

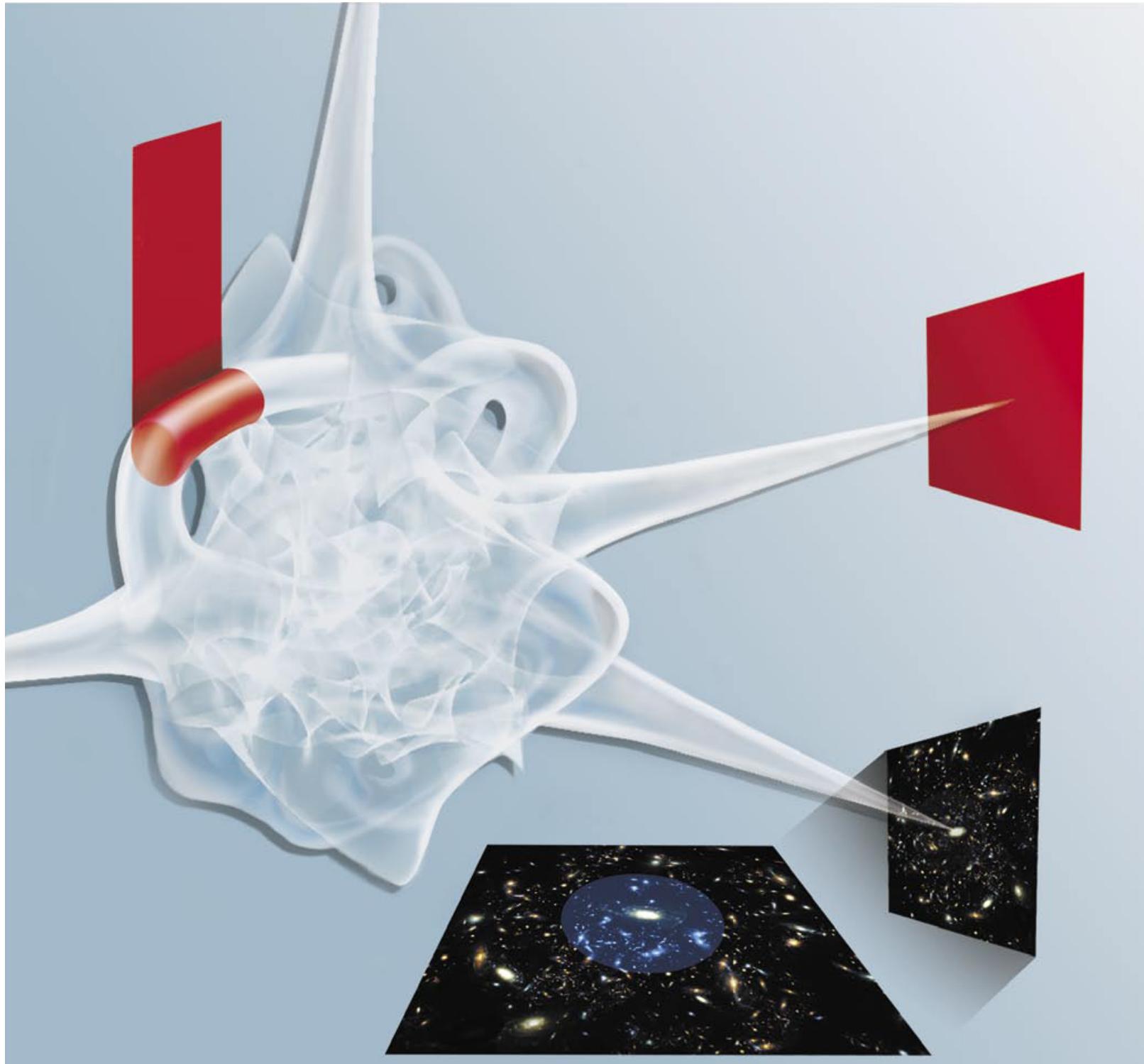
Flavour and SUSY breaking in Local String Models

F. Quevedo, Cambridge/ICTP. SUSY2010 Bonn August 2010.

R. Blumenhagen, J. Conlon, S. Krippendorf, S. Moster, FQ; JHEP 0909:007,2009
S. Krippendorf, M. Dolan, A. Maharana, FQ; arXiv:1002.1790 and to appear
C. Burgess, A. Maharana, FQ; arXiv:1005.1199
C. Burgess, M. Cicoli, M. Gomez-Reino, FQ, G. Tasinato, I. Zavala; arXiv1005.4840

