Review of Model Building in String Theory

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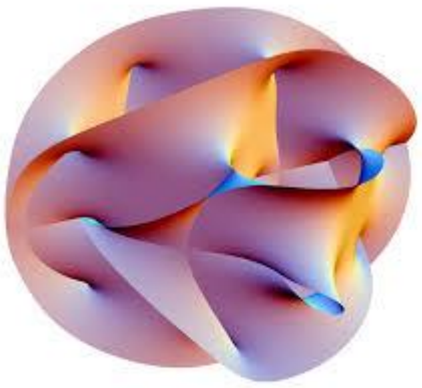
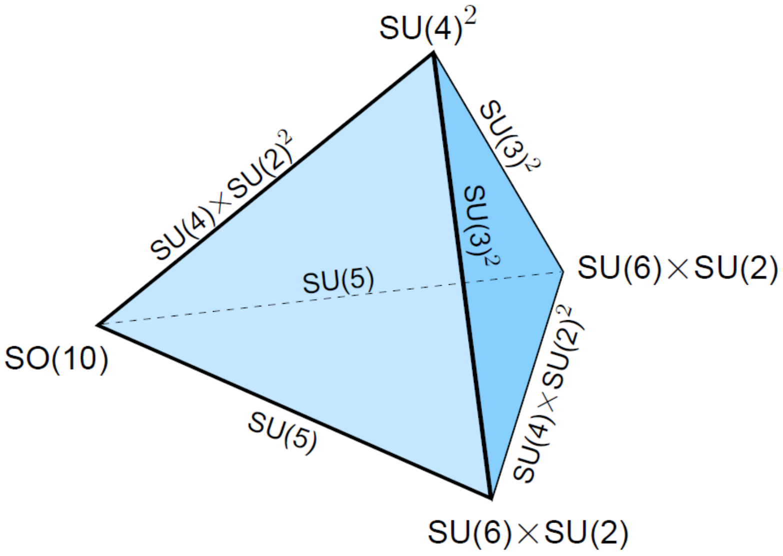
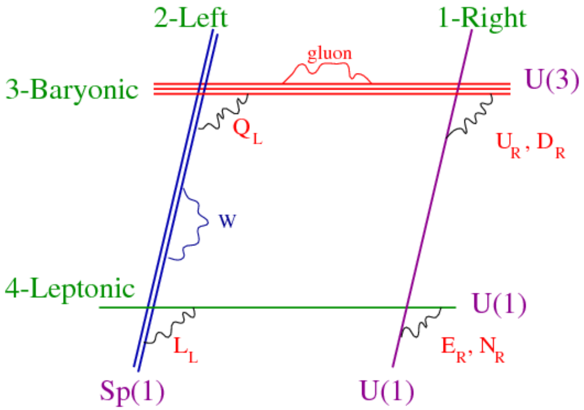
Classic Perturbative String Model Building



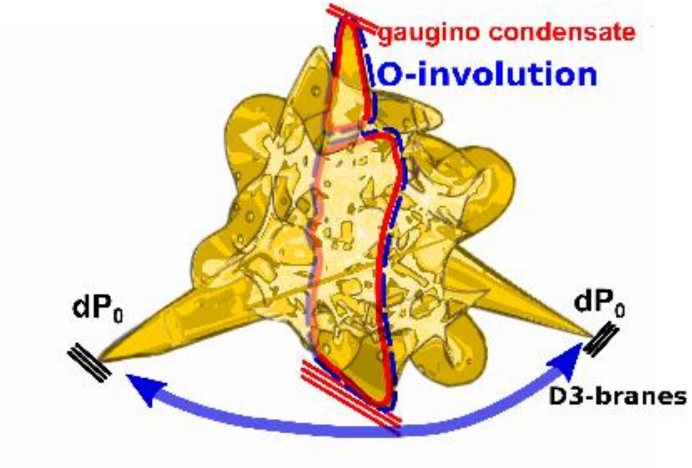
Heterotic on smooth CY manifolds with bundles



Heterotic on orbifolds



Intersecting branes



Branes at singularities

Heterotic on Calabi-Yau manifolds

- A few models with MSSM spectrum models based on Non-Abelian bundles

  [Braun, He, Ovrut, Pantev '05] [Anderson, Gray, He, Lukas '09] [Braun, Candelas, Davies, Donagi '11]

  [Braun, He, Ovrut '13]

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

  $E_8 \rightarrow SU(5) \times S[U(1)^5] \rightarrow SU(3) \times SU(2) \times U(1) \times S[U(1)^5]$

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

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

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

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	$\mathbf{e}_2$	$\mathbf{e}_2$	$\mathbf{e}_5$	$\mathbf{e}_2+\mathbf{e}_4$	$\mathbf{e}_2+\mathbf{e}_4$	$\mathbf{e}_4+\mathbf{e}_5$	$-\mathbf{e}_2-\mathbf{e}_5$	$\mathbf{e}_2+\mathbf{e}_5$

- Progress in understanding bundle moduli space and in particular enhancements from Abelian to non-Abelian bundles

  [Buchbinder, Constantin, Lukas '13] [Buchbinder, Constantin, Lukas '14]

