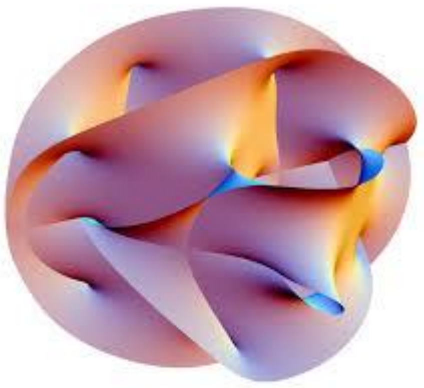
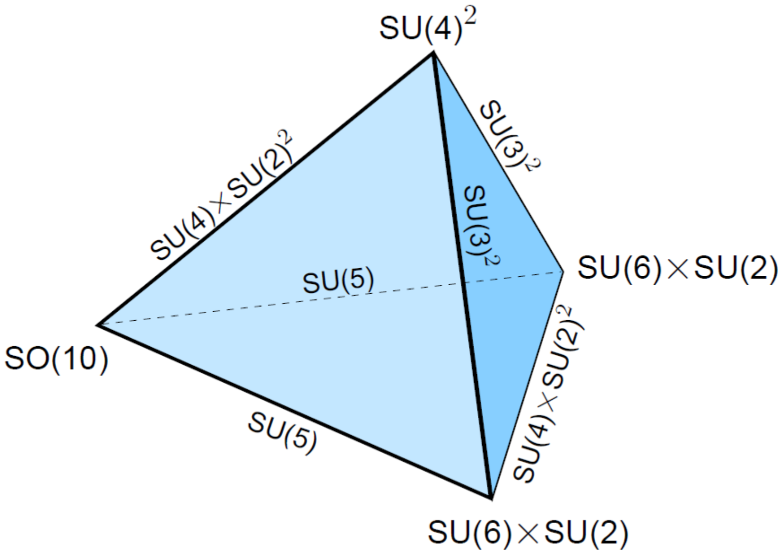
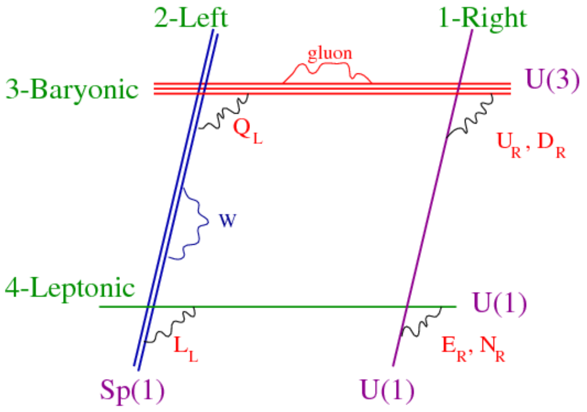
Classic Perturbative String Model Building



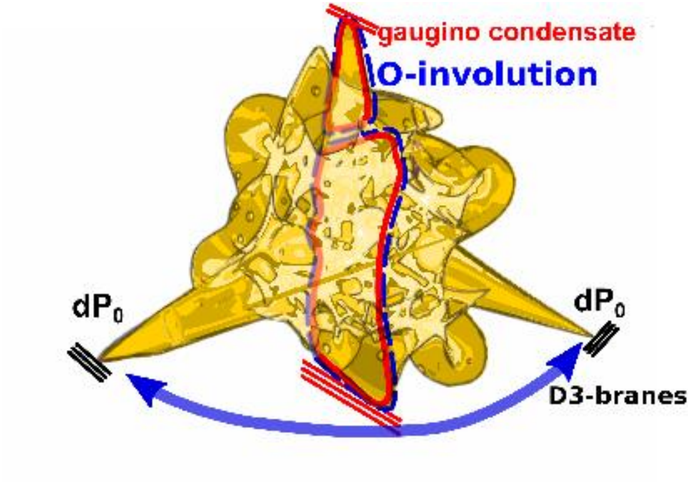
Heterotic on smooth CY manifolds with bundles



Heterotic on orbifolds



Intersecting branes



Branes at singularities

Heterotic orbifold models

- Large number~100 of models with chiral spectrum of MSSM (difficult but possible to decouple vector-like exotics by moving away from the orbifold locus)

  [Lebedev, Nilles, Ramos-Sanchez, Ratz, Vaudrevange ‘08] [Groot Nibbelink, Loukas ’13]

#	irrep	label	#	anti-irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{1/6}$	q_i			
8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{-1/2}$	ℓ_i	5	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{1/2}$	$\bar{\ell}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{1}$	$\bar{e}_i$			
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{-2/3}$	$\bar{u}_i$			
7	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{1/3}$	$\bar{d}_i$	4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{-1/3}$	d_i
4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{1/6}$	v_i	4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{-1/6}$	$\bar{v}_i$
20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{1/2}$	s_i^+	20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{-1/2}$	s_i^-
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{1/2}$	$\tilde{s}_i^+$	2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{-1/2}$	$\tilde{s}_i^-$