See also: I. Zavala's and S. Krippendorff's talks

Local String Models



Universe
D3 Brane
or
D7 Brane

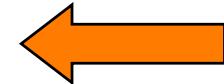
Standard Model Localised →(Bottom-up)

- **Fractional D3/D7 Brane at a singularity
(collapsed cycle)** Aldazabal et al.
- **Magnetised D7 - Brane wrapping a ‘small’ four-cycle** Blumenhagen et al.
- **Local F-Theory**

Donagi, Wijnholt; Vafa, Heckman, ...
(see Blumenhagen's talk)

D3 Branes at Singularities

- Orbifolds
- Del Pezzos 0-8
- Larger class: Toric singularities
(infinite class of models!!!)

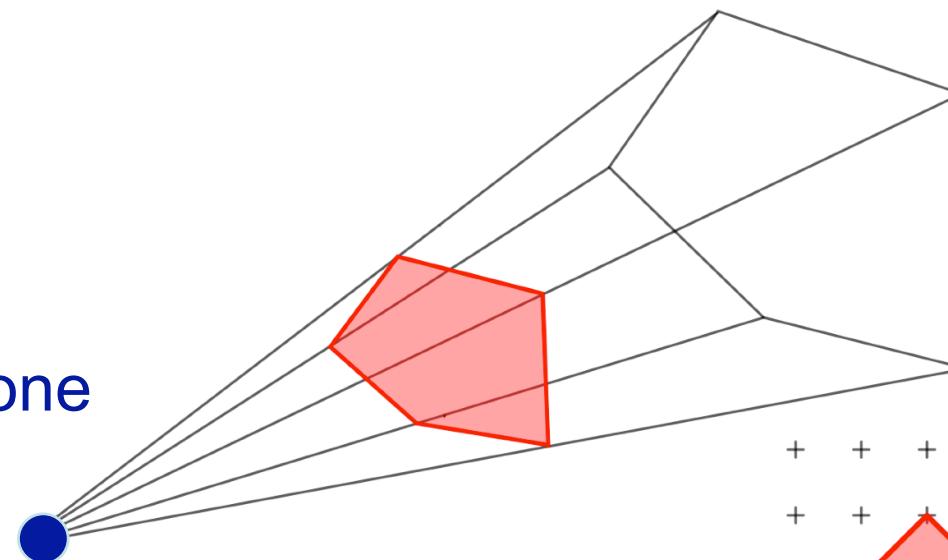


Toric Singularities

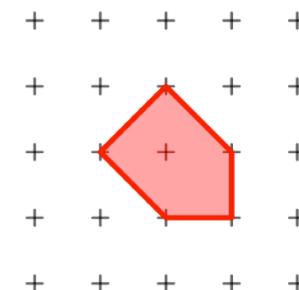
$$ds^2 = dr^2 + r^2 g_{ij} dx^i dx^j$$

Einstein-Sasaki

T^3 Fibration
Over rational
polyhedral cone

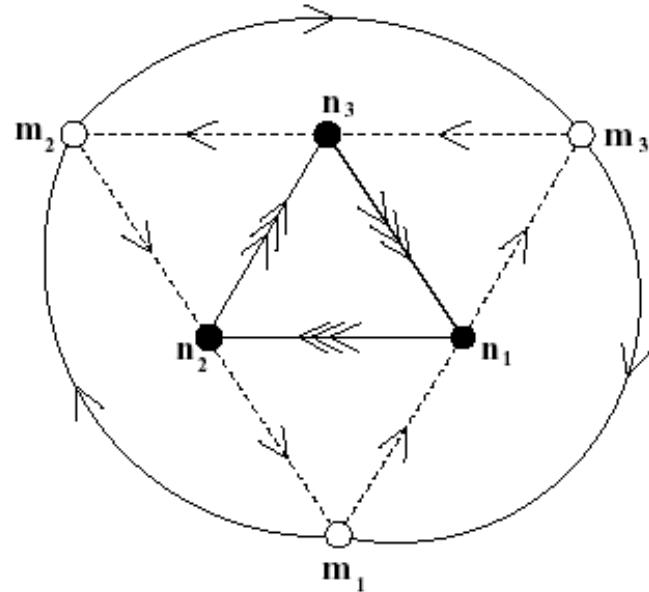


D3-branes



Toric
Diagram

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 $\Pi U(m_j)$)

