Title: Phenomenological aspects of branes at singularities

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Abstract: TBA

Phenomenological Aspects of D-branes at Singularities

F. Quevedo, Cambridge/ICTP.   PI, March 2011.

S. Krippendorf, M. Dolan, A. Maharana, FQ; arXiv:1002.1790
S. Krippendorf, M. Dolan, FQ to appear
C. Burgess, A. Maharana, FQ; arXiv:1005.1199
C. Burgess, A. Maharana, S. Krippendorf, FQ; arXiv:1102.1973
C. Burgess, M. Cicoli, FQ to appear

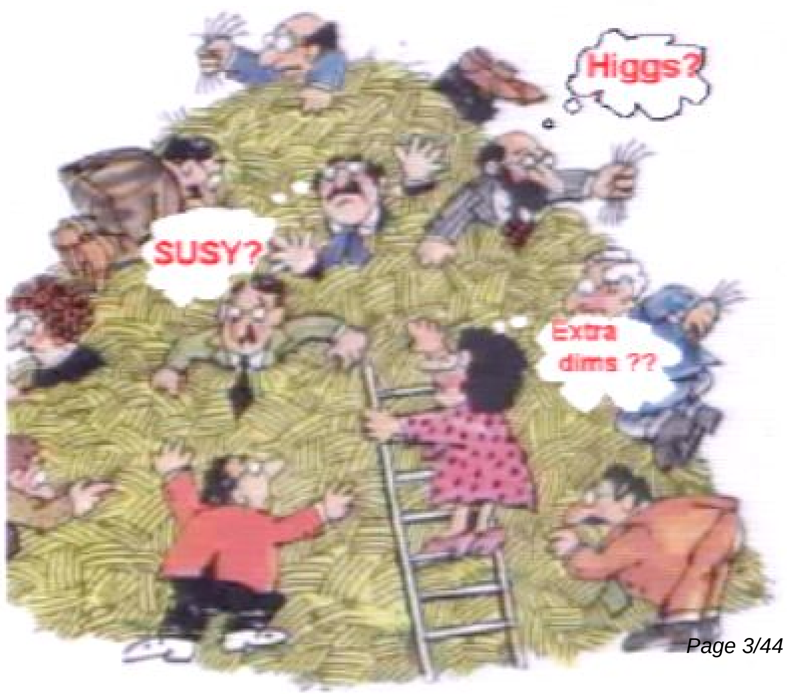
String Phenomenology

- Too many string models?

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

- Or too 'few' models?

(Realistic?)