Heterotic on Orbifolds

- 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]

Type II Intersecting branes

- Some ~MSSM models, reached scanning stages

  [Gmeiner, Blumenhagen, Honecker, Lust, Weigand ‘08][Gmeiner, Honecker ’08]

- Study when there are exact discrete symmetry remnants of gauge symmetries

  [Berasaluce-Gonzalez, Ibanez, Soler, Uranga ’11]

  [Honecker, Staessens ‘13] [Berasaluce-González, Montero, Retolaza, Uranga ‘13] [Berasaluce-González, Ramírez, Uranga ‘13] [Marchesano, Regalado, Vázquez-Mercado ’13] [Abe, Kobayashi, Ohki, Sumita, Tatsuta ‘14]

- One of the best understood frameworks for physics of U(1) fields, espcially kinetic mixing

  [Abel, Goodsell, Jaeckel, Khoze, Ringwald ‘08] [Bullimore, Conlon, Witkowski ‘10] [Shiu, Soler, Ye ‘13] [Marchesano, Regalado, Zoccarato ’14] + …

Type IIB branes at singularities

- Some ~MSSM models, can study flavour structure by moving away from singular locus

  [Dolan, Krippendorf, Quevedo ’11]

- Significant progress in embedding into global models

  [Cicoli, Klevers, Krippendorf, Mayrhofer, Quevedo, Valandro ’13]

F-theory

- Since 1995 we have known that the perturbative string theories are limits of the more unified framework of M-theory

- A fundamental description of M-theory is unknown (M=Missing?), but we know the low energy limit: 11D supergravity, and we know some of the objects M2/M5 branes

- We also know that physics associated to the string coupling is geometrised in M-theory as an extra dimension

- This fundamental insight has remained essentially unused in string phenomenology, and the development of F-theory model building is an attempt at incorporating this insight into the field

- The most basic dictionary entry between M-theory geometry and String theory is that the size of the extra dimension of M-theory is the string coupling

- Much of the work on F-theory, particularly over the past 2-3 years, has been on writing this dictionary between geometry and physics, to a sufficiently sophisticated level for model building

- F-theory is also an appropriate arena for phenomenologically realistic GUT model building

- In minimal SU(5) GUT, the top quark Yukawa coupling 5 10 10 requires the presence of exceptional gauge symmetries

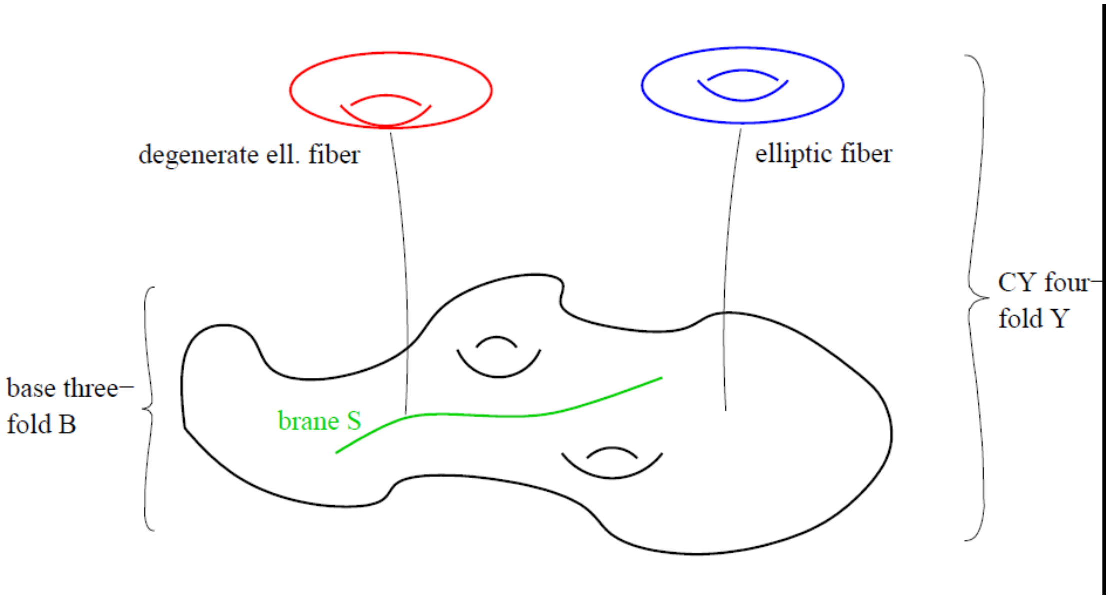
$$
\begin{aligned}
E_6 &\supset SU(5)\times U(1)_{a'}\times U(1)_{b'}\ , \\
\mathbf{78} &\rightarrow \mathbf{24}^{(0,0)}\oplus\mathbf{1}^{(0,0)}\oplus\mathbf{1}^{(0,0)}\oplus\mathbf{1}^{(-5,-3)}\oplus\mathbf{1}^{(5,3)} \\
&\quad \oplus(\mathbf{5}\oplus\bar{\mathbf{5}})^{(-3,3)}\oplus(\mathbf{10}\oplus\bar{\mathbf{10}})^{(-1,-3)}\oplus(\mathbf{10}\oplus\bar{\math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

