Happy Golden Age Peter!!!

Phenomenological Aspects of D-branes at Singularities

F. Quevedo, Cambridge/ICTP. Planck 2011/PeterFest, Lisbon

S. Krippendorf, M. Dolan, A. Maharana, FQ; arXiv:1002.1790
S. Krippendorf, M. Dolan, FQ arXiv:1106.xxxx
C. Burgess, A. Maharana, S. Krippendorf, FQ; arXiv:1102.1973
M. Cicoli, C. Burgess, FQ arXiv:1105.2107

String Phenomenology

- **Too many string models?**

(Heterotic, IIA, I, IIB, Landscape,...)

- **Or too 'few' models?**

  (Realistic?)

Recall LHC is running: Hierarchy Problem Proposals

- TeV SUSY
- Warped extra dimensions
- Large extra dimensions
- …

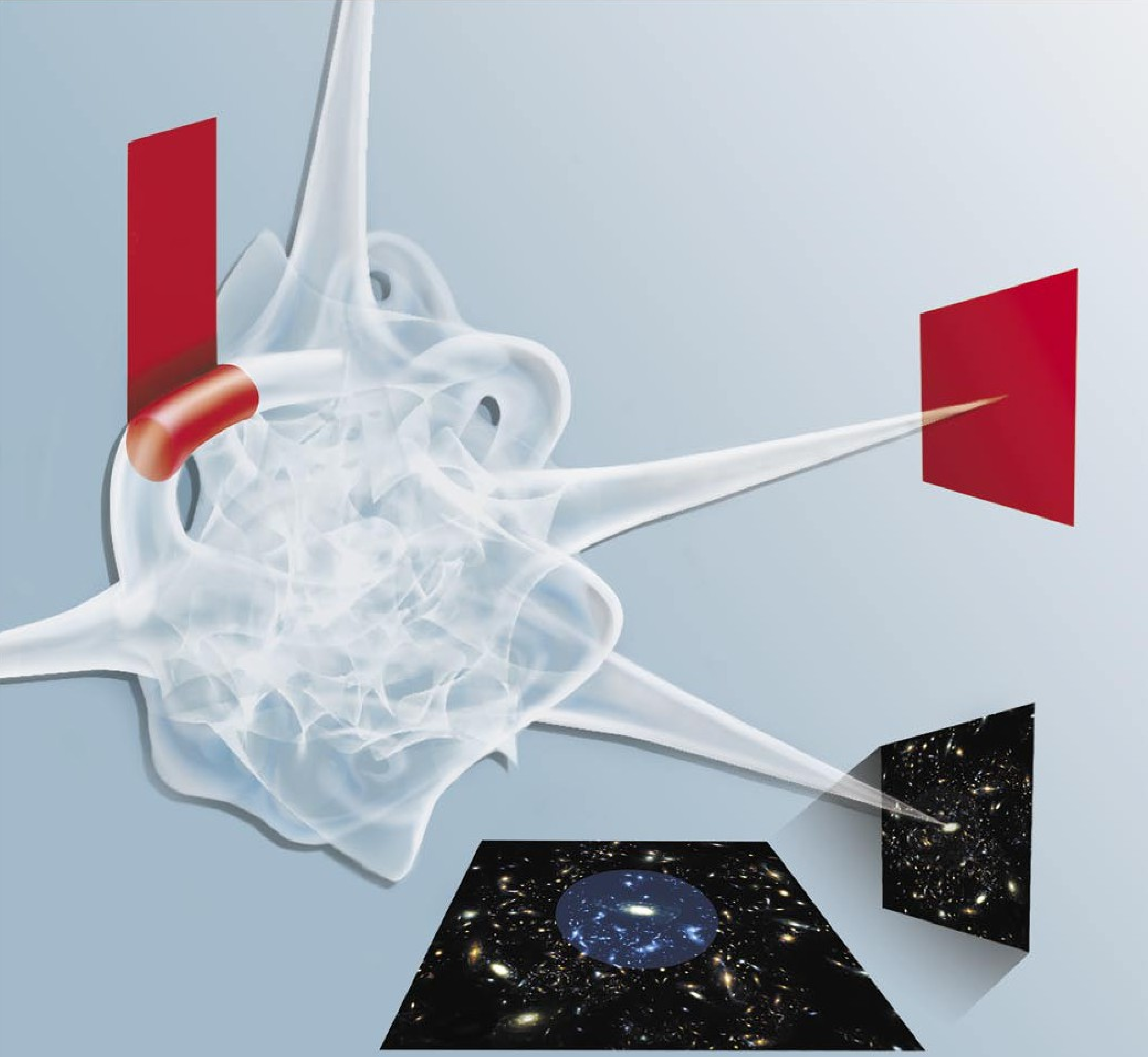
UV complete? How to fix size of extra dimensions? Unification, Flavour, Proton stability,…

Challenges

- Gauge and matter structure of SM
- Hierarchy of masses (including neutrinos)
- Flavor CKM, PMNS mixing, CP no FCNC
- Hierarchy of gauge couplings (unification?)
- ‘Stable’ proton + baryogenesis
- Dark matter (+ avoid overclosing)
- Inflation or alternative for CMB fluctuations
- Hierarchy problem
- Dark energy

N.B. If ONE of them does not work, rule out the model!!!

Local String Models



Universe

D3 Brane

or

D7 Brane

Standard Model Localised
→ (Bottom-up)

- **Fractional D3/D7 Brane at a singularity (collapsed cycle)**

  Aldazabal et al. 2000, ...