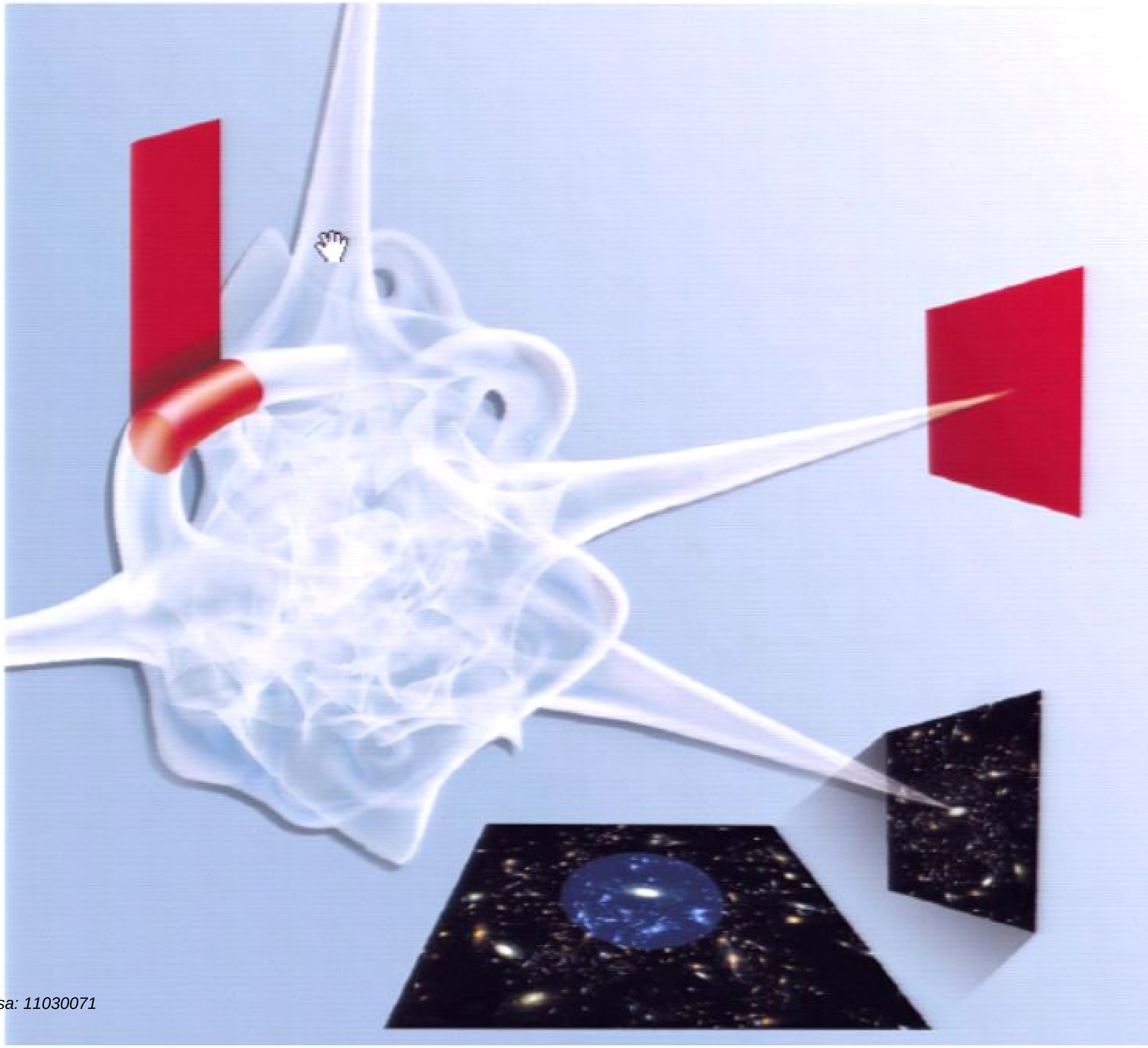


Recall LHC is running: Hierarchy Problem Proposals

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

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

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 ⇐

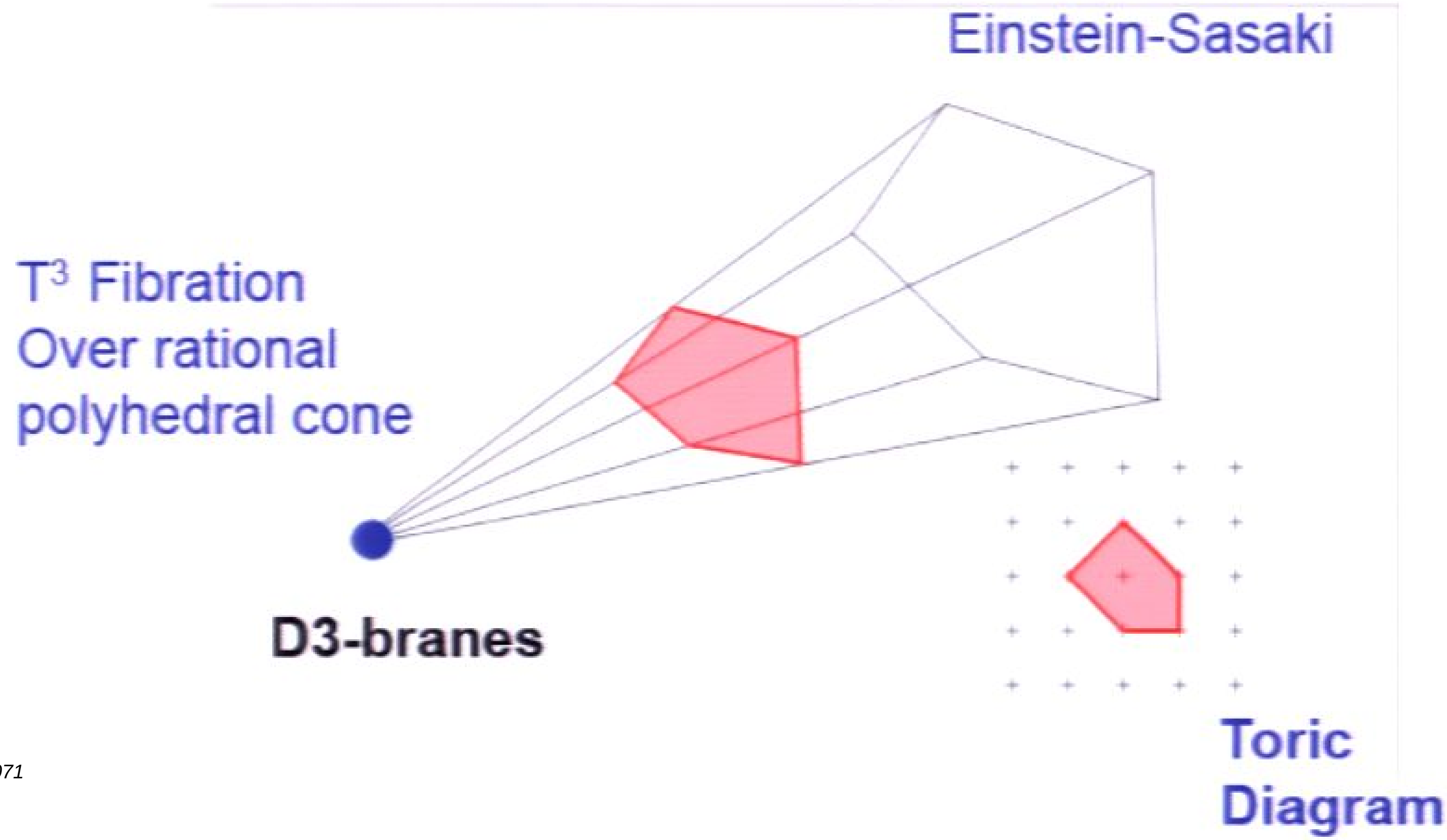
(P^2 blown-up at n arbitrary points

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

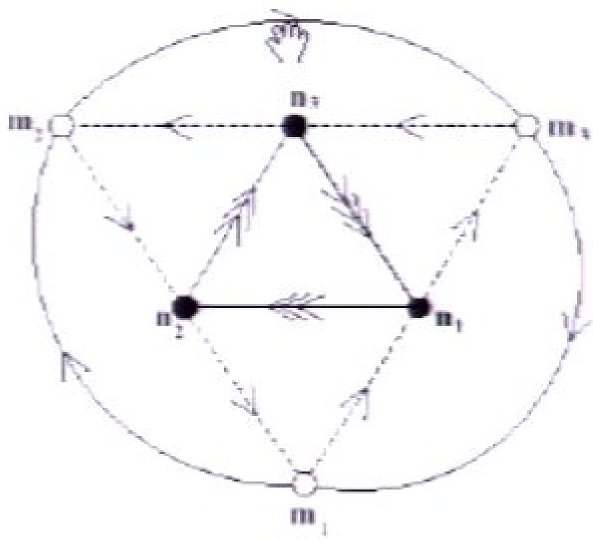
★ More general singularities, e.g. Y_{pq}, L_{abc}

Toric Singularities

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



Simple 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

$$3\left[(\mathbf{n_1},\bar{\mathbf{n}}_2,1)+(1,\mathbf{n_2},\bar{\mathbf{n}}_3)+(\bar{\mathbf{n}}_1,1,\mathbf{n_3})\right]+m_1\left[(\bar{\mathbf{n}}_1,1,1)+(1,\mathbf{n_2},1)\right]$$
$$+m_2\left[(1,\bar{\mathbf{n}}_2,1)+(1,1,\mathbf{n_3})\right]+m_3\left[(1,1,\bar{\mathbf{n}}_3)+(\mathbf{n_1},1,\mathbf{n_1})\right]$$