#	irrep	label
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{0}$	m_i
2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{0}$	m_i'
47	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{0}$	s_i
26	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{0}$	h_i
9	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{0}$	w_i

- Computer scanning technology developed: Orbifolder

  [Nilles, Ramos-Sanchez, Vaudrevange, Wingerter ’13]

- On-going progress, examples:

  Non-Abelian Orbifolds [Fischer, Ramos-Sanchez, Vaudrevange ’13]

  Discrete and R symmetries [Nilles, Ramos-Sanchez, Ratz, Vaudrevange’13]

- Alternative worldsheet approach through free-Fermionic constructions

  [Faraggi, Mehta ‘13] [Athanasopoulos, Faraggi, Mehta ‘14]

Heterotic line bundle models

- A database of 1000's of models with MSSM spectrum based on Abelian bundles:

  $E_8 \rightarrow SU(5)xS[U(1)^5] \rightarrow SU(3)xSU(2)xU(1)xS[U(1)^5]$

  [Anderson, Constantin, Gray, Lukas, EP '11-'14] [He, Lee, Lukas, Sun '13]

- The spectrum of fields is determined from decomposing the adjoint of E_8

$$E_8 \to SU(5)_{GUT} \times SU(5)_{\perp} \qquad \mathbf{248} \to (\mathbf{24},\mathbf{1}) \oplus (\mathbf{1},\mathbf{24}) \oplus (\mathbf{10},\mathbf{5}) \oplus (\bar{\mathbf{5}},\mathbf{10}) \oplus (\overline{\mathbf{10}},\bar{\mathbf{5}}) \oplus (\mathbf{5},\overline{\mathbf{10}})$$

$$\mathbf{10}_{\mathbf{e}_a}, \ \overline{\mathbf{10}}_{-\mathbf{e}_a}, \ \bar{\mathbf{5}}_{\mathbf{e}_a+\mathbf{e}_b}, \ \mathbf{5}_{-\mathbf{e}_a-\mathbf{e}_b}, \ \mathbf{1}_{\mathbf{e}_a-\mathbf{e}_b}, \ \mathbf{1}_{-\mathbf{e}_a+\mathbf{e}_b} \ ,$$

multiplet	$S(U(1)^5)$ charge	associated line bundle L	contained in
$\mathbf{10}_{\mathbf{e}_a}$	$\mathbf{e}_a$	L_a	V
$\overline{\mathbf{10}}_{-\mathbf{e}_a}$	$-\mathbf{e}_a$	L_a^*	V^*
$\bar{\mathbf{5}}_{\mathbf{e}_a+\mathbf{e}_b}$	$\mathbf{e}_a+\mathbf{e}_b$	$L_a \otimes L_b$	$\wedge^2 V$
$\mathbf{5}_{-\mathbf{e}_a-\mathbf{e}_b}$	$-\mathbf{e}_a-\mathbf{e}_b$	$L_a^* \otimes L_b^*$	$\wedge^2 V^*$
$\mathbf{1}_{\mathbf{e}_a-\mathbf{e}_b}$ $\mathbf{1}_{-\mathbf{e}_a+\mathbf{e}_b}$	$\mathbf{e}_a-\mathbf{e}_b$ $-\mathbf{e}_a+\mathbf{e}_b$	$L_a \otimes L_b^*$ $L_a^* \otimes L_b$	$V \otimes V^*$

- Relatively simple constructions: consider a CY given as an intersection of 4 equations inside the ambient space $(\mathbb{P}^1)^{\times 4} \times \mathbb{P}^3$

$$X = \left(\begin{array}{c|cccc} \mathbb{P}^1 & 1 & 1 & 0 & 0 \\ \mathbb{P}^1 & 0 & 0 & 0 & 2 \\ \mathbb{P}^1 & 0 & 0 & 2 & 0 \\ \mathbb{P}^1 & 2 & 0 & 0 & 0 \\ \mathbb{P}^3 & 1 & 1 & 1 & 1 \end{array}\right)^{5,37}_{-64}$$

- There are 5 Kahler classes inherited from the ambient space, and they have intersection numbers

$$\begin{aligned} d_{123} = d_{124} = d_{134} = d_{234} = d_{235} &= 2 \\ d_{125} = d_{135} = d_{145} = d_{245} = d_{255} = d_{345} = d_{355} &= 4 \\ d_{155} = d_{455} = d_{555} &= 8\,. \end{aligned}$$

- We expand the background flux in terms of this Kahler basis

$$\begin{aligned} V = \bigoplus_{a=1}^{5} L_a = &\ \mathcal{O}_X(1,0,0,-1,0) \oplus \mathcal{O}_X(1,-1,-2,0,1) \oplus \mathcal{O}_X(0,1,1,1,-1) \oplus \\ &\ \mathcal{O}_X(0,-1,1,0,0)_X \oplus \mathcal{O}_X(-2,1,0,0,0)\,. \end{aligned}$$