- **Magnetised D7 - Brane wrapping a 'small' four-cycle**

  Blumenhagen et al. 2008

- **Local F-Theory**

  Donagi, Wijnholt; Vafa, Heckman, … 2009

Standard Model at (Fractional) D3/D7 Branes at Singularities

★ **Collapsing single 4-cycle:**

del Pezzo surfaces dP_n, n=0,1, …,8 ⬅

(P^2 blown-up at n arbitrary points

$c_1>0$, $b_2=n+1$, 2n-8 parameters, n>3)

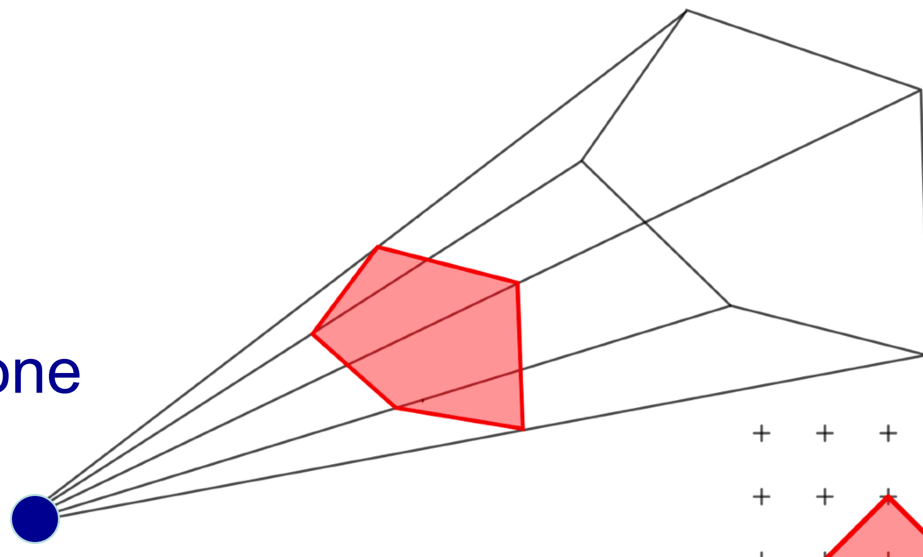
★ **More general singularities, e.g. Y_{pq}, L_{abc}**

Toric Singularities

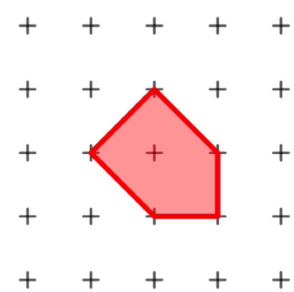
$$ds^2 = dr^2 + r^2 g_{ij}\, dx^i dx^j$$

Einstein-Sasaki

T^3 Fibration
Over rational
polyhedral cone



D3-branes



Toric Diagram

General Results Toric

1. **Maximum number of families = 3**
   (except for one case F0 with 4 families, dual to a 2-family model, also non-toric phases unbounded)

2. **Quark Mass hierarchy: (M,m,0) with M>>m**
   (structure of Yukawas imply one zero e-value, only dP0 has m=M)

The Needle on a Haystack

(search with a magnet!)

- Not simple GUT groups (SU(5), SO(10),…)
  Search for PS, LR, SM,…

- Many U(1)'s but if $U(1)_Y = \Sigma_i\, U(1)_i$, 'wrong' normalisation for MSSM unification (5/3). Also keep hypercharge massless in compact case.

- Then $U(1)_Y$ in G non-abelian (SU(4),…)

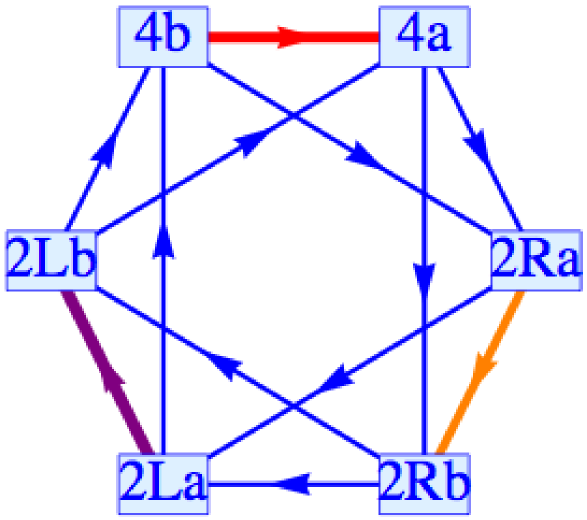
- ALL SM in D3's   at least G=PS, $SU(3)^3$