Arrows=bi-fundamentals

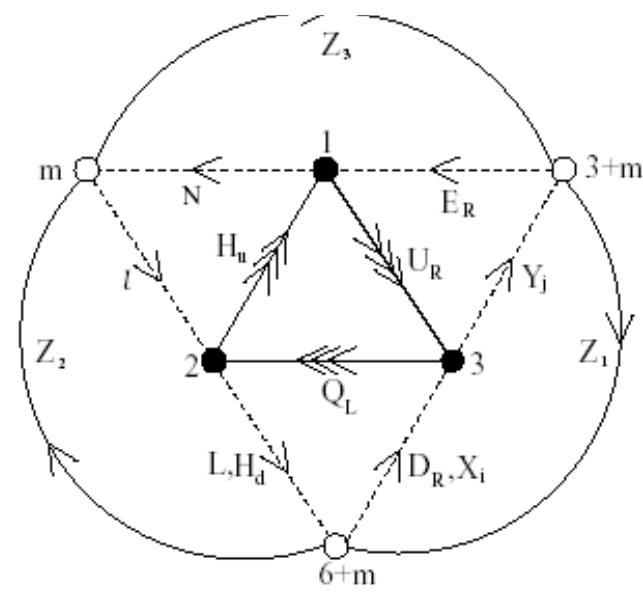
$$3 [(\mathbf{n}_1, \bar{\mathbf{n}}_2, \mathbf{1}) + (\mathbf{1}, \mathbf{n}_2, \bar{\mathbf{n}}_3) + (\bar{\mathbf{n}}_1, \mathbf{1}, \mathbf{n}_3)] + m_1 [(\bar{\mathbf{n}}_1, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{n}_2, \mathbf{1})] \\ + m_2 [(\mathbf{1}, \bar{\mathbf{n}}_2, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{n}_3)] + m_3 [(\mathbf{1}, \mathbf{1}, \bar{\mathbf{n}}_3) + (\mathbf{n}_1, \mathbf{1}, \mathbf{n}_1)] \quad \text{3 Families!}$$

$$m_2 = 3(n_3 - n_1) + m_1 \quad m_3 = 3(n_3 - n_2) + m_1 \quad \text{Anomaly/tadpole cancelation}$$

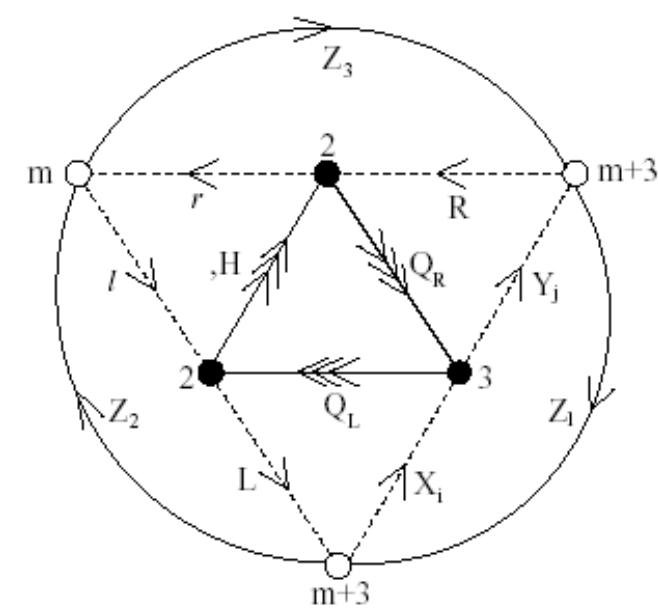
$$Q_{anomaly-free} = - \sum_{i=1}^3 \frac{Q_i}{n_i},$$

Hypercharge ($n_i \neq n_j$)