- With these bundles one finds

$$h^1(X,L_2) = 4\,, \quad h^1(X,L_5) = 2\,. \qquad h^1(X,L_2\otimes L_4) = 4\,, \quad h^1(X,L_4\otimes L_5) = 2\,, \quad h^1(X,L_2\otimes L_5) = 1\,, \quad h^1(X,L_2^*\otimes L_5^*) = 1\,.$$

- The resulting spectrum, after Wilson-line breaking to the Standard Model is

name	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}_1$	$\bar{\mathbf{5}}_2$	$\bar{\mathbf{5}}_3$	H_u	H_d
$S(U(1)^5)$ charge	$\mathbf{e}_2$	$\mathbf{e}_2$	$\mathbf{e}_5$	$\mathbf{e}_2+\mathbf{e}_4$	$\mathbf{e}_2+\mathbf{e}_4$	$\mathbf{e}_4+\mathbf{e}_5$	$-\mathbf{e}_2-\mathbf{e}_5$	$\mathbf{e}_2+\mathbf{e}_5$

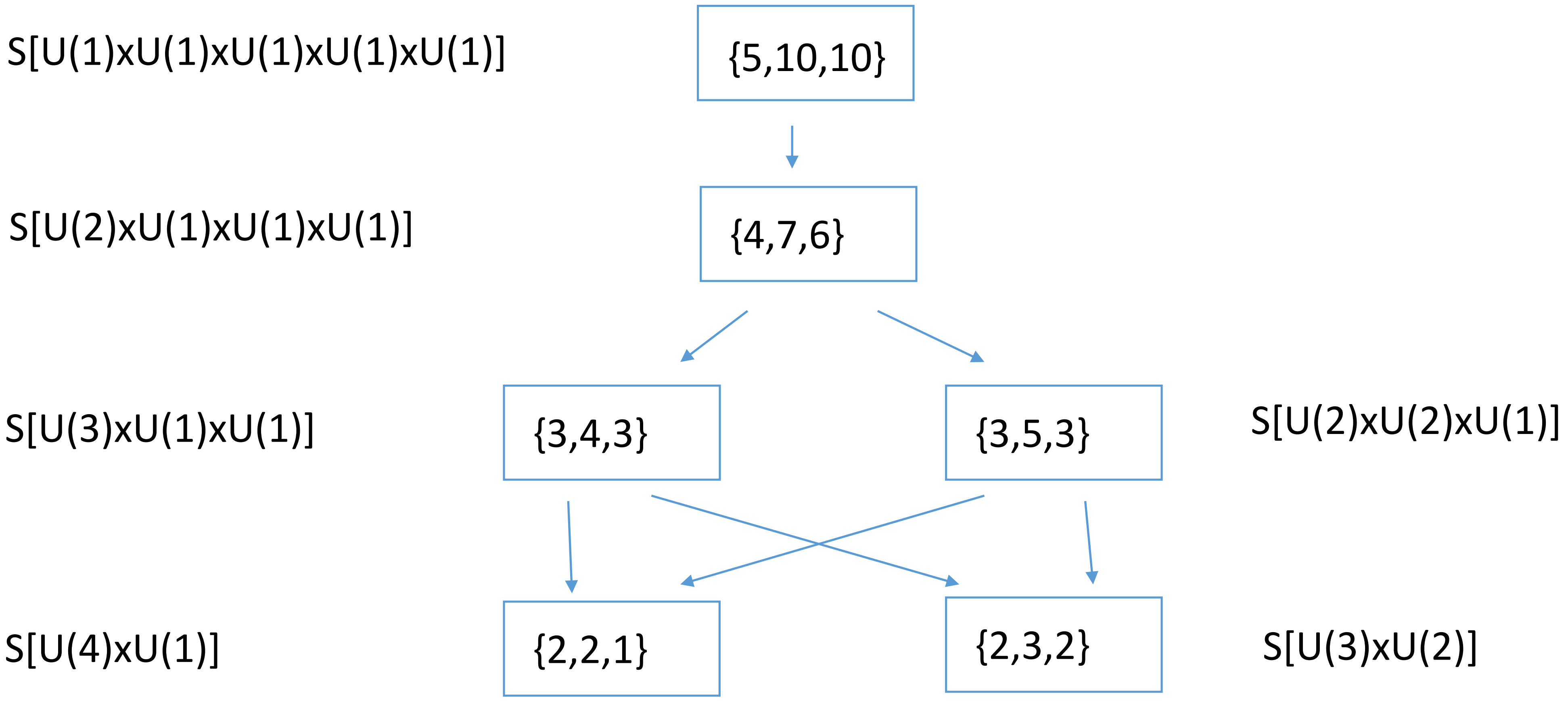
name	C_1	C_2	C_3	C_4	C_5	C_6	C_7
$S(U(1)^5)$ charge	$\mathbf{e}_2-\mathbf{e}_1$	$\mathbf{e}_5-\mathbf{e}_1$	$\mathbf{e}_2-\mathbf{e}_3$	$\mathbf{e}_2-\mathbf{e}_4$	$\mathbf{e}_2-\mathbf{e}_5$	$\mathbf{e}_5-\mathbf{e}_2$	$\mathbf{e}_4-\mathbf{e}_5$
multiplicity	2	4	2	6	5	1	3