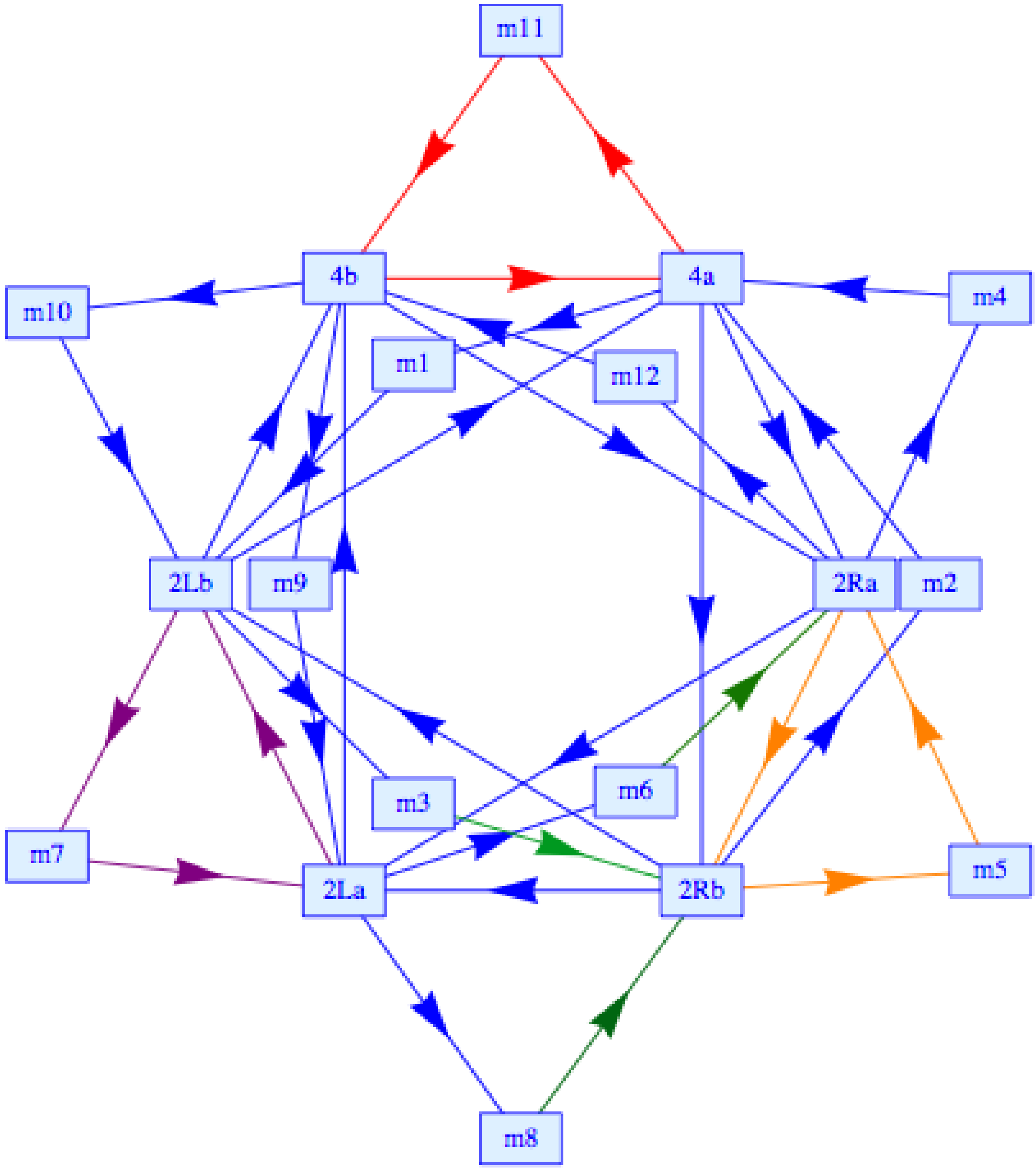
Minimal del Pezzo?

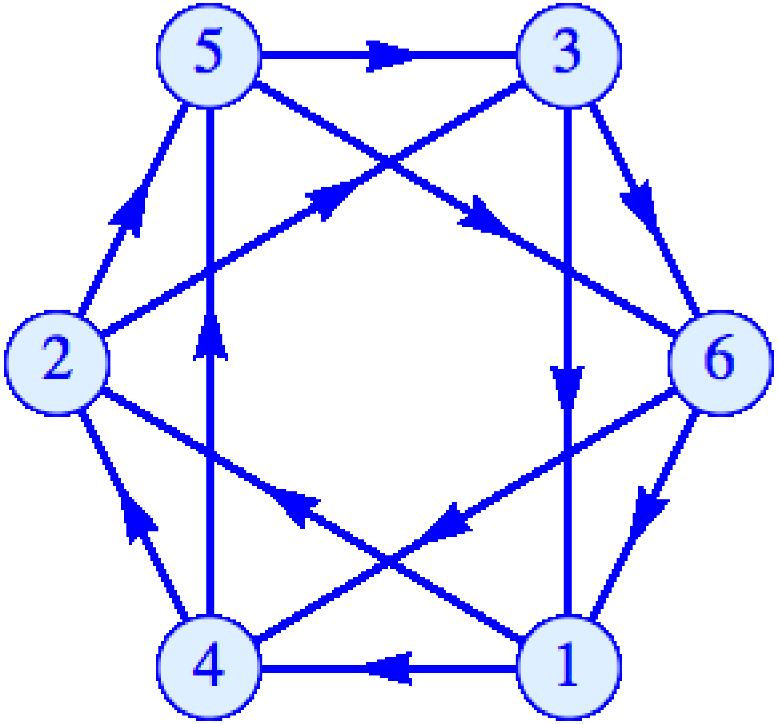
- dP0 no hierarchy of masses (unless non-commutative), no CKM
- dP1, dP2 no CKM or PMNS, no control of kinetic terms (FCNC?).
- dP3 flavor diagonal kinetic terms and realistic CKM, PMNS matrices.