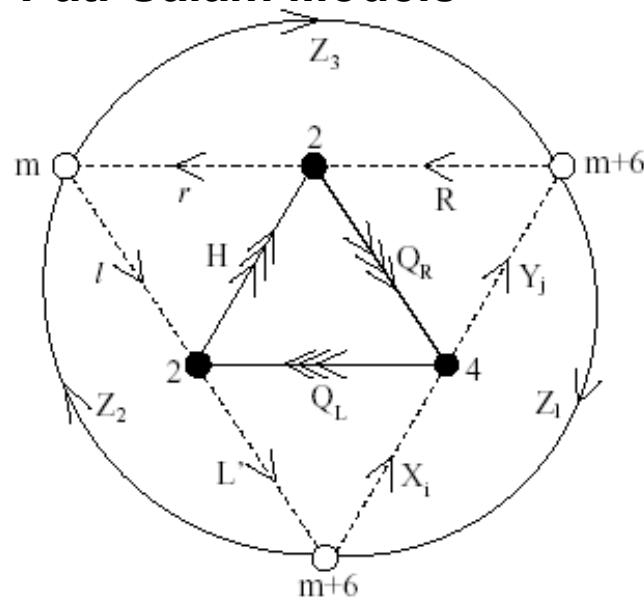
Standard Models



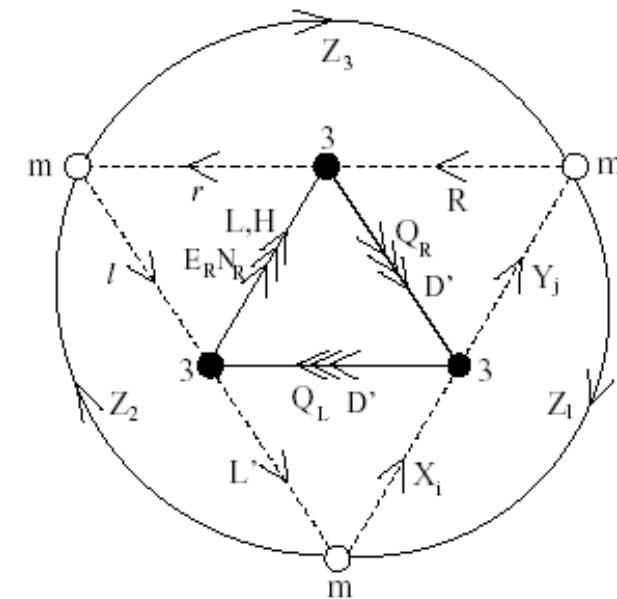
LR-Symmetric Models



Pati-Salam Models



Trinification Models

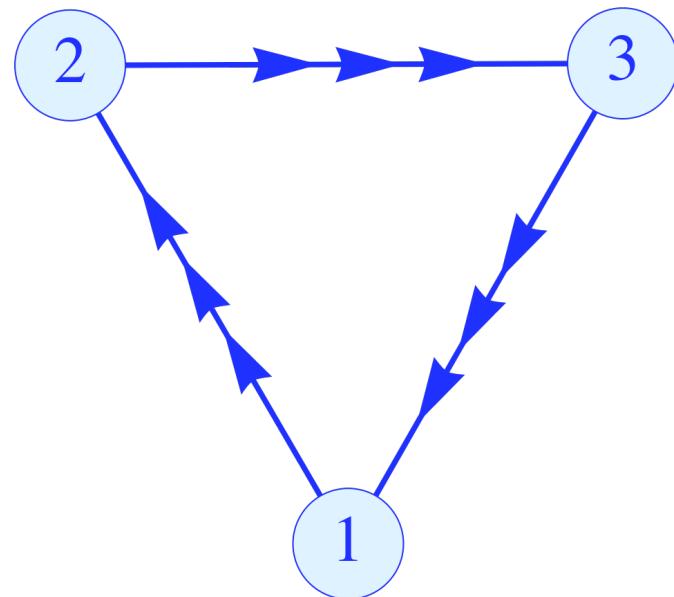
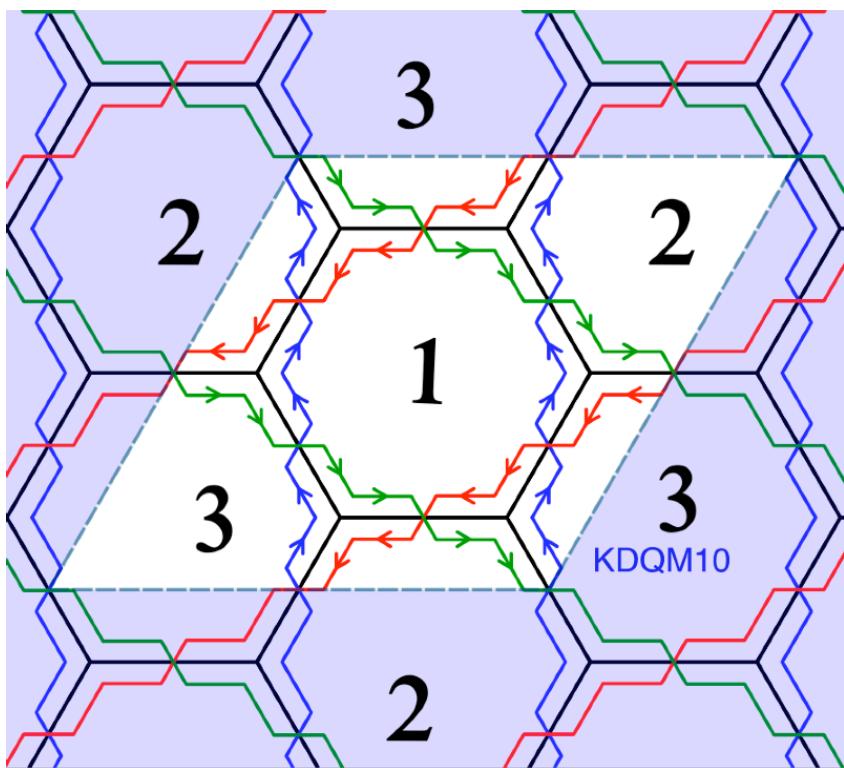