- F-theory is defined as a certain limit in M-theory moduli space

- Consider compactifications of M-theory on a Calabi-Yau fourfold which has a torus fibration, and shrink the volume of the torus to zero [Vafa '96]

- This describes the T-dual configuration to a 4-dimensional N=1 compactification of type IIB string theory

- Some 7-brane data is geometrised as the singularity structure of the CY 4-fold



[Image from talk by Weigand]

La Prima Donna: The Torus

- A lot of, but not all, information is encoded just in the fibration without specifying the base

  Often one would just specify the fibration: an equation describing a torus which behaves in certain ways as a function of the parameters in the equation

  It is important to note that not all fibrations can be combined with all bases to form a CY four-fold: there are compatibility conditions which must be checked

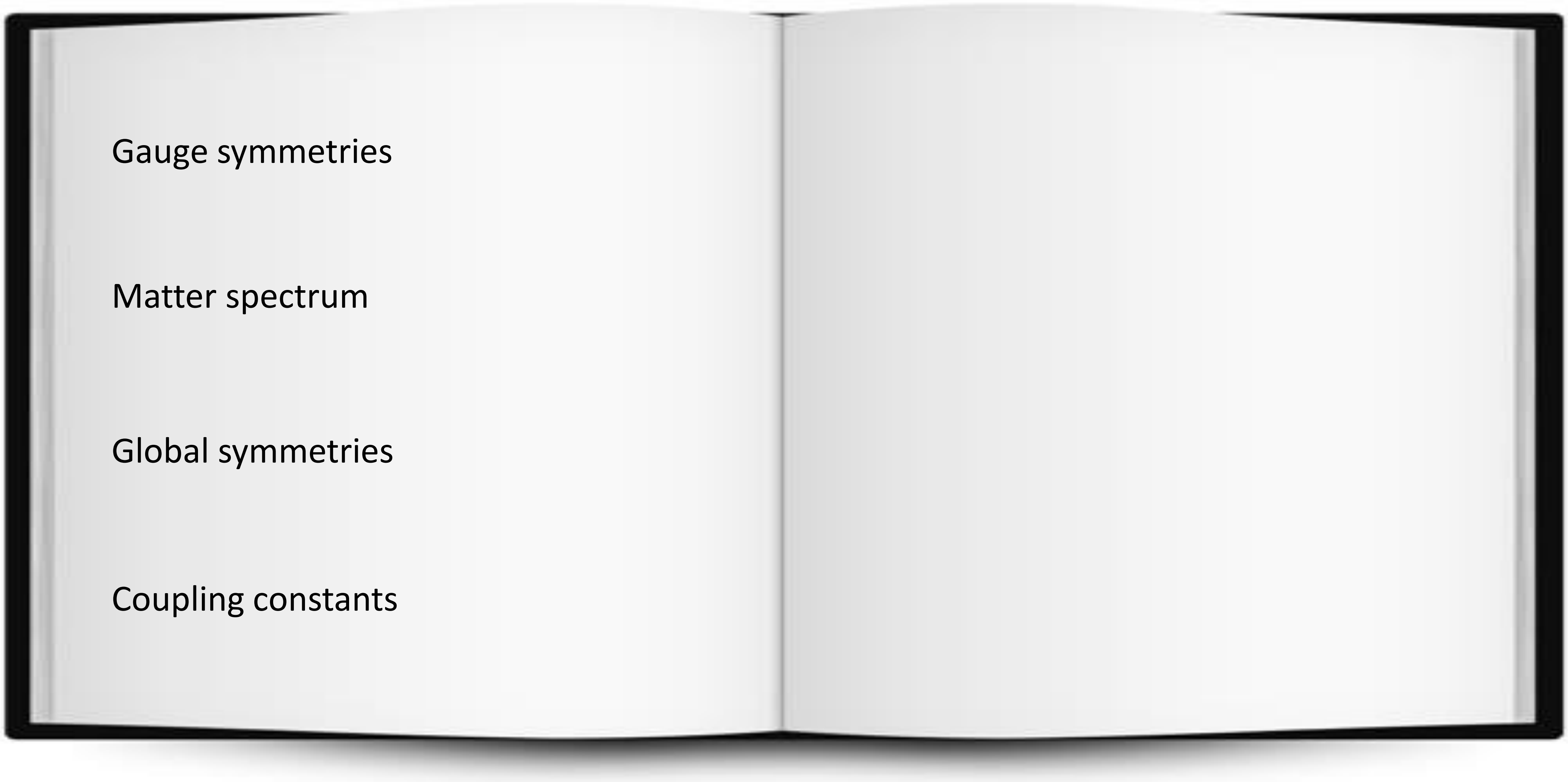
- This is the analogue of discussing the brane content of a string compactification without specifying the CY geometry explicitly

  For example the equation for the torus in Weierstrass form is :

$$y^2 = x^3 + fxz^4 + gz^6 \qquad (x, y, z) \simeq (\lambda^2 x, \lambda^3 y, \lambda^1 z) \leftrightarrow \mathbb{P}_{2,3,1}$$