3 Families!

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

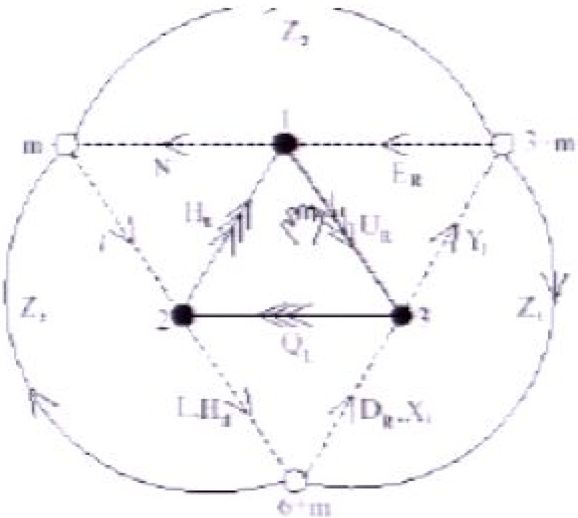
Anomaly/tadpole cancelation

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

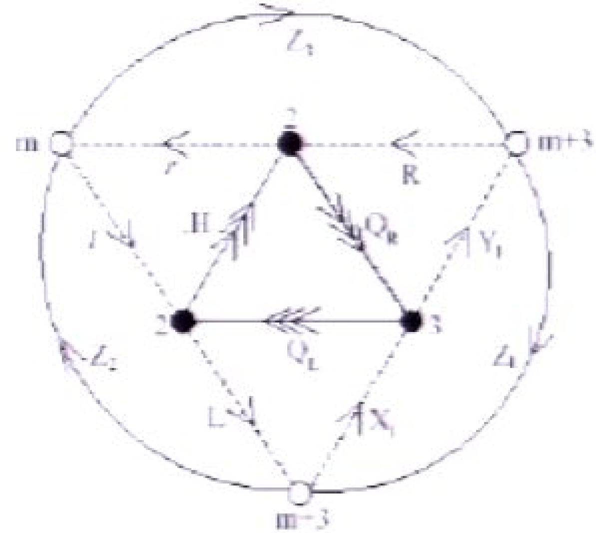
Hypercharge ($n_i \neq n_j$)

D7s:Franco-Uranga

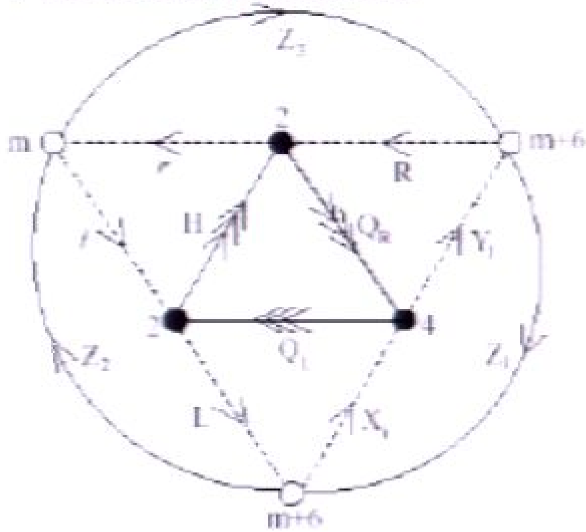
Standard Models



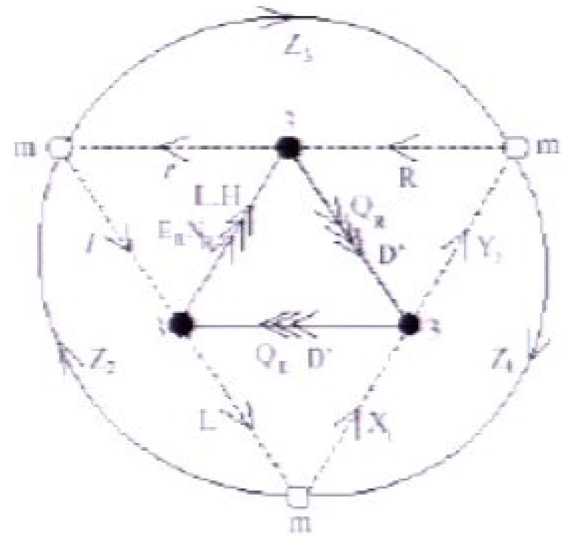
LR-Symmetric Models



Pati-Salam Models



Trinification Models



Problem for dP_0: Yukawa couplings

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

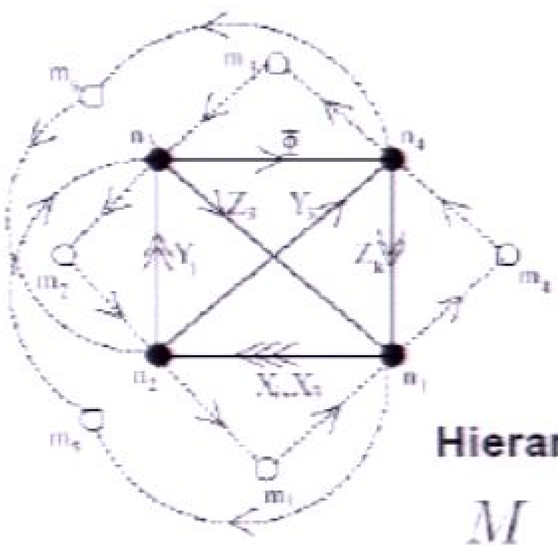
Conlon, Maharana, FQ 2008

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

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!!!!

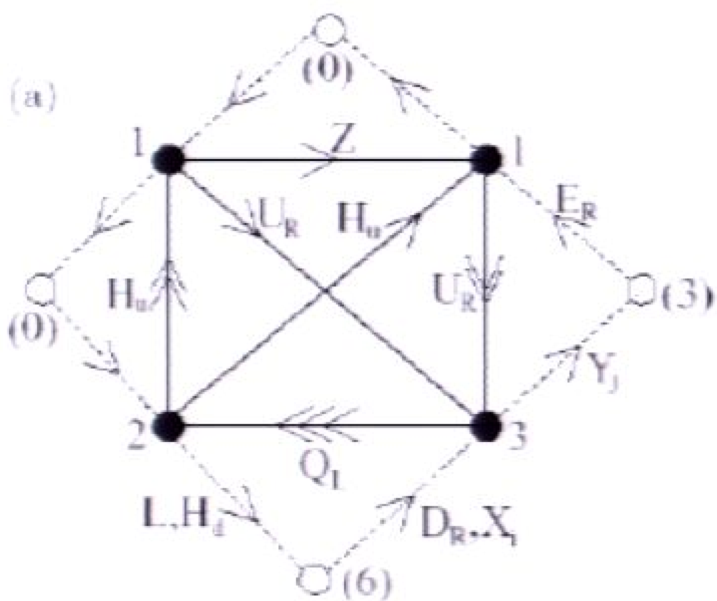
$$M \gg m \qquad \frac{\langle\Phi\rangle}{\Lambda} \ll 1$$