- The standard model fields are charged under (massive) U(1) symmetries, leading to selection rules on operators

$$\bar{\mathbf{5}}_{\mathbf{e}_a+\mathbf{e}_b}\bar{\mathbf{5}}_{\mathbf{e}_c+\mathbf{e}_d}\mathbf{10}_{\mathbf{e}_f} \qquad\qquad \mathbf{e}_a+\mathbf{e}_b+\mathbf{e}_c+\mathbf{e}_d+\mathbf{e}_f \qquad (1,1,1,1,1).$$

- Selection rules can be broken by Higgsing GUT singlets, this amounts to a recombination of the bundles to non-Abelian ones. E.g. S[U(1)xU(1)xU(1)xU(1)xU(1)] $\longrightarrow$ S[U(2)xU(1)xU(1)xU(1)]

This generates a type of tree of possible U(1) structures coming from E_8



The different charged states are denoted {#10,#5,#1}

These are all the possibilities for the smooth perturbative heterotic string

The role of exceptional symmetries in string model building?

From a classification perspective the smooth perturbative Heterotic models are on a very different footing to perturbative type II models

Branes / Bundles

	SU(10)
E_8	SU(9)
E_7	SU(8)
E_6	SU(7)
SO(10)	SU(6)
SU(5)	SU(5)
Heterotic	Type II

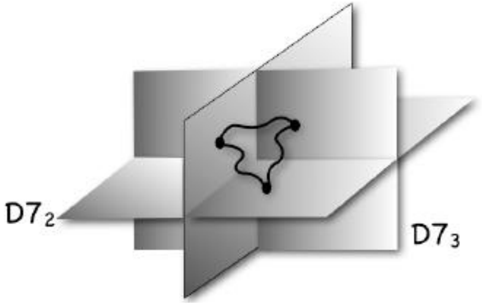
The finiteness of the (compact) exceptional branch translates to restricted model building possibilities

Exceptional structures in IIB/F-theory

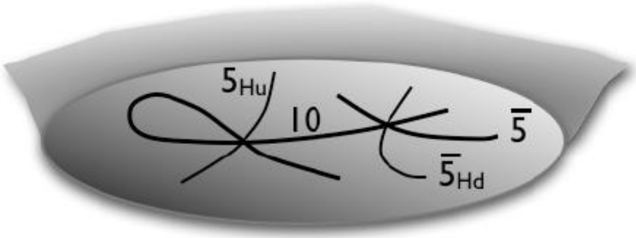
Exceptional symmetries also appear in F-theory model building but in a different format

In F-theory we associate a symmetry to gauge groups / matter representations / Yukawa couplings

✦ Type IIB:



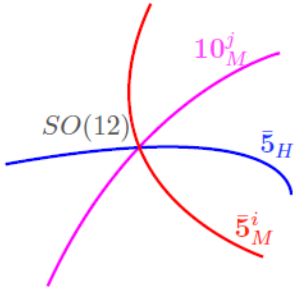
✦ F-theory:



Images from F. Marchesano

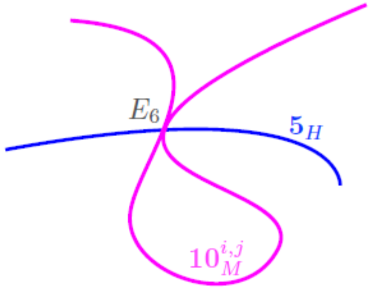
Down-type

$Y_D^{ij} : \bar{\mathbf{5}}_H\, \bar{\mathbf{5}}_M^i\, \mathbf{10}_M^j$



Up-type

$Y_U^{ij} : \mathbf{5}_H\, \mathbf{10}_M^i\, \mathbf{10}_M^j$



$$
\begin{aligned}
E_6 \quad &\supset \quad SU(5) \times U(1)_{a'} \times U(1)_{b'} \,, \\
\mathbf{78} \quad &\to \quad \mathbf{24}^{(0,0)} \oplus \mathbf{1}^{(0,0)} \oplus \mathbf{1}^{(0,0)} \oplus \mathbf{1}^{(-5,-3)} \oplus \mathbf{1}^{(5,3)} \\
&\qquad \oplus (\mathbf{5} \oplus \bar{\mathbf{5}})^{(-3,3)} \oplus (\mathbf{10} \oplus \overline{\mathbf{10}})^{(-1,-3)} \oplus (\mathbf{10} \oplus \overline{\mathbf{10}})^{(4,0)} \,.
\end{aligned}
$$

Exceptional structures in F-theory

[Baume,EP,Schwieger '15]

Are there constraints on possible F-theory models coming from the finiteness of exceptional structures and the existence of an E_6 point?