A dictionary for Model Builders

In building a model of particle physics we would like to specify…



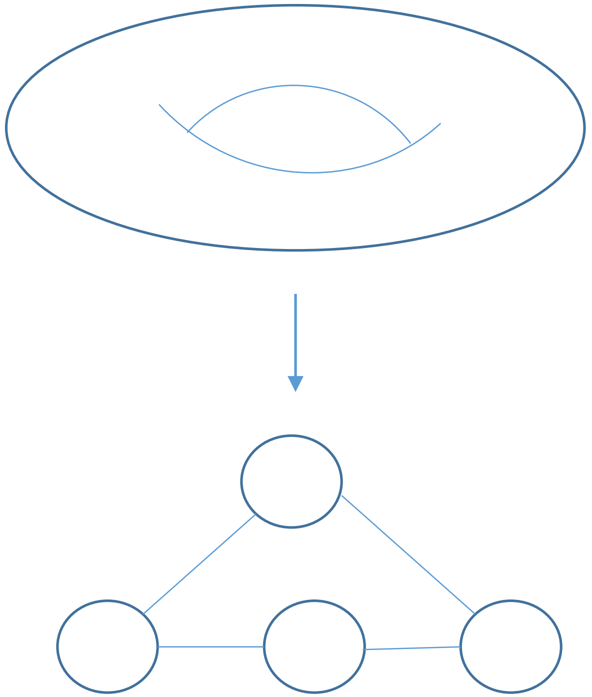
Gauge symmetries

- Non-Abelian gauge symmetries are associated to divisors on which the discriminant of the fibration vanishes to some order

$$y^2 = x^3 + fxz^4 + gz^6 \qquad (x, y, z) \simeq (\lambda^2 x, \lambda^3 y, \lambda^1 z) \leftrightarrow \mathbb{P}_{2,3,1}$$

$$\Delta = 4f^3 + 27g^2$$

ord(f)	ord(g)	ord(Δ)	fiber type	singularity type
≥ 0	≥ 0	0	smooth	none
0	0	n	I_n	A_{n-1}
≥ 1	1	2	II	none
1	≥ 2	3	III	A_1
≥ 2	2	4	IV	A_2
2	≥ 3	$n+6$	I_n^*	D_{n+4}
≥ 2	3	$n+6$	I_n^*	D_{n+4}
≥ 3	4	8	IV^*	E_6
3	≥ 5	9	III^*	E_7
≥ 4	5	10	II^*	E_8



- The fibre pinches and can be resolved into intersecting spheres recreating the associated Dynkin diagram
- Note: the resolution is a tool for studying the geometry, the physical F-theory limit has vanishing fibre volume
- Note: this gives the gauge algebra, gauge group can depend on Mordel-Weil torsion

[Aspinwall, Morrison '98] [Mayrhofer, Morrison, Till, Weigand '14]

- (Massless) Abelian gauge groups are associated to divisors which intersect the fibre at one point, otherwise known as sections of the fibration

[Morrison, Vafa ’96]

- Much recent work on studying fibrations which have multiple sections which are easy to identify

Fibration	Ambient	Sections with generic coefficients
$y^2 = x^3 + f x z^4 + g z^6$	$\mathbb{P}_{[2,3,1]}$	1
$y^2 = x^3 + a_1 x y z + a_2 x^2 z^2 + a_3 y z^3 + a_4 x z^4 + a_6 z^5$	$\mathbb{P}_{[2,3,1]}$	1
$\mathrm{B}\,\mathrm{v}^2\,\mathrm{w} + s\,\mathrm{w}^2 = \mathrm{C}_3\,\mathrm{v}^3\,\mathrm{u} + \mathrm{C}_2\,s\,\mathrm{v}^2\,\mathrm{u}^2 + \mathrm{C}_1\,s^2\,\mathrm{v}\,\mathrm{u}^3 + \mathrm{C}_0\,s^3\,\mathrm{u}^4$	$\mathbb{P}_{[1,1,2]}$	2
$p_T = \mathrm{v}\,\mathrm{w}(c_1\,\mathrm{w} + c_2\,\mathrm{v}) + \mathrm{u}\,(b_0\,\mathrm{v}^2 + b_1\,\mathrm{v}\,\mathrm{w} + b_2\,\mathrm{w}^2) + \mathrm{u}^2(d_0\,\mathrm{v} + d_1\,\mathrm{w} + d_2\,\mathrm{u}).$	$\mathbb{P}_{[1,1,1]}$	3
[Cvetic, Klevers, Piragua, Song ‘14]	$\mathbb{P}_{[1,1,1,1]}$	4

[Morrison, Park ’12] [Borchmann,Mayrhofer, EP, Weigand ’13][Cvetic, Klevers, Piragua ‘13][Braun, Grimm, Keitel ,13]
[Grimm Weigand ’10]

Combining Abelian and Non-Abelian Gauge symmetries

- To combine the two just need to require certain vanishing order of the coefficients of the fibrations over a divisor that supports the non-Abelian symmetry

- Can map to Weierstrass form by coordinate change and read off the required vanishing order of f and g, or can do directly using the toric technology of tops