‘Realistic’ ‘Pati-Salam’ Model (dP3)

- Break symmetry to SM (+ U(1) or LR)
- Breaking U(1) to SM: RH sneutrino (R-parity broken)
- Quark+ lepton mass hierarchies
- See-saw neutrino masses
- Stable proton
- CKM, CP
- Controlled kinetic terms!!
- Gauge Unification




m11
4b
4a
m10
m4
m1
m12
2Lb
m9
2Ra
m2
m3
m6
m7
2La
2Rb
m5
m8



$$\langle \rho_{53} \rangle = \begin{pmatrix} v_1 & 0 & 0 & 0 \\ 0 & v_1 & 0 & 0 \\ 0 & 0 & v_1 & 0 \\ 0 & 0 & 0 & v_2 \end{pmatrix}$$

$$\langle \Phi_{61} \rangle = \begin{pmatrix} \phi & 0 \\ 0 & \tilde{\phi} \end{pmatrix} \quad \langle \Psi_{42} \rangle = \begin{pmatrix} \psi & 0 \\ 0 & \psi \end{pmatrix}$$

total #	Fields	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_x$
3	Q^L_1, Q^L_2, Q^L_3	3	$\bar{2}$	a	a
3	u_1, u_2, u_3	$\bar{3}$	1	$-a+k$	$-a-k$
3	d_1, d_2, d_3	$\bar{3}$	1	$-a-k$	$-a+k$
3	L_1, L_2, L_3	1	$\bar{2}$	$-3a$	$-3a$
3	ν_1, ν_2, ν_3	1	1	$3a+k$	$3a-k$
3	e_1, e_2, e_3	1	1	$3a-k$	$3a+k$
3	H^u_1, H^u_2, H^u_3	1	2	$-k$	k
3	H^d_1, H^d_2, H^d_3	1	2	k	$-k$

$$W_{\rm D3D3} = \begin{pmatrix} Q_1^L \\ Q_2^L \\ Q_3^L \end{pmatrix} \begin{pmatrix} 0 & H_3 \frac{\rho_{53}}{\Lambda} & -H_2 \\ -H_3 \frac{\rho_{53}\Phi_{61}\Psi_{42}}{\Lambda^3} & 0 & H_1 \frac{\Phi_{61}}{\Lambda} \\ H_2 \frac{\Psi_{42}}{\Lambda} & -H_1 & 0 \end{pmatrix} \begin{pmatrix} Q_1^R \\ Q_2^R \\ Q_3^R \end{pmatrix} +$$

Quarks+leptons

$$A(\rho,\phi)e^{-aT_i}\nu_1\nu_1 + \frac{\Phi_{61}^2}{\Lambda}A(\rho,\phi)e^{-aT_i}\nu_2\nu_2 + \frac{\rho_{53}^2}{\Lambda}A(\rho,\phi)e^{-aT_i}\nu_3\nu_3$$

$$+ \; Ae^{-aT_s}H.H$$

$$K_{\rm matter} \supset \frac{a + f(\tau_s, \tau_b)}{\mathcal{V}^{2/3}} \left(Q^i_{L,R}\bar{Q}^i_{L,R} + H_i\bar{H}_i + \Phi_{61}\bar{\Phi}_{61} + \Psi_{42}\bar{\Psi}_{42} + \rho_{53}\bar{\rho}_{53}\right)$$

- CKM Matrix

$$\frac{X_{12}^u}{Y_{64}^u} \sim \epsilon, \ \frac{Z_{14}^u v_1}{Y_{64}^u \Lambda} \sim \epsilon, \ \frac{\Phi_{61}^u}{\Lambda} \sim \epsilon^2, \ \frac{\Phi_{61}^d v_1 Z_{14}^d}{\Lambda^2 Y_{64}^d} \sim \epsilon$$

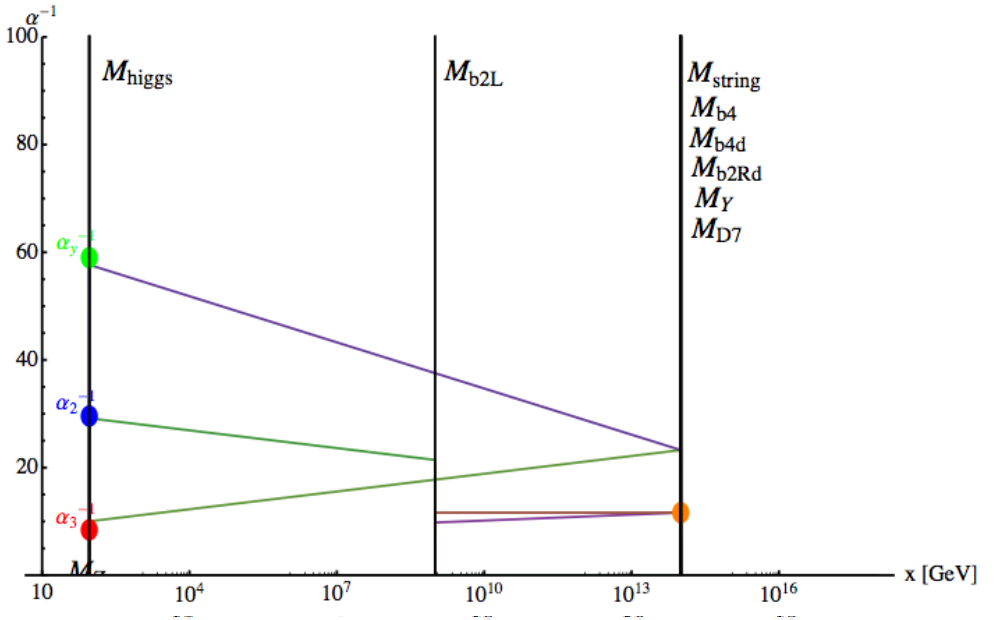
$$|V_{\rm CKM}| = \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