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

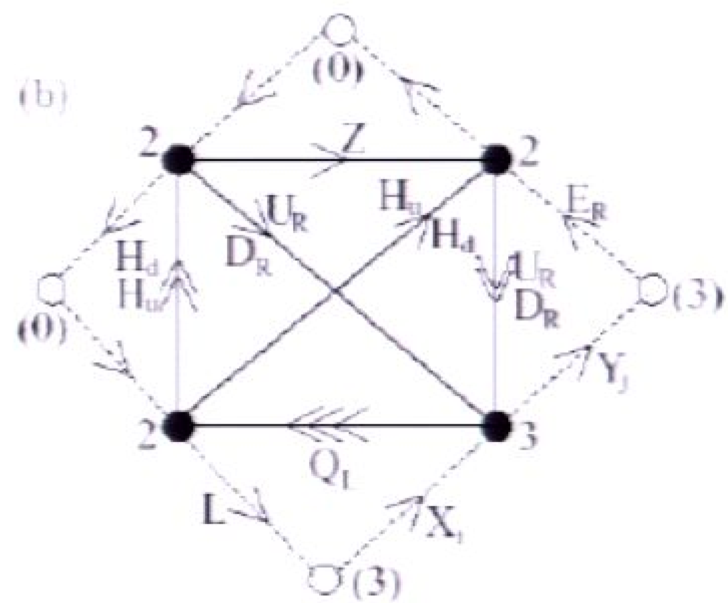
Higgsing gives back dP_0!!!

e.g. ‘Realistic’ dP_1 Models

Standard Model



LR Symmetric Model



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)

3. Realistic CKM

- General structure CKM=1+ corrections is generic.
- The rest may depend on kinetic terms corrections.
- If subdominant: Depends if quarks are both D3D3 or D3D3/D3D7.
- D3D3+D3D7: dP1 realistic CKM and CP violation

$$V_{\rm u} = \begin{pmatrix} a\frac{\Phi_{61}}{\Lambda}X_{12} & -bY_{12}X_{12} & -cZ_{12} \\ aY_{12} & b\frac{\Phi_{61}}{\Lambda}(X_{12}^2+Z_{12}^2) & 0 \\ a\frac{\Phi_{61}}{\Lambda}Z_{12} & -bY_{12}Z_{12} & cX_{12} \end{pmatrix}, \qquad V_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_2 & s_2 \\ 0 & -s_2 & c_2 \end{pmatrix}.$$

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

- D3D7 dP1: no second-third generation mixing, but works for dP2+…

4. CP violation

Jarlskog invariant $J = 3.05^{+0.19}_{-0.20} \times 10^{-5} \approx \epsilon^{6.5}$.

D3D3 case (similar for D3D3/D3D7)

$$J = \frac{|\Psi_d|^2}{\Lambda^4} \frac{|X_u|^2 \, \mathrm{Im}(Y_u \bar{Y}_d Z_d \bar{Z}_u \bar{\Phi}_u \Phi_d)}{(m_s^2 - m_d^2)(m_t^2 - m_u^2)(m_t^2 - m_c^2)} \approx \epsilon^6 \sin\delta$$

The Needle on a Haystack

(search with a magnet!)

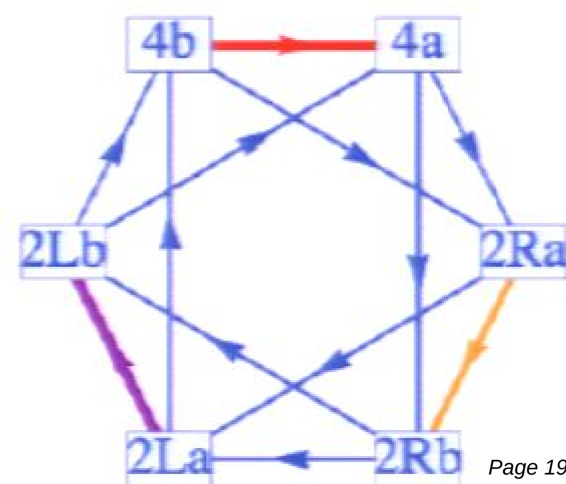
- Not simple GUT groups (SU(5), SO(10),…)
- Search for PS, LR, SM,…
- Many U(1)'s but if $U(1)_Y = \Sigma_i U(1)_i$, 'wrong' normalisation for MSSM unification (5/3).
- Then $U(1)_Y$ in G non-abelian (SU(4),…)
- ALL SM in D3's at least G=PS, $SU(3)^3$

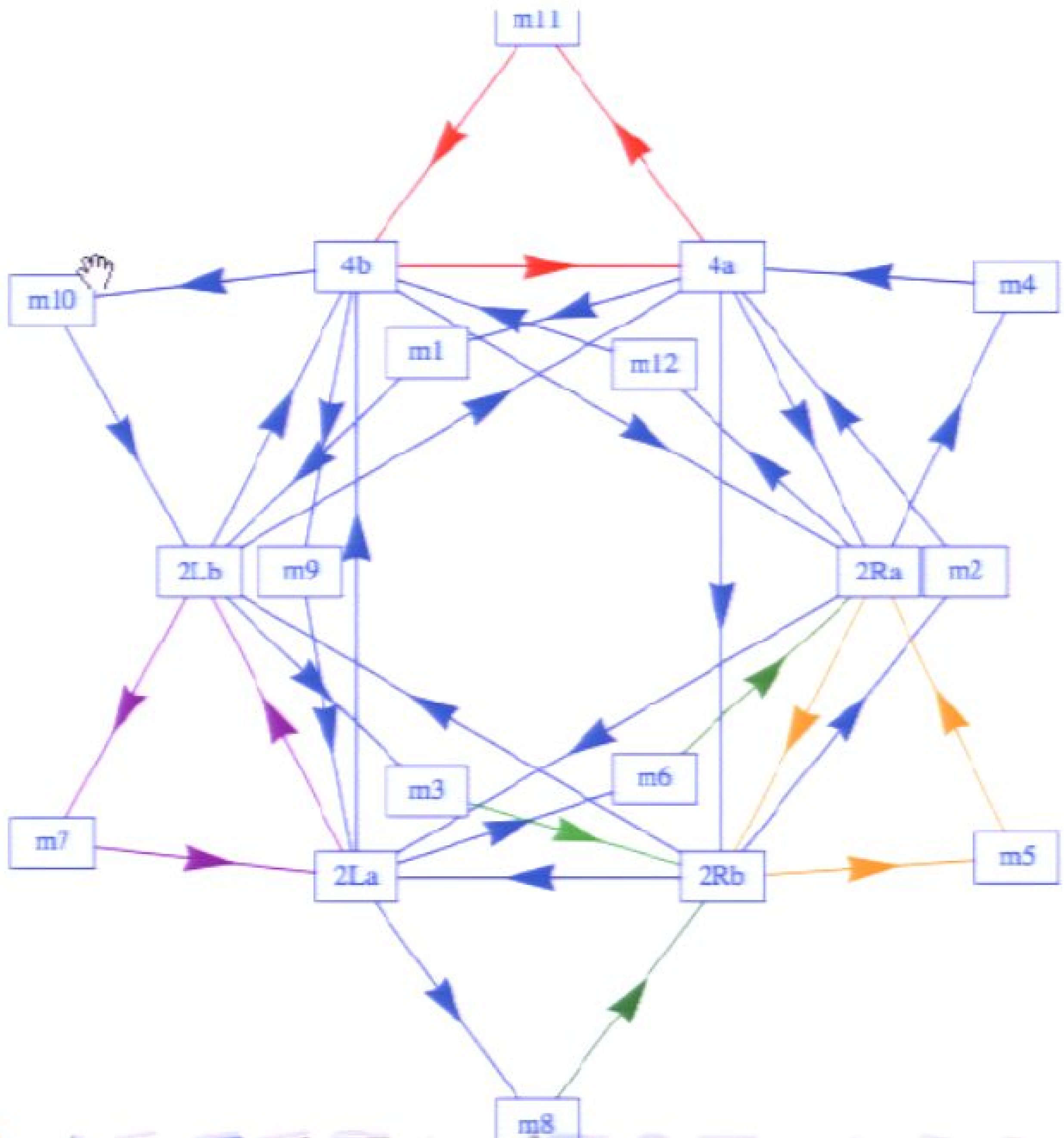
Minimal del Pezzo?