- Example of an SU(5)xU(1)xU(1) fibration

$$0 = b_{0,1} w \mathrm{u} \mathrm{v}^2 s_0^2 + d_{0,1} w \mathrm{u}^2 \mathrm{v} s_0^2 s_1 + d_{2,1} w \mathrm{u}^3 s_0^2 s_1^2 + c_{2,2} w^2 \mathrm{v}^2 \mathrm{w} s_0 + b_1 \mathrm{u} \mathrm{v} \mathrm{w} s_0 s_1 \\ + d_1 \mathrm{u}^2 \mathrm{w} s_0 s_1^2 + c_{1,1} w \mathrm{v} \mathrm{w}^2 s_1 + b_2 \mathrm{u} \mathrm{w}^2 s_1^2 \, .$$

- Note that there are 2 types of ways to engineer gauge symmetries: by specifying just the vanishing order of the coefficients (torically) or by also specifying certain relations between them (non-toric)

- Examples of fibrations with Abelian and non-Abelian gauge symmetries that arise from special relations between the coefficients

[Grimm, Weigand '10] [Mayrhofer, EP, Weigand '12] [Kuntzler, Schafer-Nameki '14]

The matter representations

[Borchmann,Mayrhofer,EP,Weigand '13]

- At the end each such construction gives the possible matter representations

$$0 = b_{0,1} w \mathrm{u} \mathrm{v}^2 s_0^2 + d_{0,1} w \mathrm{u}^2 \mathrm{v} s_0^2 s_1 + d_{2,1} w \mathrm{u}^3 s_0^2 s_1^2 + c_{2,2} w^2 \mathrm{v}^2 \mathrm{w} s_0 + b_1 \mathrm{u} \mathrm{v} \mathrm{w} s_0 s_1$$
$$+ d_1 \mathrm{u}^2 \mathrm{w} s_0 s_1^2 + c_{1,1} w \mathrm{v} \mathrm{w}^2 s_1 + b_2 \mathrm{u} \mathrm{w}^2 s_1^2 \,.$$

Curve (on $w=0$)	matter representation
$\{b_1 = 0\}$	$\mathbf{10}_{2,2} + \overline{\mathbf{10}}_{-2,-2}$
$\{b_{0,1} = 0\}$	$\mathbf{5}_{-4,1} + \overline{\mathbf{5}}_{4,-1}$
$\{b_2 = 0\}$	$\mathbf{5}_{-4,-4} + \overline{\mathbf{5}}_{4,4}$
$\{c_{1,1} = 0\}$	$\mathbf{5}_{1,6} + \overline{\mathbf{5}}_{-1,-6}$
$\{b_{0,1}c_{1,1} - b_1 c_{2,2} = 0\}$	$\mathbf{5}_{1,-4} + \overline{\mathbf{5}}_{-1,4}$
$\{b_{0,1}d_1^2 - b_1 d_{0,1} d_1 + b_1^2 d_{2,1} = 0\}$	$\mathbf{5}_{1,1} + \overline{\mathbf{5}}_{-1,-1}$

$C_{\mathbf{1}^{(1)}} : \mathbf{1}_{5,-5} + c.c.,\quad C_{\mathbf{1}^{(2)}} : \mathbf{1}_{5,0} + c.c.,\quad C_{\mathbf{1}^{(3)}} : \mathbf{1}_{-5,-10} + c.c.,$

$C_{\mathbf{1}^{(4)}} : \mathbf{1}_{-5,-5} + c.c.,\quad C_{\mathbf{1}^{(5)}} : \mathbf{1}_{0,10} + c.c.,\quad C_{\mathbf{1}^{(6)}} : \mathbf{1}_{0,5} + c.c.$

Point (on $w=0$)	Yukawa coupling
$\{c_{1,1} = b_2 = 0\}$	$\mathbf{5}_{-4,-4}\overline{\mathbf{5}}_{-1,-6}\mathbf{1}_{5,10}$
$\{b_{0,1}c_{1,1} - b_1 c_{2,2} = b_2 = 0\}$	$\mathbf{5}_{-4,-4}\overline{\mathbf{5}}_{-1,4}\mathbf{1}_{5,0}$
$\{b_{0,1}d_1^2 - b_1 d_{0,1} d_1 + b_1^2 d_{2,1} = b_2 = 0\}$	$\mathbf{5}_{-4,-4}\overline{\mathbf{5}}_{-1,-1}\mathbf{1}_{5,5}$
$\{c_{1,1} = c_{2,2} = 0\}$	$\mathbf{5}_{1,6}\overline{\mathbf{5}}_{-1,4}\mathbf{1}_{0,-10}$
$\{c_{1,1} = b_{0,1}d_1^2 - b_1 d_{0,1} d_1 + b_1^2 d_{2,1} = 0\}$	$\mathbf{5}_{1,6}\overline{\mathbf{5}}_{-1,-1}\mathbf{1}_{0,-5}$
$\{b_{0,1}c_{1,1} - b_1 c_{2,2} = b_{0,1}d_1^2 - b_1 d_{0,1} d_1 + b_1^2 d_{2,1} = 0\}$	$\mathbf{5}_{1,-4}\overline{\mathbf{5}}_{-1,-1}\mathbf{1}_{0,5}$