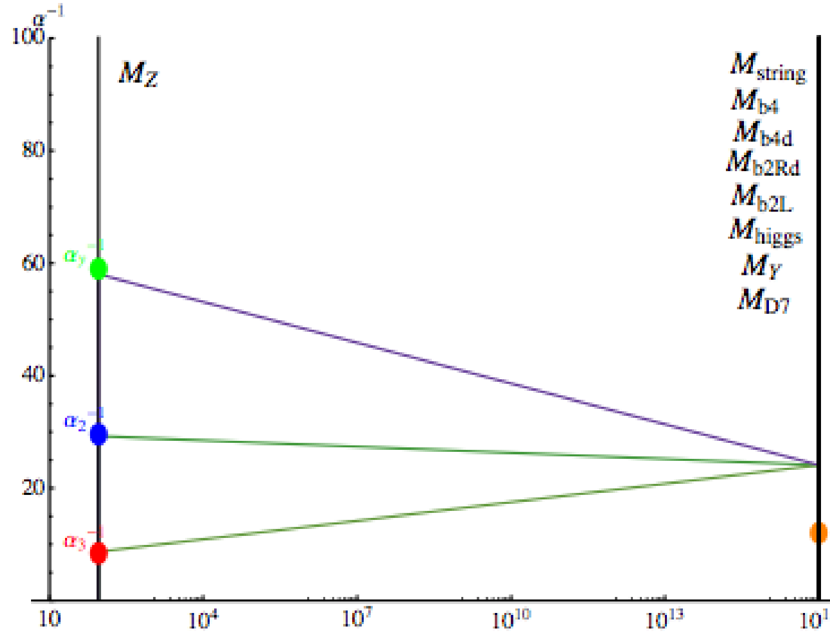
- PMNS Matrix

$$\frac{Z_{14}^d \rho_{53} \Phi_{61}^d}{\Lambda^2 Y_{64}^d}, \ \frac{v_1}{v_2} \sim \epsilon^2$$

- 14 Parameters vs 21 Observables

Gauge Coupling Unification





String scale value of all couplings given by dilaton so unification.

Standard GUT scale unification or ‘intermediate’ scale Ms>10^{12} GeV

Need moduli stabilisation to fix scales.. (Large volume scenarios?....)

Aside: Anisotropic Moduli Fixing

- **K3 Fibrations:**

$$\mathcal{V} = \lambda_1 t_1 t_2^2 + \lambda_2 t_3^3,$$
$$\tau_i = \partial\mathcal{V}/\partial t_i,$$

Poly-Instantons

Blumenhagen et al.

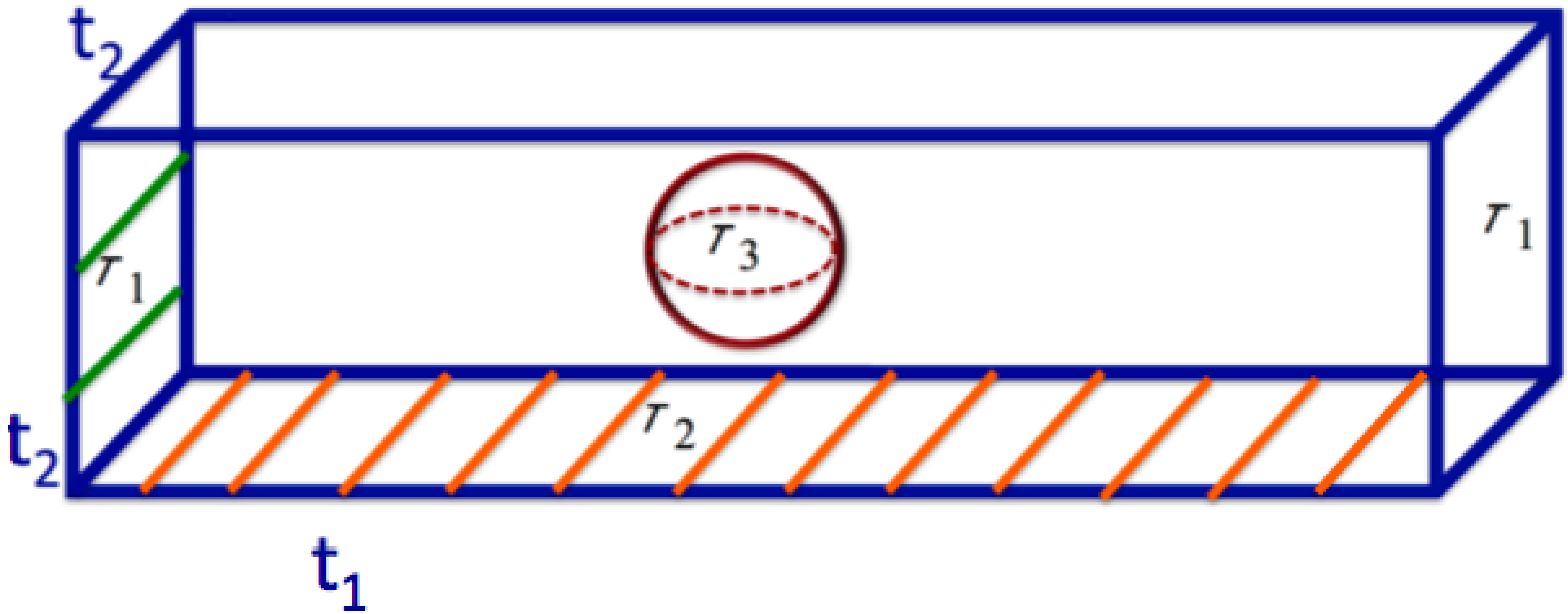
$$h_{2,0}(\Sigma_j) = 1 \text{ and } h_{1,0}(\Sigma_j) = 0,$$

K3 ! size t_2^2

$$W = W_0 + A_i e^{-2\pi\left(T_i + C_j e^{-2\pi T_j}\right)}.$$

i=3, j=1

Large Hierarchy: $\langle t_1 \rangle \gg \sqrt{\langle \tau_1 \rangle} \simeq \sqrt{\langle \tau_3 \rangle}$ and so $L \gg l \gtrsim d\,.$



$$d \simeq \langle \tau_3 \rangle^{1/4} \sim l \simeq \langle \tau_1 \rangle^{1/4} \sim 10^{-17} \text{ mm} \ll L \simeq \langle t_1 \rangle^{1/2} = \sqrt{\langle \mathcal{V} \rangle / \langle \tau_1 \rangle} \sim 0.01 \text{ mm}\,.$$

$$\mathcal{V} \simeq 5.2 \times 10^{28} \;\Rightarrow\; M_s \simeq \frac{M_p}{\sqrt{4\pi\mathcal{V}}} \simeq 3\,\text{TeV}.$$

(For W_0=10, g_s=0.01, etc.)