Relevant Questions

1. Quiver: Matter content + superpotential
2. Given a singularity find the quiver theory

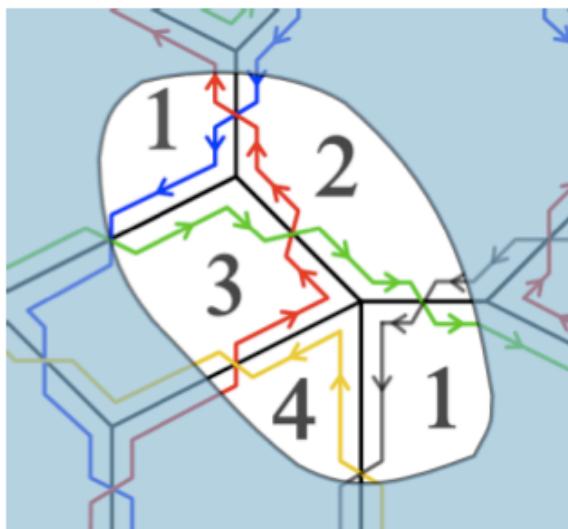
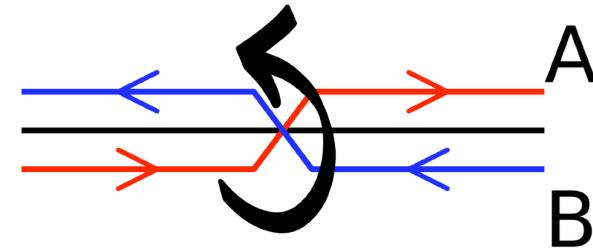
Answer to Question 1:

Dimer Diagrams (e.g. dP0)



DIMERS

- Faces
= gauge groups
- Intersection of zigzag paths
= bi-fundamental matter
- Vertices (faces orbited by zigzag paths)
= superpotential terms, e.g.:



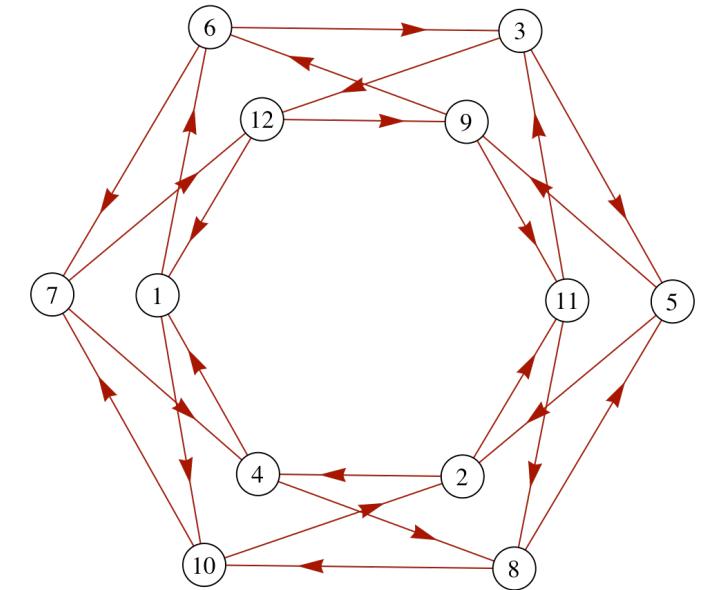
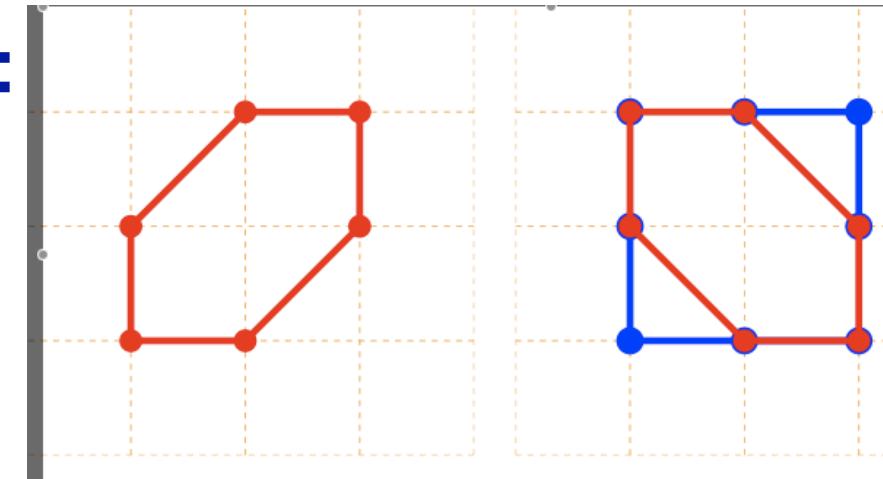
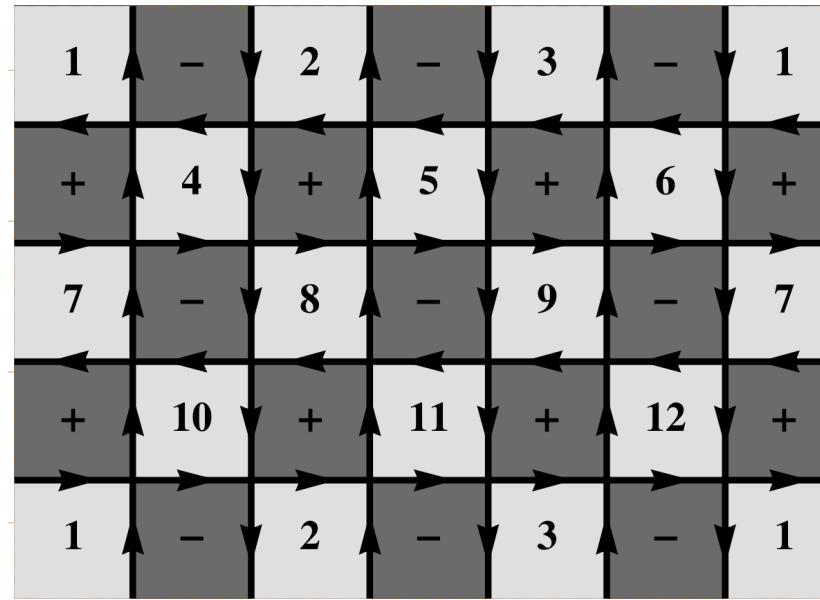
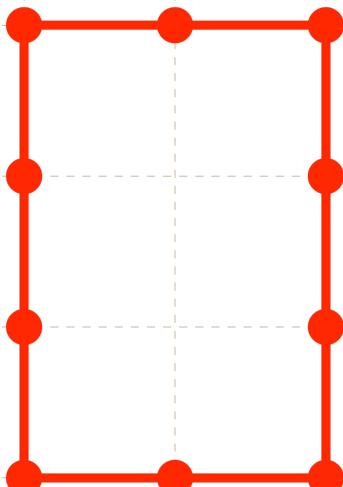
Superpotential for these two vertices:

$$W = X_{13}X_{32}X_{21} - X_{14}X_{43}X_{32}X_{21}$$

Answer to Question 2

Gulotta's Algorithm:

Gulotta 0807.3012



General Results

- 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)**

See Krippendorf's talk

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

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

$$V_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \quad \text{Works due to SU(2)xU(1) isometry}$$

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

4. CP violation

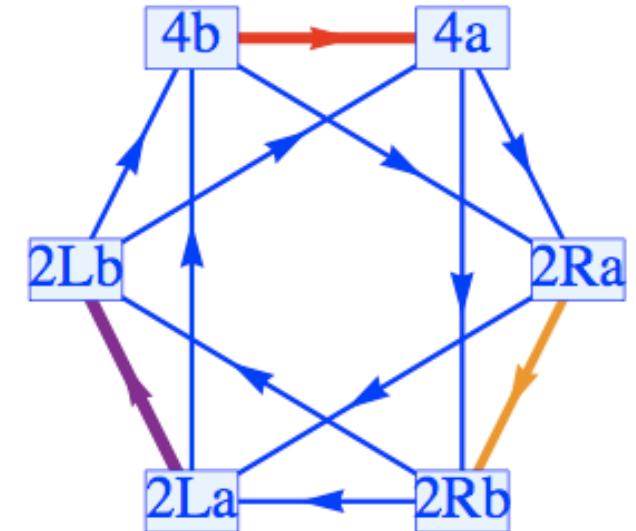
Jarlskog invariant $J = 3.05_{-0.20}^{+0.19} \times 10^{-5} \approx \epsilon^{6.5}$.