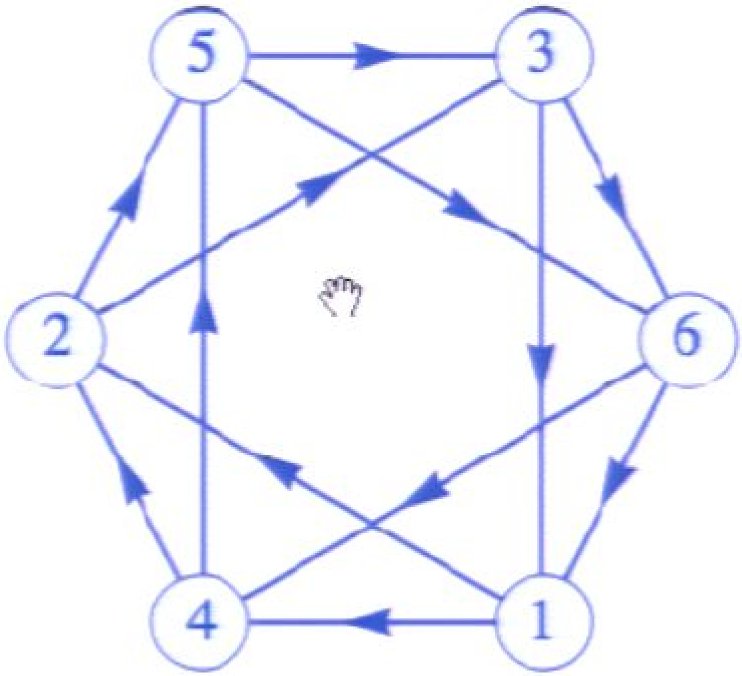
- dP0 no hierarchy of masses (unless non-commutative), no CKM
- dP1, dP2 CKM but no control of kinetic terms (FCNC?).
- dP3 flavour diagonal kinetic terms and realistic CKM, PMNS matrices.

Realistic Pati-Salam Model (dP3)

- Break symmetry to SM + U(1) or LR
- Breaking to SM: RH neutrino (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	$X^L_{45}, Y^L_{25}, Z^L_{23}$	3	$\bar{2}$	a	a
3	$X^u_{36}, Y^u_{31}, Z^u_{56}$	$\bar{3}$	1	$-a+k$	$-a-k$
3	$X^d_{36}, Y^d_{31}, Z^d_{56}$	$\bar{3}$	1	$-a-k$	$-a+k$
3	$L^1_{45}, L^2_{25}, L^3_{23}$	1	$\bar{2}$	$-3a$	$-3a$
3	$\nu^1_{36}, \nu^2_{31}, \nu^3_{56}$	1	1	$3a+k$	$3a-k$
3	$e^1_{36}, e^2_{31}, e^3_{56}$	1	1	$3a-k$	$3a+k$
3	$X^u_{12}, Y^u_{64}, Z^u_{14}$	1	2	$-k$	k
3	$X^d_{12}, Y^d_{64}, Z^d_{14}$	1	2	k	$-k$

$$W = \begin{pmatrix} X^L_{45} \\ Y^L_{25} \\ Z^L_{23} \end{pmatrix} \begin{pmatrix} 0 & Z^u_{14}\frac{v_1}{\Lambda} & -Y^u_{64} \\ -Z^u_{14}\frac{v_1\phi\psi}{\Lambda^3} & 0 & X^u_{12}\frac{\phi}{\Lambda} \\ Y^u_{64}\frac{\psi}{\Lambda} & -X^u_{12} & 0 \end{pmatrix} \begin{pmatrix} X^u_{36} \\ Y^u_{31} \\ Z^u_{56} \end{pmatrix}$$

$$+ \begin{pmatrix} X^L_{45} \\ Y^L_{25} \\ Z^L_{23} \end{pmatrix} \begin{pmatrix} 0 & Z^d_{14}\frac{v_1}{\Lambda} & -Y^d_{64} \\ -Z^d_{14}\frac{v_1\tilde{\phi}\tilde{\psi}}{\Lambda^3} & 0 & X^d_{12}\frac{\tilde{\phi}}{\Lambda} \\ Y^d_{64}\frac{\tilde{\psi}}{\Lambda} & -X^d_{12} & 0 \end{pmatrix} \begin{pmatrix} X^d_{36} \\ Y^d_{31} \\ Z^d_{56} \end{pmatrix} + \begin{pmatrix} L^1_{45} \\ L^2_{25} \\ L^3_{23} \end{pmatrix} \begin{pmatrix} 0 & Z^u_{14}\frac{v_2}{\Lambda} & -Y^u_{64} \\ -Z^u_{14}\frac{v_2\phi\psi}{\Lambda^3} & 0 & X^u_{12}\frac{\phi}{\Lambda} \\ Y^u_{64}\frac{\psi}{\Lambda} & -X^u_{12} & 0 \end{pmatrix} \begin{pmatrix} \nu^1_{36} \\ \nu^2_{31} \\ \nu^3_{56} \end{pmatrix}$$

$$+ \begin{pmatrix} L^1_{45} \\ L^2_{25} \\ L^3_{23} \end{pmatrix} \begin{pmatrix} 0 & Z^d_{14}\frac{v_2}{\Lambda} & -Y^d_{64} \\ -Z^d_{14}\frac{v_2\tilde{\phi}\tilde{\psi}}{\Lambda^3} & 0 & X^d_{12}\frac{\tilde{\phi}}{\Lambda} \\ Y^d_{64}\frac{\tilde{\psi}}{\Lambda} & -X^d_{12} & 0 \end{pmatrix} \begin{pmatrix} e^1_{36} \\ e^2_{31} \\ e^3_{56} \end{pmatrix}$$