- To determine the actual massless matter need to know the background flux…

A dictionary for Model Builders

In building a model of particle physics we would like to specify…

Gauge symmetries

Matter spectrum

Global symmetries

Coupling constants

Elliptic fibration form and constraints on coefficients

The matter spectrum and G_4 flux

- The key player in the matter spectrum is the background flux

$$G_4 \in H^{2,2}\left(Y^4\right)$$

→ 'Closed String Flux'

↓ 'One leg along fibre'

'Open String Flux'

$$H^{2,2}_{\text{Vert}} = H^{1,1} \wedge H^{1,1}$$

Massless U(1) fluxes: flux in base x U(1) generator

$$G = F \wedge w_{U(1)}$$

$$H^{2,2}_{\text{Hor}} \neq H^{1,1} \wedge H^{1,1}$$

Massive/projected out U(1) fluxes?

[Braun, Collinucci, Valandro '11,'14]

'Spectral Cover Flux': A flux using the SU(5) generators

[Grimm, Weigand '10] [Braun, Collinucci, Valandro '11] [Krause, Mayrhofer, Weigand '11] [Grimm, Hayashi '11] [Marsano, Schafer-Nameki '11] …

Possible to classify G_{Ver} on specific bases, for example P^3

[Cvetič, Grassi, Klevers, Piragua '14]

The matter spectrum and G_4 flux

- Over a matter curve the fibre enhances further from the gauge theory Dynkin diagram
- A matter representation is associated to some combination of spheres in the fibre along with the matter curve to form a matter surface C_R

  [Krause, Mayrhofer, Weigand '11] [Grimm, Hayashi '11] [Marsano, Schafer-Nameki '11] [Kuntzler, Schafer-Nameki '12] [Lawrie, Schäfer-Nameki '12] [Hayashi,Lawrie, Schäfer-Nameki '13] [Hayashi,Lawrie, Morrison,Schäfer-Nameki '13]
- The prescription for the chiral index computation for a given matter representation R

$$\chi = \int_{C_R} G_4 \xrightarrow{\text{U(1) flux}} q_R \int_C F$$

- Can use to build 3 (chiral) generation GUT models [Krause, Mayrhofer, Weigand '11]
- Vector-like spectrum remains a difficult problem
- Progress in terms of Chow groups and Deligne Cohomology [Bies, Mayrhofer, Pehle, Weigand '14]

  [see also Anderson, Heckman, Katz '13]

Open Challenge: Hypercharge Flux

- One of the most interesting ideas to emerge from F-theory is Hypercharge flux GUT breaking

[Buican et al. '06] [Donagi, Wijnholt '08][Beasley, Heckman, Vafa '08]

SU(5) → SU(3)x SU(2)x$U(1)_Y$

- Hypercharge generator remains massless if hypercharge flux satisfies

$$\int_S f_Y \wedge \iota^* \omega_\alpha = 0 \qquad \forall \quad \omega_\alpha \in H^2_+(X).$$

Most general possibility not yet understood in F-theory

[Buican et al. '06] [Mayrhofer, EP, Weigand '13]
[Braun, Collinucci, Valandro '14]

- Also from IIB we know that hypercharge flux can split the gauge couplings, to some extent

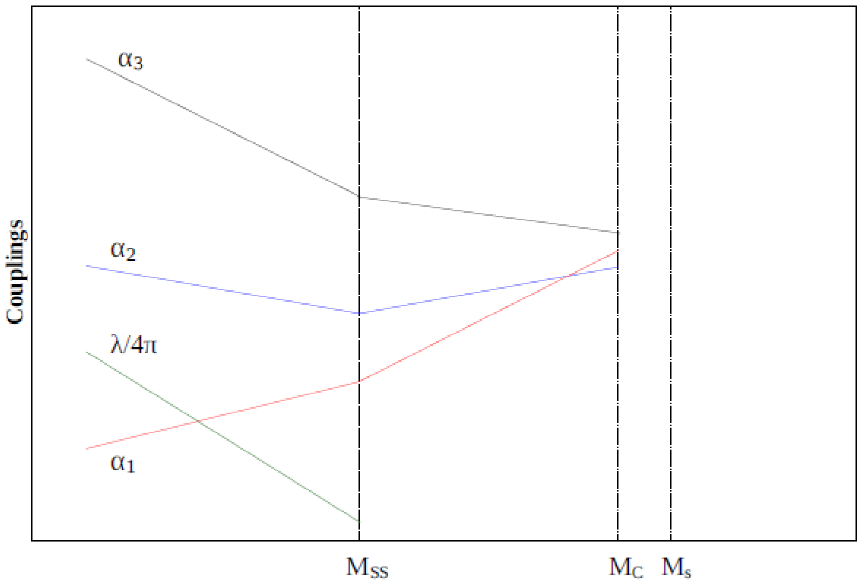
$$\delta \mathrm{Re} f_i = \frac{1}{10} \delta_i C_0 \int_S f_Y \wedge f_Y + \delta_i C_0 \int_S f_Y \wedge f_S$$

[Blumenhagen '08] [Mayrhofer, EP, Weigand '13]