D3D3 case (similar for D3D3/D3D7)

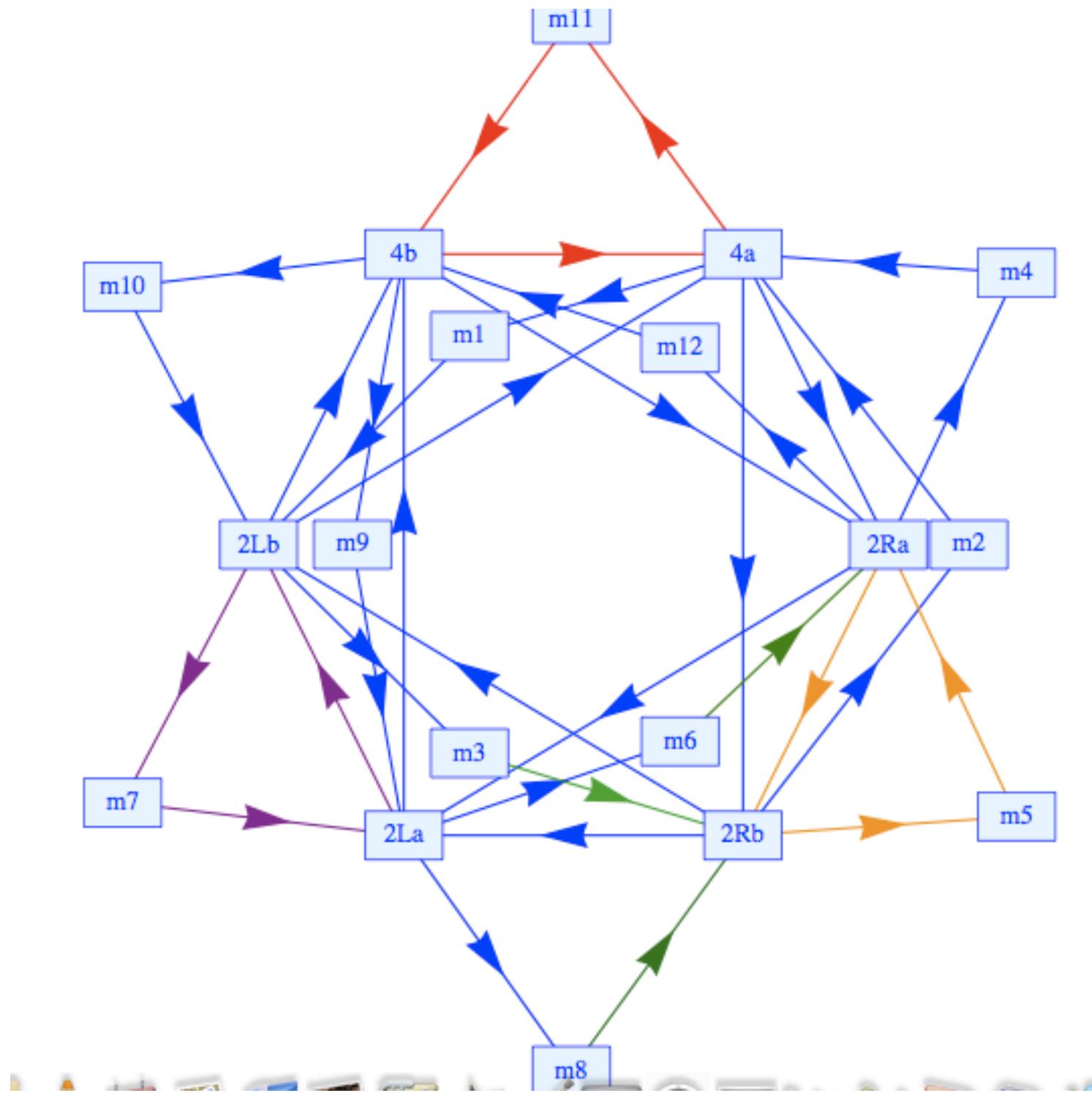
$$J = \frac{|\Psi_d|^2}{\Lambda^4} \frac{|X_u|^2 \operatorname{Im}(Y_u \bar{Y}_d Z_d \bar{Z}_u \bar{\Phi}_u \Phi_d)}{(m_s^2 - m_d^2)(m_t^2 - m_u^2)(m_t^2 - m_c^2)} \approx \epsilon^6 \sin \delta$$

Realistic Pati-Salam Model (dP3)

- Break symmetry to SM + U(1)
- All quark+ lepton masses
- See-saw neutrino masses
- Stable proton
- CKM, CP
- Controled kinetic terms
- Unification?