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

$$Ae^{-aT_i}H.H$$

- **CKM Matrix**

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

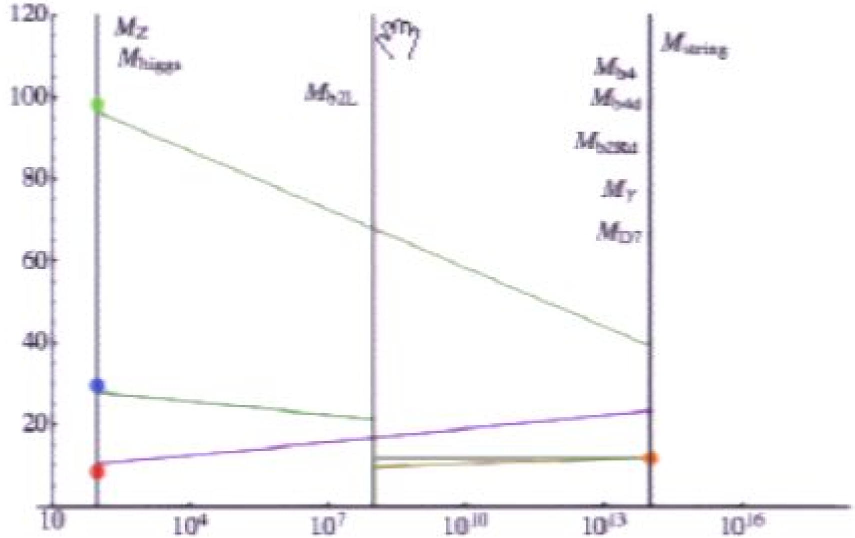
$$|V_{\rm CKM}| = \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

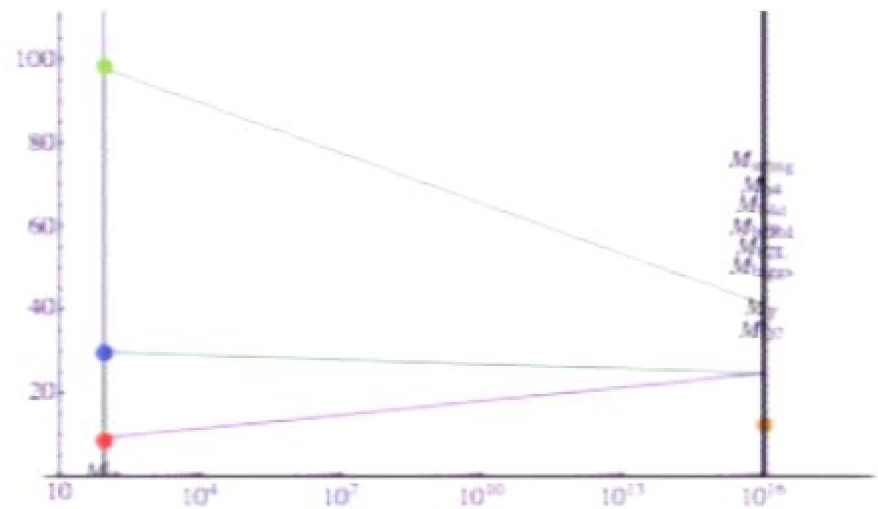
- **PMNS Matrix**

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

- **14 Parameters vs 21 Observables**

Gauge Coupling Unification



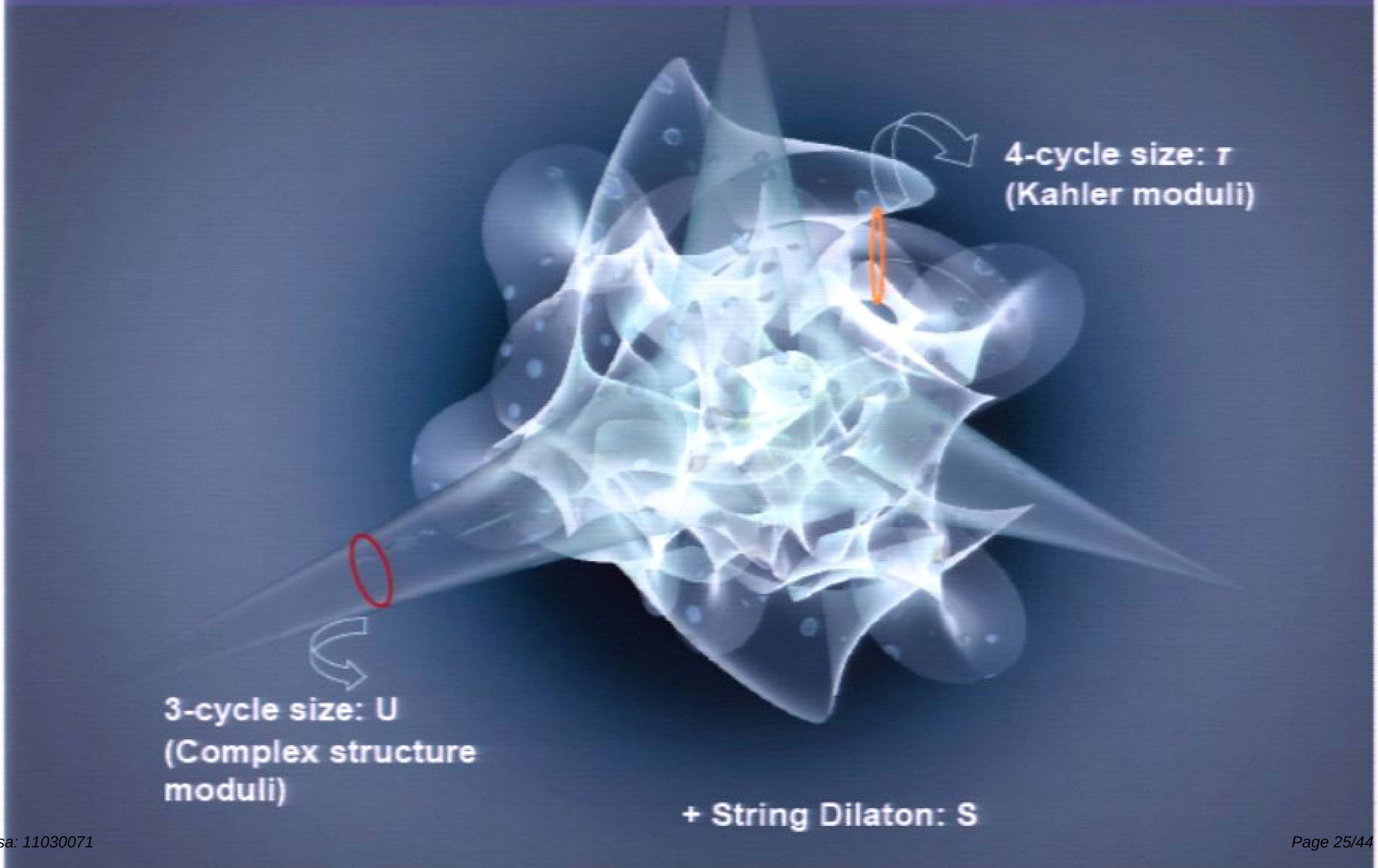


String scale value of all couplings given by dilaton so unification.