There are certainly more possibilities than in perturbative Heterotic constructions

For example, consider a theory with 1 U(1). From E_8 we have 2 possibilities:

4-1 Theory: 10_{-4}, 10_1, 5_{-3}, 5_2, 1_5

3-2 Theory: 10_{-2}, 10_3, 5_{-6}, 5_4, 5_{-1}, 1_5

An example F-theory model gives:

BGK: 10_{-1}, 5_{-8}, 5_{-3}, 5_2, 5_7, 1_5, 1_{10}

[Braun,Grimm,Keitel '13]

Is there any connection between the F-theory spectra in the literature and E_8 at all?

A proposition for extending E_8

In the decomposition SU(5)xU(1)^4 the spectrum exhibits the property that there are not enough singlets to make all possible 1 5 5 couplings

$$\mathbf{10}_i : t_i \,, \quad \bar{\mathbf{5}}_{ij} : t_i + t_j \,, \quad \mathbf{1}_{ij} : t_i - t_j \,,$$

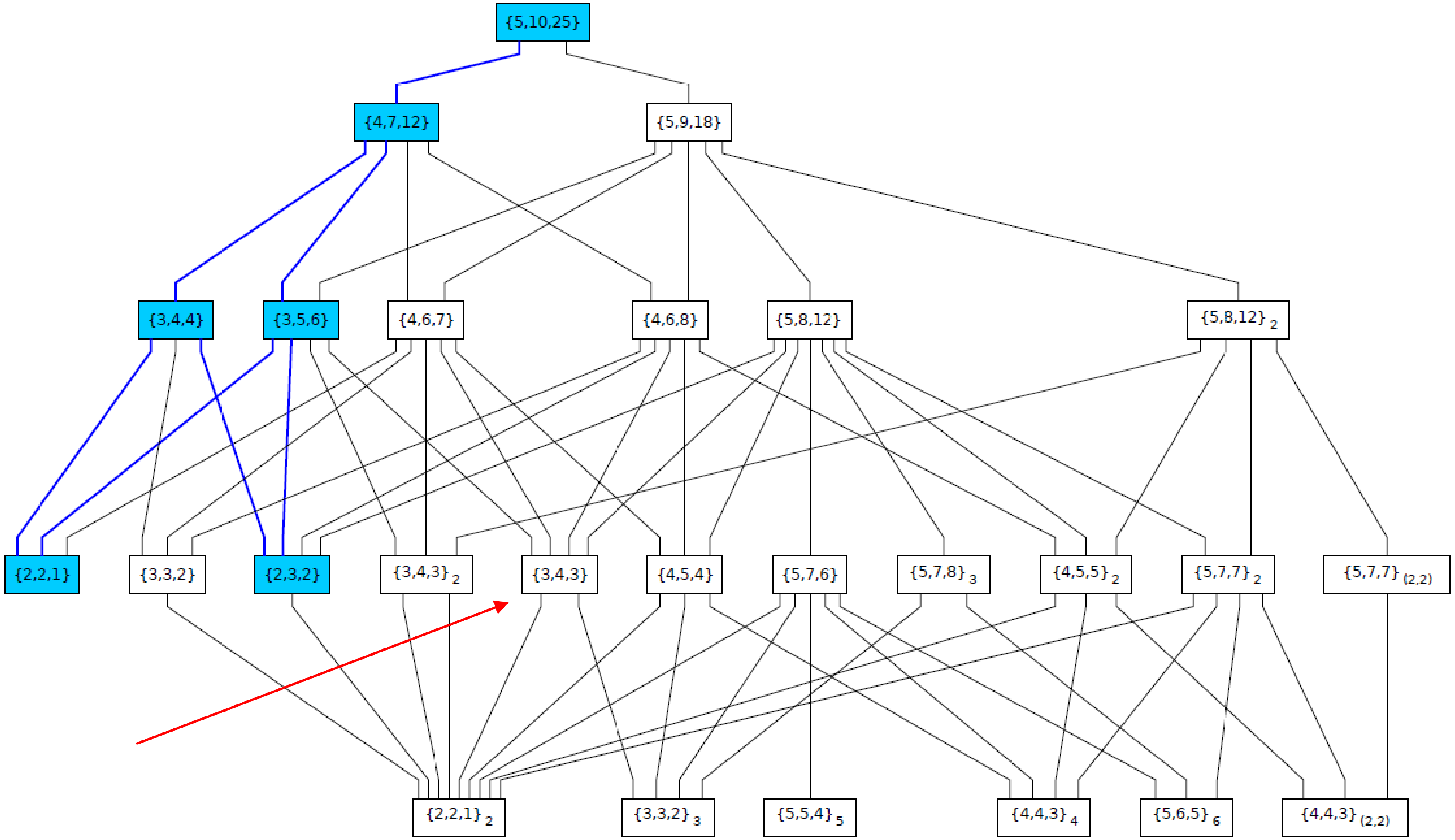
A natural extension is then to include a new set of 15 GUT singlets with charges such that they allow for a 1 5 5 coupling with all the fields