Living on the edge!!

OPEN QUESTIONS

- Flavor mixings depends on ratios of vev's: obtain them dynamically
- Explicit 37 masses from 77 vevs
- Intermediate scale unification and soft terms?
- Obtain correct neutrino masses (and mu term) dynamically
- Compact model building + …

Thank you for your Physics and Friendship Peter !
And Best Wishes for a Productive Future Career

SUSY BREAKING

Several Scenarios

- F-term of volume modulus ~ approximate no-scale (M_{soft} (~F_T/Mp)) ~vanish!

1. SM cycle breaks SUSY:
   M_{soft}~1TeV (~F_T/M_{string}~Mp/V~$M_{3/2}$)
   Volume~10^{15} and M_{string}~10^{12} GeV.

2. SM cycle does not break SUSY
   $M_{1/2} \sim F_S/Mp \sim Mp/V^2 << M_{3/2}$
   Extreme case: V~10^7, M_{string}~10^{15} GeV

Scenario 2.

- Uplifting to de Sitter important De Alwis 2006
- Gravitino very heavy $M_{3/2}>10^8$ GeV !!
- Generically no CMP! ($M_{volume}>M_{soft}$)
- Minimal volume $V\sim10^{6\text{-}7}$.

★ TeV soft terms and $M_{string}\sim10^{15}$ GeV
★ Unification scale $M_X\sim M_{string}\ V^{1/6}\sim10^{16}$ GeV !
★ Right scale for inflation! Conlon+Palti
★ No CMP !!!

But: Calculations less under control + FCNC? De Alwis 2010

Implications

- **Intermediate scale scenario**

  $M_V \simeq M_p/\mathcal{V}^{3/2}$ ~1MeV (CMP!?)

- **GUT scale scenarios**

  $M_V \simeq M_p/\mathcal{V}^{3/2}$ ~1-10 TeV

- **TeV Scenario**

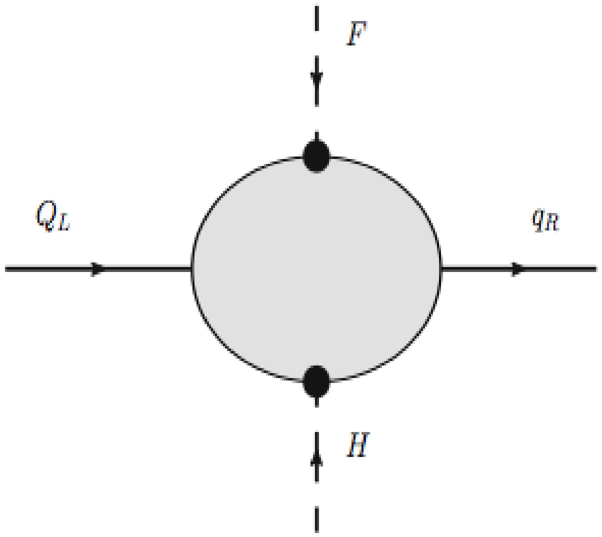
SUSY broken on the brane:

$M_V \sim M_p/\mathcal{V} \sim 10^{-3}$ eV $\gg M_p/\mathcal{V}^{3/2}$

But potential destabilisation of LV minimum (back reaction?)

Perturbative quark masses

- Ibanez 1982



$\Delta m \sim \langle H \rangle F/M^2 \sim$

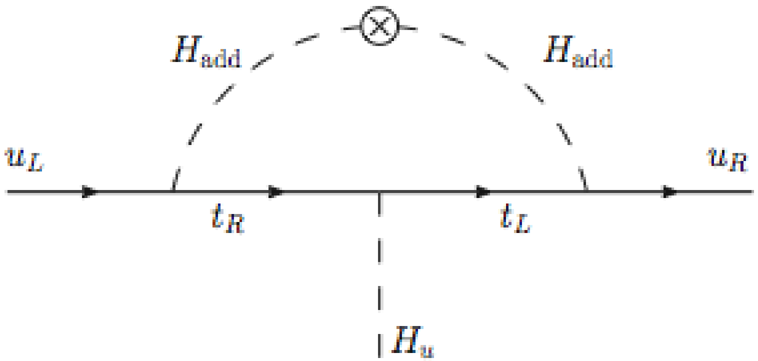
$M_W\, M_{3/2}{}^2/Mp^2 \sim 10^{-30}\, M_W$?