Standard GUT scale unification or 'intermediate' scale

Need moduli stabilisation to fix scales...

MODULI STABILISATION

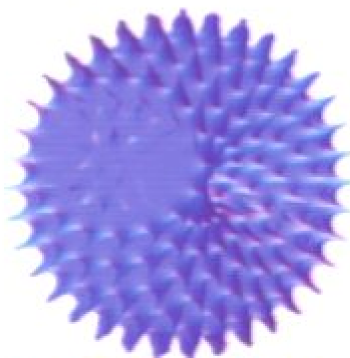


LARGE Volume Scenario

Exponentially Large Volumes

Example : BBCQ, CQS (2005)

$\mathbb{P}^4_{[1,1,1,6,9]}$,



*From P. Berglund!

$$\mathcal{K} = -2\ln\left(\frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right) + \frac{\xi}{2g_s^{3/2}}\right)$$

$$W = W_0 + A_s e^{-a_s T_s}.$$

Perturbative (alpha') corrections to K

Volume

Fluxes

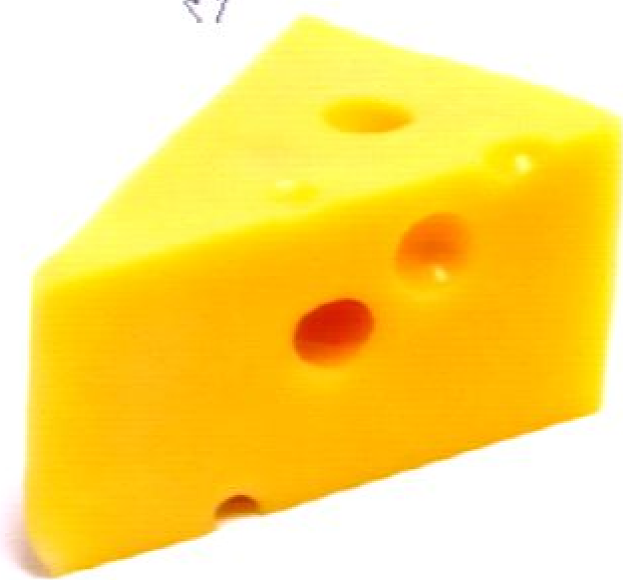
Nonperturbative corrections to W

$$V = \sum_{\Phi=S,U} \frac{\hat{K}^{\Phi\bar{\Phi}} D_\Phi W \bar{D}_{\bar{\Phi}} \bar{W}}{\mathcal{V}^2} + \frac{\lambda (a_s A_s)^2 \sqrt{\tau_s} e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{\mu W_0 a_s A_s \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\nu\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

$$\Rightarrow \quad \mathcal{V} \sim e^{a_s\tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

Exponentially large volumen + Broken SUSY!!!

e.g.Swiss Cheese Calabi-Yau's



$$\mathcal{V} \sim \tau_l^{\frac{3}{2}} - \sum_{s=1}^{h^{1,1}-1} \tau_s^{\frac{3}{2}} \, .$$

Very generic

$\mathbb{P}_{[1,3,3,3,5]}[15]$ $\quad \mathbb{P}^4_{1,2,2,10,15}(30)$ $\quad \mathbb{P}^4_{1,1,2,2,6}(12)/\mathbb{Z}_2$ $\quad \mathbf{M}_{\mathbf{n}}^{(\mathrm{dP}_8)^{\mathbf{n}}}$

Blumenhagen, et al., Grimm et al., Kreuzer et al. 08

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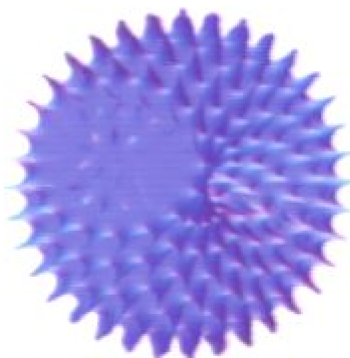

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Blumenhagen, et al., Grimm et al., Kreuzer et al. 08

LARGE Volume Implies

Standard Model on brane wrapping small cycle or at singularity

(SM D7 cannot wrap the exponentially large cycle since $g^2=1/\mathcal{V}^{2/3}$)

➡ **Local String Models! ('Bottom-up')**
Also: generically hyperweak new interactions.

Relevant Scales

- String scale $M_s = M_P / V^{1/2}$
- Kaluza-Klein scale $M_{KK} = M_P / V^{2/3}$
- Gravitino mass $m_{3/2} = W_0 \, M_P / V$
- Volume modulus mass $M_V = M_p / V^{3/2}$
- Lighter (fibre) moduli $M_l = M_p / V^{5/3}$

General Scenarios

- $M_{String} = M_{GUT} \sim 10^{16}$ GeV ($V \sim 10^{5}$)
- $W_0 \sim 10^{-11} << 1$ (or $W_0 \sim 1$ plus warping) to get TeV soft terms
- Fits with coupling unification
- Natural scale of most string inflation models.
- Axi-volume quintessence scale (w=-0.999….)
- $M_{String} = M_{int.} \sim 10^{12}$ GeV ($V \sim 10^{15}$)
- $W_0 \sim 1$
- $m_{3/2} \sim 1$ TeV (solves hierarchy problem!!!)
- QCD axion scale
- neutrino masses LLHH
- $M_{String} = 1$ TeV ($V \sim 10^{30}$)
- $W_0 \sim 1$
- Most exciting, but 5th Force (volume modulus $m \sim 10^{-15}$ eV naively but...)