$$\mathbf{1}_{ijkl} : \; t_i + t_j - t_k - t_l$$

Now Higgsing with these new singlets leads to an extended Higgsing tree

The combinatorics are that 4 choose 25 is 12650, but a computer analysis reveals a surprisingly compact structure

Extended E_8 Tree



Looked at 30 fibrations constructed in the literature

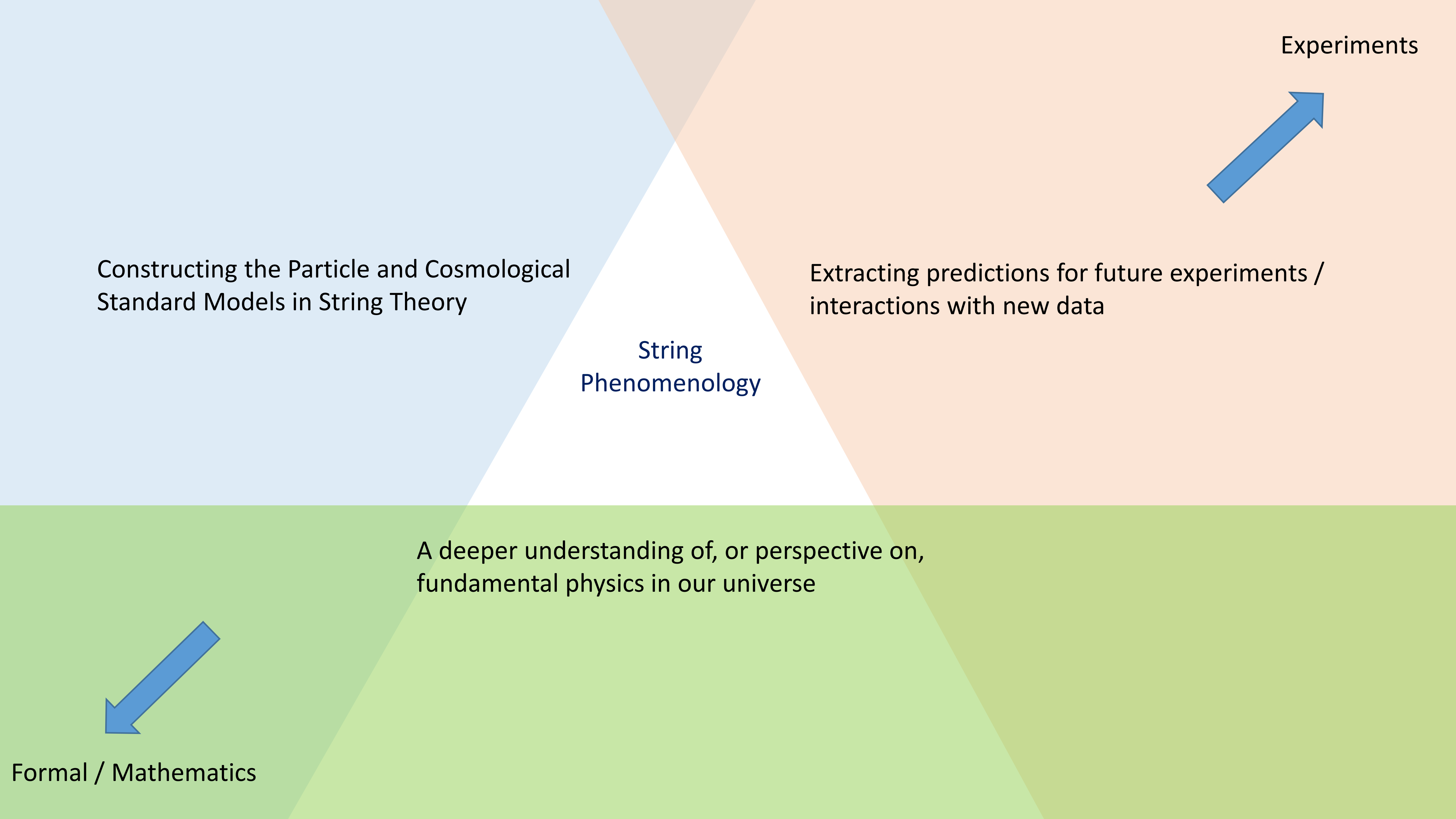
[Borchmann, Braun, Cvetic, Garca-Etxebarria, Grassi, Grimm, Kapfer, Keitel, Klevers, Kuntzler, Lawrie, Mayrhofer, EP, Piragua, Sacco, Schafer-Nameki, Till, Weigand]