Analogous effect not yet understood in F-theory

[Donagi,Wijhnolt '08] [Blumenhagen '08] [Conlon, EP '09] [Mayrhofer, EP, Weigand '13] [Hebecker, Unwin '14]

- Such modification to gauge coupling unification can be used to constrain the scale of supersymmetry breaking



[Ibanez, Marchesano, Regalado, Valenzuela '13]
[Hebecker, Unwin '14]

- Hypercharge flux can induce doublet-triplet splitting if it restricts appropriately to matter curves

  [Marsano, Saulina, Schafer-Nameki '10] [Dudas, EP '10] [Dolan, Marsano, Saulina, Schafer-Nameki '12] …

  Difficult to identify the component of the matter curve it can couple to in global models

- Possible to by-pass by breaking with Wilson lines, or by building directly the Standard Model

  [Marsano, Clemens, Pantev, Raby, Tseng '12] [Choi '10] [Lin, Weigand '14]

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G_4 Flux

Global Symmetries

- Effective global symmetries, or selection rules, arise from massive gauge symmetries in string theory
- There are two types of massive U(1) gauge symmetries in IIB string theory: those that gain a mass from flux and those which gain a 'geometric' mass

$$\int_{D7} F \wedge F \wedge C_+^{(4)} \longrightarrow \int_{M_4} F \wedge C_+^{(2)} \int_{S_4} f \wedge \omega_+^{(2)}$$

$$\int_{D7} F \wedge C_-^{(6)} \longrightarrow \int_{M_4} F \wedge C_+^{(2)} \int_{S_4} \tilde{\omega}_-^{(4)}$$

- Flux massive U(1)s are well understood in the presence of G_4-flux $\int_{M_{11}} G_4 \wedge C_3 \wedge C_3$

  [Cvetič, Grimm, Klevers '14]

- Geometrically massive U(1)s are less understood but under investigation
- Conjectured to arise from non-closed 2-forms in M-theory [Grimm, Weigand '10] [Grimm, Kerstan, EP, Weigand '11]

$$G_4 = d\left(c^{(0)}\alpha^{(3)} + A^{(1)} \wedge w^{(2)}\right) = \left(dc^{(0)} + A^{(1)}\right) \wedge \alpha^{(3)}$$

- Recent work making this more concrete [Braun, Collinucci, Valandro '14]

  Schematically: D7-D7' pair on homologically different cycles described by singularity of type

$$AB = CD + g_s E$$

  At weak coupling $g_s \rightarrow 0$ this looks like a conifold which can be resolved to give a 2-cycle and associated U(1)

  At finite coupling the singularity only has a non-Kahler resolution which matches non-closed 2-form

$$dJ = v\, dw^{(2)} \neq 0$$

- Relation to fibrations which do not have a section

  [Morrison, Taylor '14] [Anderson, García-Etxebarria, Grimm, Keitel '14]

- Understanding such symmetries can have crucial role to play in model building since in IIB string theory hypercharge flux can induce anomalies with respect to such U(1)s, but not with respect to flux-massive U(1)s

  [Mayrhofer, EP, Weigand '13]

- In local models some work relating discrete symmetries to Higgs bundle background

  [Antoniadis, Leontaris '13] [Karozas, King, Leontaris, Meadowcroft '14]

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G_4 Flux

Non-closed forms?

Coupling Constants

- There are 3 levels of approximations to *classical* coupling constants:

  1. Algebraic geometry → vanishing or not
  2. Symmetries and scaling → order of magnitude
  3. Wavefunction overlaps → full physical answer

- The only one we can do fully is the first, which delivers limited information: so far all couplings compatible with U(1) symmetries are present

- Combining 1 and 2 leads to some results:

  Gauge coupling unification is disturbed to some extent (though may be as small as 1%) by Hypercharge flux

  [Donagi, Wijnholt '08] [Blumenhagen '08] [Conlon, EP '09] [Mayrhofer, EP, Weigand '13] [Hebecker, Unwin '14]

  Taking different generations/Higgs to arise on different matter curves can lead to realistic models of flavour, as well as controlling proton decay, R-parity, Neutrinos, etc…

  [Too many papers to list…]

Local wavefunctions overlaps

- A full understanding of physical couplings would require moduli stabilisation as well as a very detailed geometry of the background geometry and flux

- Can by-pass the complications in bottom-up toy models which consider only the local region associated to a coupling and choosing the local geometry and flux by hand

[Heckman, Vafa ‘09] [Font, Ibanez ‘09] [Conlon, EP ‘09] … [Font, Marchesano, Regalado, Zoccarato ‘13]

- Recall couplings are given in terms of internal wavefunction overlaps

$$\Psi_{8D} = \phi_{4\mathrm{D}} \times \psi_{\mathrm{int}} \qquad \int_{4D\times S} \Psi^1 \Psi^2 \Psi^3 = \int_{4D} \phi^1 \phi^2 \phi^3 \left(\int_S \psi^1 \psi^2 \psi^3 \right)$$

- The wavfunctions are solutions to some Dirac equation in a local flux background

$$\mathbb{D}^- \Psi = 0 \qquad \psi \sim e^{-|\langle \phi_H \rangle|^2} e^{-\langle F \rangle}$$