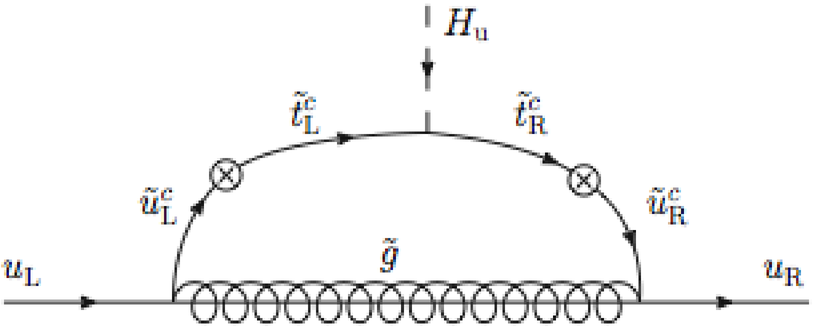
Scenario 1: $\Delta m \sim M_W\, M_{3/2}{}^2/Ms^2 \sim .1 MeV$!

Scenario 2: $\Delta m \sim M_W\, M_{3/2}{}^2/Mp^2 \sim .1\ MeV$!

Burgess, Krippendorf, Maharana, FQ

Explicit diagrams





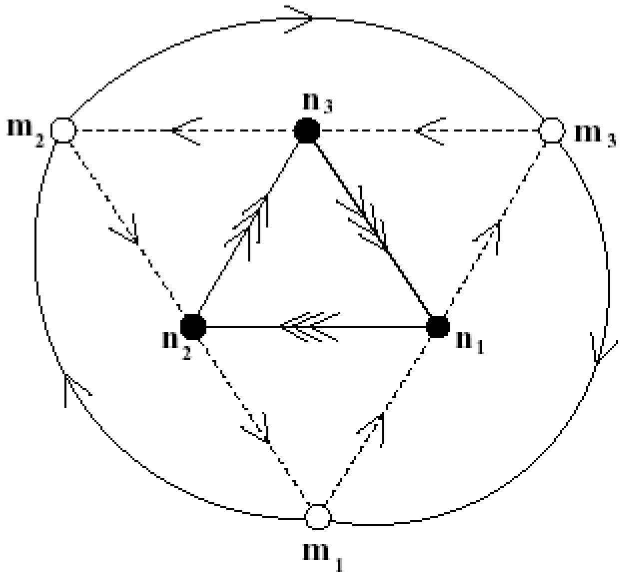
$$m_{\rm up} \sim m_t \frac{F_{\rm SUSY}}{m^2_{H_{\rm add}}} .$$

$$m_{\rm up} \sim m_{\tilde{t}}\, \epsilon^2 .$$

$$\epsilon < 10^{-3} \frac{M_{\rm susy}}{500{\rm GeV}}$$

Other sources: non-commutative B background,…

Del Pezzo Singularities/Quivers



e.g. del Pezzo 0 (C_3/Z_3)

n_i D3 Branes (group $\Pi U(n_i)$)

m_j D7 Branes (group $\Pi U(m_i)$)

Arrows=bi-fundamentals

$$3\left[(\mathbf{n}_1,\bar{\mathbf{n}}_2,\mathbf{1})+(\mathbf{1},\mathbf{n}_2,\bar{\mathbf{n}}_3)+(\bar{\mathbf{n}}_1,\mathbf{1},\mathbf{n}_3)\right]+m_1\left[(\bar{\mathbf{n}}_1,\mathbf{1},\mathbf{1})+(\mathbf{1},\mathbf{n}_2,\mathbf{1})\right]$$
$$+m_2\left[(\mathbf{1},\bar{\mathbf{n}}_2,\mathbf{1})+(\mathbf{1},\mathbf{1},\mathbf{n}_3)\right]+m_3\left[(\mathbf{1},\mathbf{1},\bar{\mathbf{n}}_3)+(\mathbf{n}_1,\mathbf{1},\mathbf{n}_1)\right]$$

3 Families!

$$m_2=3\,(n_3-n_1)+m_1 \qquad m_3=3\,(n_3-n_2)+m_1$$

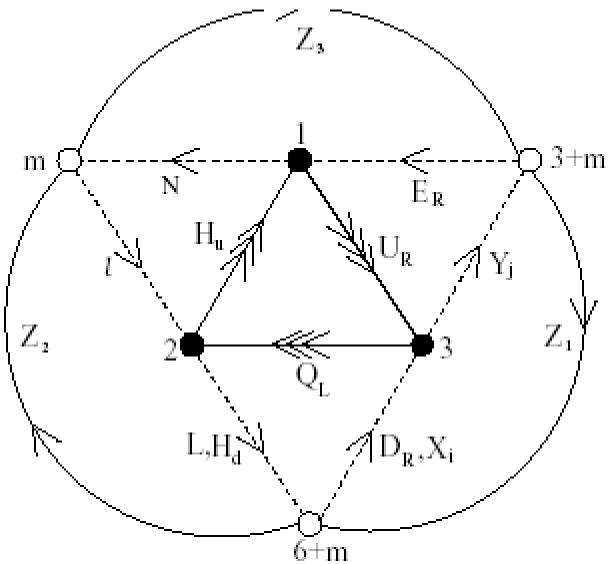
Anomaly/tadpole cancelation

$$Q_{anomaly-free}=-\sum_{i=1}^{3}\frac{Q_i}{n_i},$$

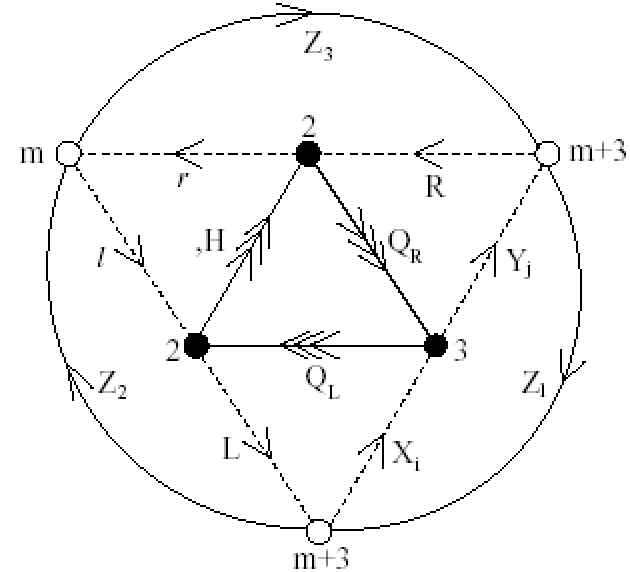
Hypercharge ($n_i \neq n_j$)