Find in total that 1/29 and 27/29 of flat fibrations embeddable in E_8 and our extended set respectively

1 fibration not possible to turn off non-flat loci

2 fibrations can not be embedded even in the extended set

Model	spectrum embedded in
No $U(1)$ models	
[24, 25]	$\{2,2,2\}_2$
[25]	$\{2,2,2\}_2$
One $U(1)$ models	
[12]	$\{3,4,2\}$
[19], [22] fiber type $I_5^{(01)}$	$\{3,3,2\}$
[22] fiber type $I_{5,ncnc}^{(01)}$	$\{3,3,2\}$
[19], [22] fiber type $I_5^{(0\vert 1)}$	$\{4,5,4\}$ or $\mathbf{\{2,3,2\}}$
[19], [22] fiber type $I_{5,nc}^{(0\vert 1)}$	$\mathbf{\{2,3,2\}}$
[19], [22] fiber type $I_{5,nc}^{(0\Vert 1)}$	$\{3,4,3\}$
Two $U(1)$'s models	
[11] $4-1$ split	$\mathbf{\{2,2,1\}}$
[11] $3-2$ split	$\mathbf{\{2,3,2\}}$
Top 1	$\mathbf{\{3,5,6\}}$
Top 2	$\{5,8,12\}$
Top 3	$\{4,6,7\}$
Top 4	$\{4,6,8\}$
[26]	$\{5,8,12\}$
$I_5^{s(0\vert 1\Vert 2)}$ $(2,2,2,0,0,0,0,0)$	$\mathbf{\{3,4,4\}}$, $\{4,6,7\}$, $\{5,8,12\}$ $*$
$I_5^{s(0\vert 1\vert 2)}$ $(2,1,1,1,0,0,1,0)$	$\mathbf{\{3,5,6\}}$
$I_5^{s(0\vert 1\Vert 2)}$ $(2,1,1,1,0,0,1,0)$	$\{5,8,12\}$
$I_5^{s(1\vert 0\vert 2)}$ $(3,2,1,1,0,0,0,0)$	$\{5,8,12\}$
$I_5^{s(01\vert 2)}$ $(3,2,1,1,0,0,0,0)$	$\{4,6,8\}$
$I_5^{s(0\vert 12)}$ $(4,2,0,2,0,0,0,0)$	Not embeddable
$I_5^{s(012)}$ $(5,2,0,2,0,0,0,0)$	Not embeddable
$I_5^{s(01\Vert 2)}$ $(2,2,2,0,0,0,0,0)$	$\{4,6,7\}$
$I_5^{s(0\vert 1\Vert 2)}$ $(2,1,1,1,0,0,0,0)$	$\mathbf{\{3,5,6\}}$ $*$
$I_5^{s(01\Vert 2)}$ $(2,1,1,1,0,0,0,0)$	$\{4,6,7\}$
$I_5^{s(1\vert 0\vert 2)}$ $(2,1,1,1,0,0,0,0)$	$\{5,8,12\}$
$I_5^{s(0\vert 2\Vert 1)}$ $(1,1,1,1,0,0,1,0)$	$\{5,8,12\}$
$I_5^{s(0\vert 1\Vert 2)}$ $(1,1,1,0,0,0,0,0)$	No consistent way to turn off non-flat points.
[15] 2 Fibrations	Any of the 2 $U(1)$ models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A deeper understanding of, or perspective on, fundamental physics in our universe
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Discrete symmetries

Discrete symmetries are often used in particle physics model building. For example matter-parity in the MSSM

They are also interesting from a fundamental physics perspective and in particular in relation to their realisation in theories of quantum gravity

There are good arguments that in any quantum theory of gravity, and in particular string theory, there should not exist global continuous symmetries

It is conjectured that this is so also true for discrete global symmetries but the arguments are less clear for this case

One implication of this is the existence of Z_p charged particles and strings in the UV theory – interesting to understand from a string theory perspective

Consider a U(1) gauge theory broken to Z_p by a p-charged Higgs field

$$\Phi = re^{i\phi} \qquad\qquad A_1 \to A_1 + d\lambda\ , \quad \phi \to \phi + p\lambda$$

Such a theory has Wilson line operators

$$W_A\left(\Sigma_1, n_A\right) = \exp\left[n_A\left(-i\,\phi|_{\partial\Sigma_1} + ip\int_{\Sigma_1} A_1\right)\right]$$

For p=1 this operator can be thought of as an operator creating an electrically charged state at one end of the line and propagating it to the other end, i.e. the world-line of an electric particle, in the limit where the mass of the particle is very large

For p not unity we see that we must have p world-lines ending on one instanton – this is because each such world-line has a discrete Z_p charge and the neutral configuration involves p of them