- Wavefunctions localised justifying local approximation

- Some results:

Yukawa coupling at a single point is always rank 1 in generation space in the absence of flux/non-perturbative effects

[Cecotti, Cheng, Heckman, Vafa ’09] [Conlon, EP ‘09] [Marchesano, Martucci ‘09]

Using non-perturbative effects can engineer local models with reasonable flavour structure
[Aparicio, Font, Ibanez, Marchesano ’11] [Font, Ibáñez, Marchesano, Regalado ‘12] [Marchesano, Martucci ‘09]

Top quark Yukawa coupling can be fixed to be order 1 by some local choice of flux

[Font, Marchesano, Regalado, Zoccarato ‘13]

Local fluxes determine the local chirality of the spectrum – can model build in a local region
[EP ‘12]

Coupling between massless and massive modes can be calculated, regions in parameter space may lead to control over dimension 5 and 6 proton decay – though generically seems difficult

[Camara, Dudas, EP ’11] [Ibáñez, Marchesano, Regalado, Valenzuela ‘12] [Hebecker, Unwin ‘14]

Can calculate flavour-changing soft terms, as expected these are significant for non gauge-mediated susy breaking

[Camara, Dudas, EP ’11] [Camara, Ibanez, Valenzuela ’13 ‘14]

A dictionary for Model Builders

In building a model of particle physics we would like to specify…

Gauge symmetries

Matter spectrum

Global symmetries

Coupling constants

Elliptic fibration form and constraints on coefficients

G_4 Flux

Non-closed forms?

Symmetries, wavefunction overlaps

Challenges for the Future?

What are the implications for phenomenology?

- Much of the recent work on global models has been about developing the model building technology
- Are there any deep implications for phenomenology? Any general conclusions? Can we expect to find some?
- Rich spectrum of phenomenological ideas, mostly based on local models, following 2008, can we:

1. Identify how these are constrained by global models?

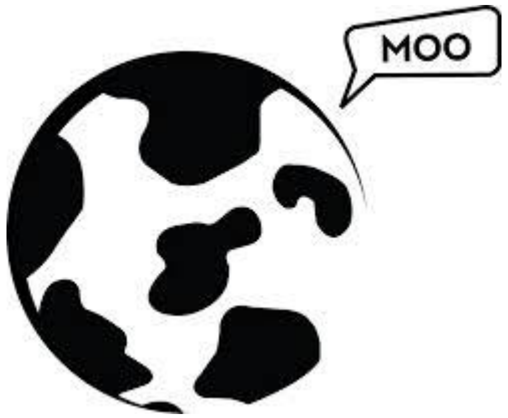
   Hypercharge flux and anomalies? Possible matter spectrum? Patterns of Yukawa couplings?

2. Identify new types of models which were not studied?

   [Krippendorf, Pena, Oehlmann, Ruehle ‘14]

   Spectrum of fields going beyond E_8? Global symmetries from massive U(1)s?

From Holomorphic to Physical



- Beautiful algebraic geometry techniques are incredibly effective at extracting discrete data such as generations number, symmetries, etc..

- What about real numbers?

- Progress in understanding the effective action Kahler potential

  [Grimm '10] [Grimm, Klevers, Poretschkin '12] [Grimm, Savelli, Weissenbacher '13] [Grimm,Keitel,Savelli,Weissenbacher '13] [Junghans, Shiu '14]

- Physical coupling can be estimated from a local perspective by computing wavefunction overlaps

- Can we connect the pieces?

global geometry + effective action + wavefunction overlaps + moduli stabilisation + supersymmetry breaking?

F-theory as a Unifying Framework?

- For a long time type IIB and Heterotic String model building has been essentially separate

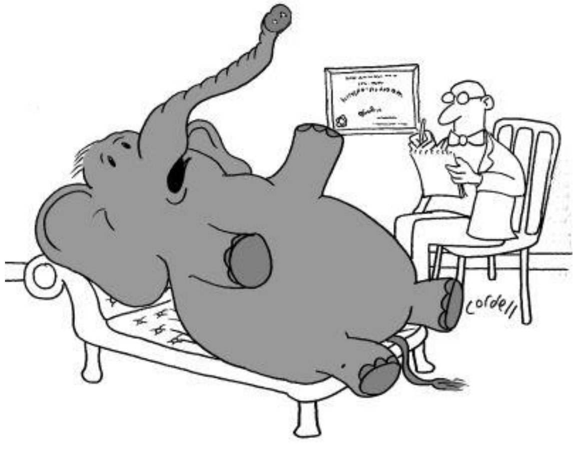
- Can we understood Heterotic/F-theory duality to a sufficient level that talks on model building would apply to both frameworks?

- Significant progress in this direction, but much more needed

  [Hayashi,Tatar,Toda,Watari, Yamazaki ‘08] [Donagi,Wijnholt ‘09] [Donagi,Katz,Wijnholt ‘12] [Clingher,Donagi,Wijnholt ‘12] [Anderson,Taylor ‘14] + …

- Can we use ‘geometrisation’ ideas to develop M-theory model building?

  [Pantev, Wijnholt ‘09]



"Whenever I walk in a room, everyone ignores me."

Thanks