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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

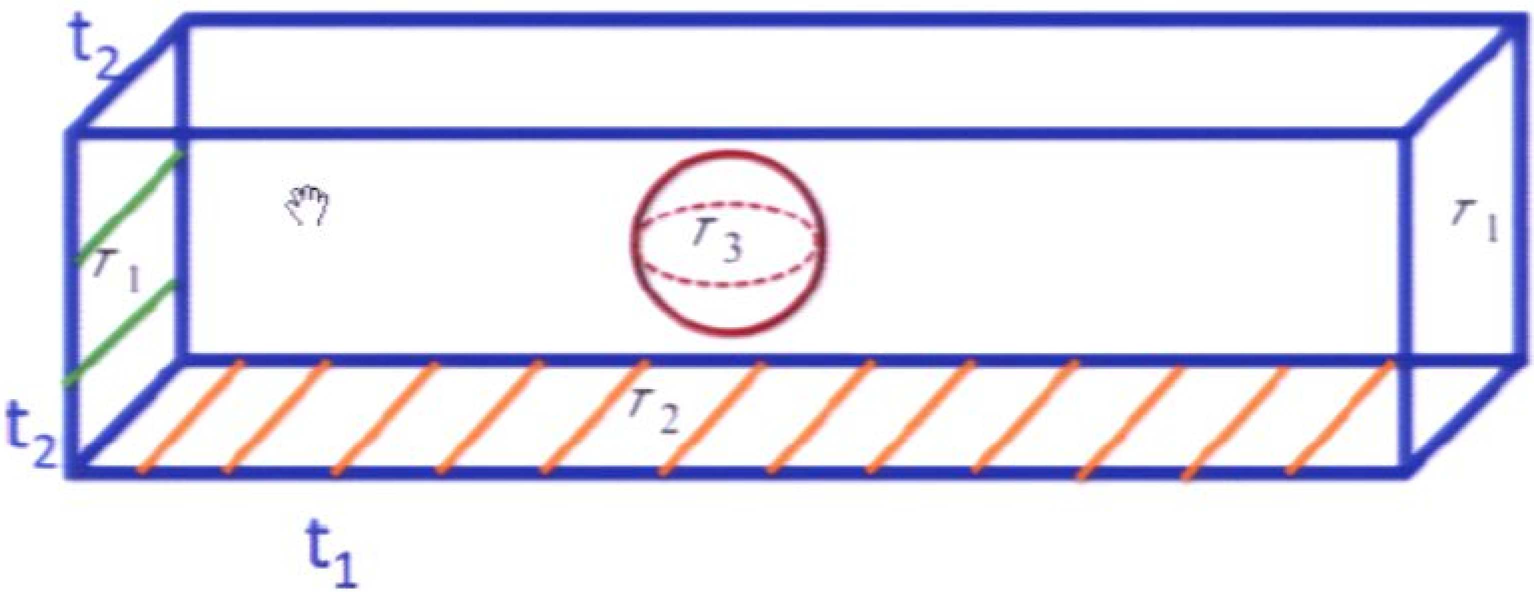
Blumenhagen et al.

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

[redacted]

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!!

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
   $M_{1/2}$ ~ F_S/Mp ~ 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 $V\sim10^{6-7}$.

★ 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

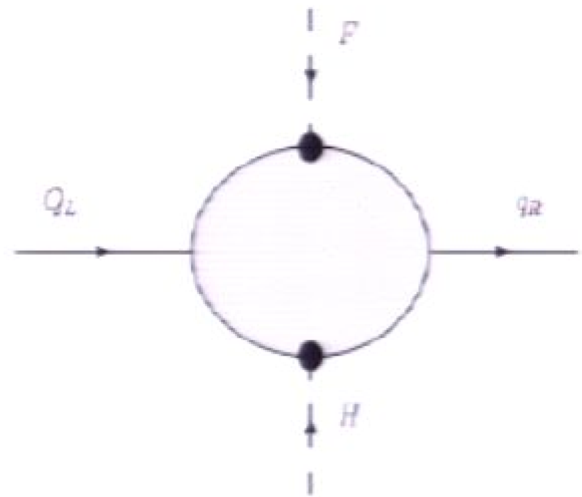
SUSY broken on the brane:

$Mv \sim Mp/V \sim 10^{-3}$ eV>>$Mp/V^{3/2}$

But potential destabilisation of LV minimum (back reaction?)

Perturbative quark masses

- Ibanez 1982



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

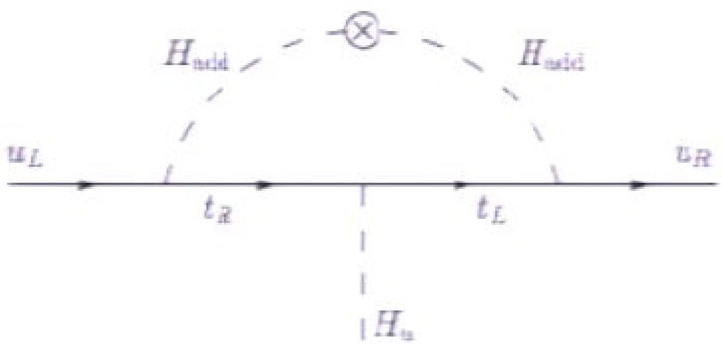
$M_W \, M_{3/2}^2 / Mp^2 \sim 10^{-30} \, M_W$?

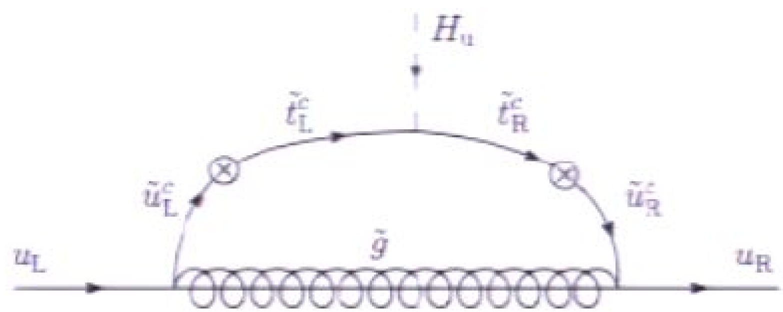
Scenario 1: $\Delta m \sim M_W \, M_{3/2}^2 / Ms^2 \sim .1 MeV$!

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,...

CONCLUSIONS

- Continuous progress on Local model building and Large volume scenario
- Several SUSY breaking scenarios
  ($m \sim m_{3/2}$, $m_{3/2}^{3/2}/M_p^{1/2}$, $m_{3/2}^2/M_p$), ($M_s \sim 10^3 - 10^{16}$ GeV)
  (see Conlon et al, Choi et al also)
- Local model building(3-families, mass hierarchies (M,m,0) (0-evalue lift), CKM, dP3: flavour, unification,…)
- Many open questions

  (More explicit SUSY breaking. Flat directions,
  A fully realistic compact model? ...)