Completeness conjecture

The completeness conjecture states that for any such operator in the effective quantum field theory, the associated would be particle must actually be a state in the full theory of quantum gravity

The idea is that as we send its mass to infinity it forms a black hole which decays through Hawking radiation to an extremal state of that charge

Therefore in string theory a Z_p discrete symmetry must be accompanied by Z_p charged particles

Consider the magnetic formulation of the Higgsing structure

$$dA_1 = F \rightarrow \star F = \tilde{F} = dV_1 \qquad B_2 \rightarrow B_2 + d\Lambda_1 \;, \quad V_1 \rightarrow V_1 + p\Lambda_1$$

There are therefore also the operators

$$W_B\left(\Sigma_2, n_B\right) = \exp\left[n_B\left(-i\int_{\partial\Sigma_2} V_1 + ip\int_{\Sigma_2} B_2\right)\right]$$

These are p strings ending on a monopole

In string theory we expect a Z_p discrete symmetry to therefore be accompanied by Z_p charged particles and strings

[Banks,Seiberg '10]

This structure has been studied in detail for closed-string Ramond-Ramond U(1)s and given a geometric interpretation

[Camara,Ibanez,Marchesano '10]

[Berasaluce-Gonzalez,Ibanez,Camara,Soler,Montero,Retolaza,Uranga,Ramírez,Regalado,Vazquez-Mercado,Ecker, Honecker,Staessens '10-15]

[Ratz,Vaudrevange,Nilles,Ramos-Sánchez,Trautner,Raby,Ross... '08-15]

Consider type IIA string theory on a Calabi-Yau threefold, with 4-cycles (=2-forms) leading to gauge fields

$$C_3 = A \wedge w^{(2)}$$

D2 branes wrapping the dual 2-cycles give rise to particles charged under the U(1)

The discrete symmetries were associated to a torsional cycle

$$p\,\mathcal{C}_3 = \partial \mathcal{C}_4 \qquad\qquad p\,\tilde{\mathcal{C}}_2 = \partial \tilde{\mathcal{C}}_3 \qquad\qquad d\omega_2 = p\,\alpha_3$$

D4	D4	D2	D2	C_3
Strings	Monopoles	Particles	Instantons	U(1)

We now see the appearance of Z_p charged particles and strings

Can this geometric perspective be realised for “open string” discrete symmetries – for example the MSSM matter parity?

See talks on F-theory…

Summary of Talk

Presented a collection of topics which highlight different aspects of the field of string phenomenology

String pheno is a field at the intersection of multiple aspects of physics (and mathematics)

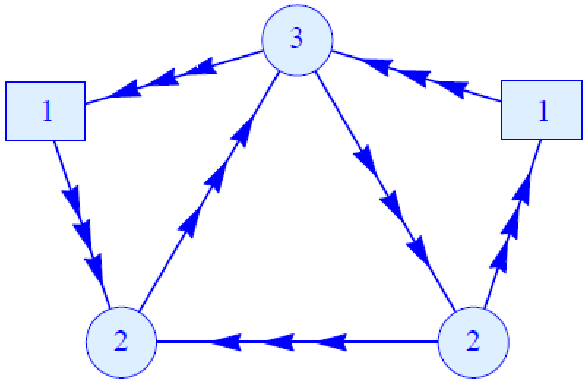
Active research in interactions with experiments, in model building, and in fundamental aspects

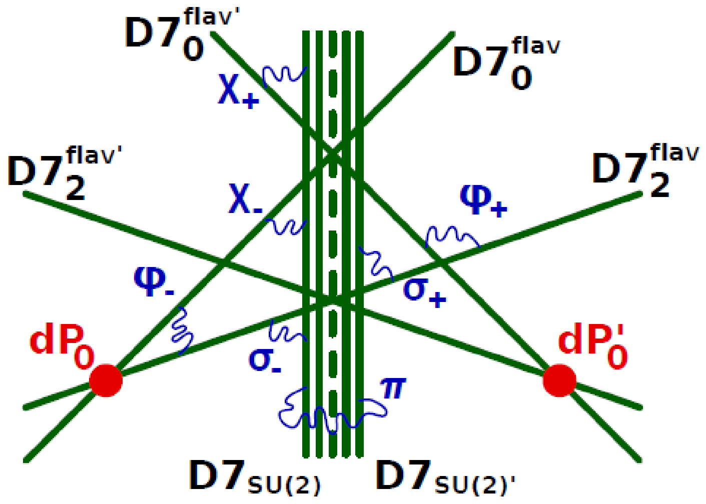
Thanks

Cutting edge in full picture model building: Perturbative IIB

[Cicoli, Krippendorf, Mayrhofer, Quevedo,Valandro '12-13]

- Combine D-branes at singularities with full moduli stabilisation





Matter spectrum is quite good, typically most serious issues are multiple Higgses.

Progress on the issue of uplifting to de-Sitter but more remains to be explicitly calculated