D7s:Franco-Uranga

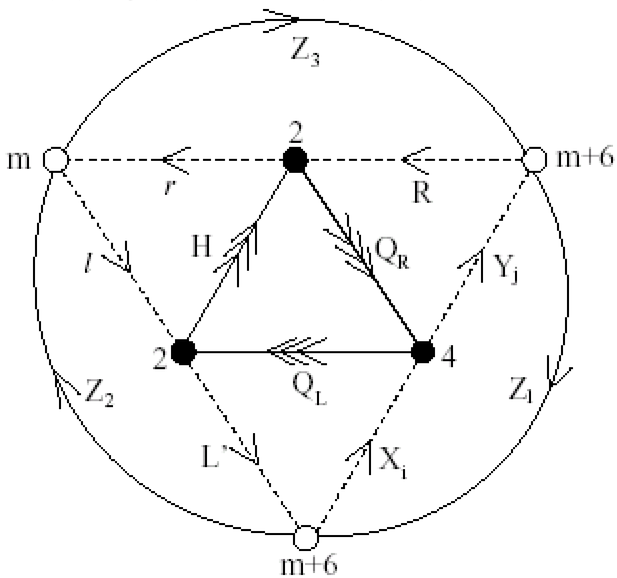
Standard Models



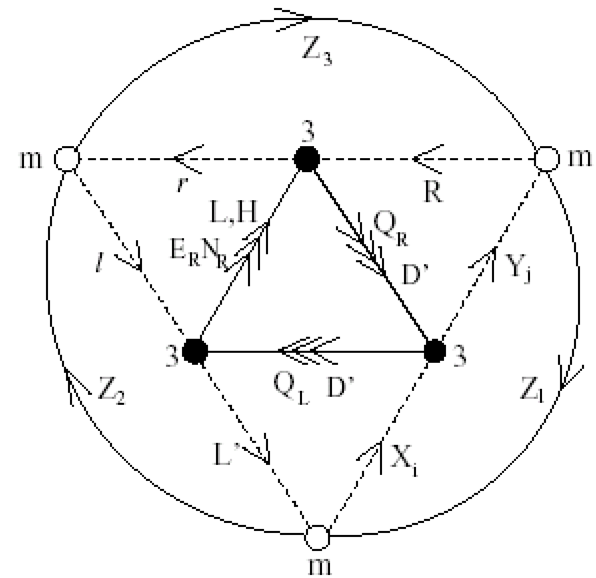
LR-Symmetric Models



Pati-Salam Models



Trinification Models



Problem for dP_0: Yukawa couplings

Conlon, Maharana, FQ 2008

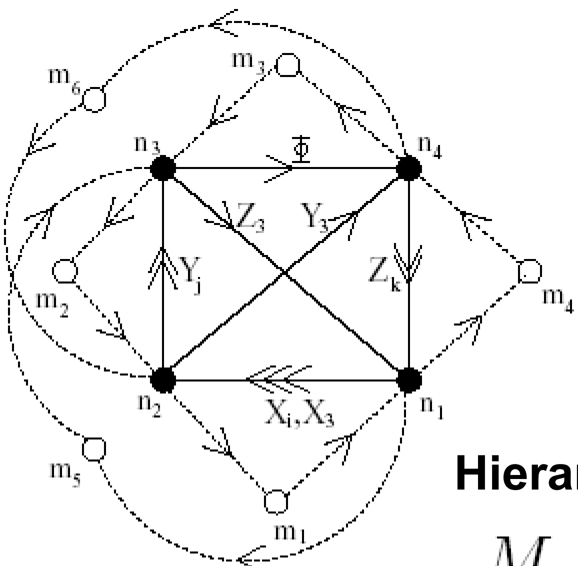
$$W = \epsilon_{ijk}\Phi^i_{33}\Phi^j_{33}\Phi^k_{33} + \sum \Phi^i_{33}\Phi_{37_i}\Phi_{7_i3},$$

$$Y_{ijk} \sim \begin{pmatrix} 0 & M & 0 \\ -M & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

E-values (M,M,0).

From global flavour symmetry SU(3) (?)

Del Pezzo1 Singularity



$$m_4 = n_4 + n_3 - n_1 - n_2 + m_1 - m_2 + m_3,$$

$$m_5 = n_1 - 2n_2 + n_4 + m_2 - m_3,$$

$$m_6 = n_4 - 3n_1 + 2n_3 + m_1 - m_2$$

$$W = \epsilon_{ij}X_iY_jZ_3 - \epsilon_{ij}X_iY_3Z_j + \frac{\Phi}{\Lambda}X_3\epsilon_{ij}Y_iZ_j,$$

SU(2)xU(1) Flavour symmetry

Hierarchy in 3 generation masses!!!!

$$M \gg m \qquad \frac{\langle\Phi\rangle}{\Lambda} \ll 1$$

$$\begin{pmatrix} M^2 & 0 & 0 \\ 0 & m^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Higgsing gives back dP_0!!!