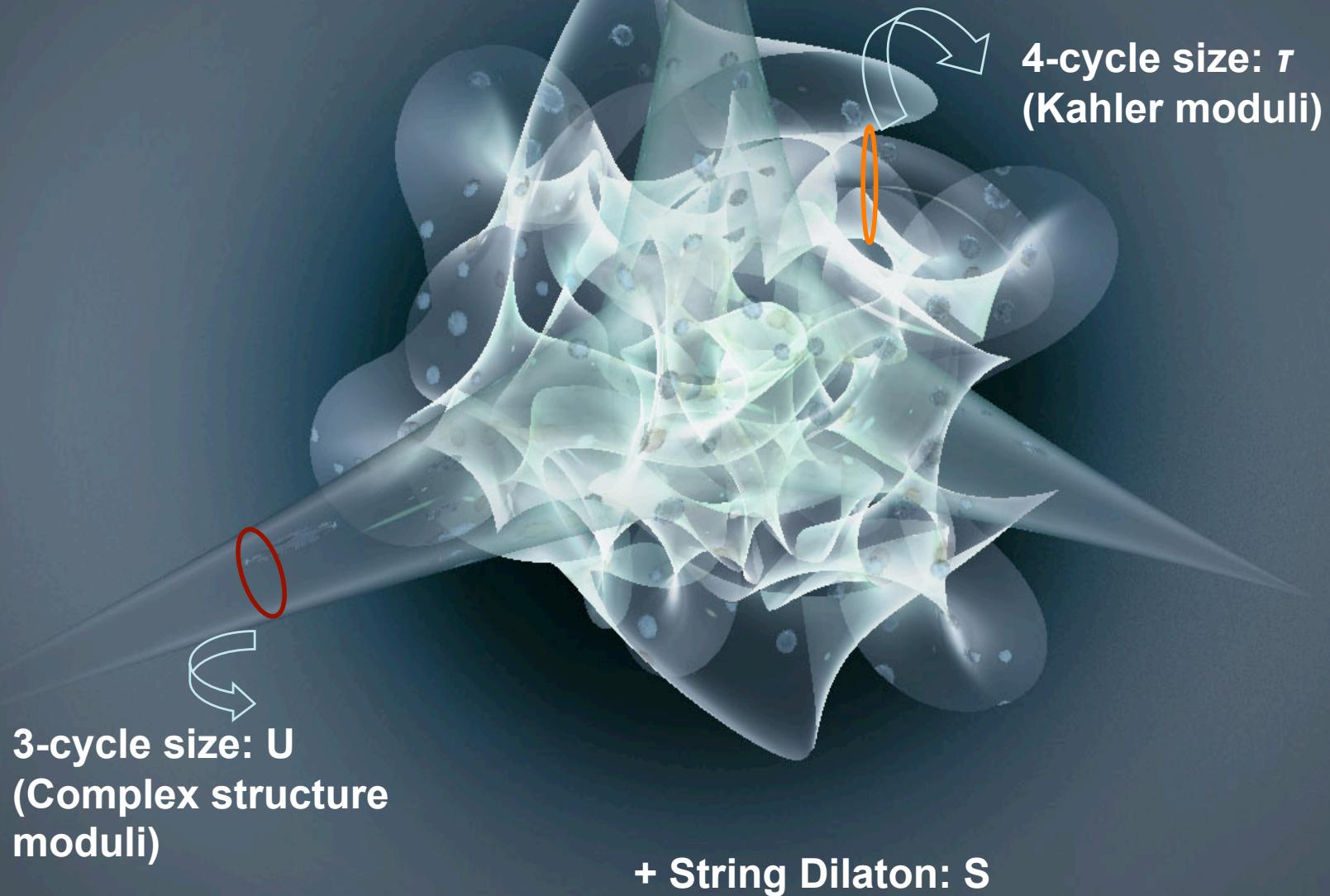


In progress...



LARGE Volume Scenario

MODULI STABILISATION

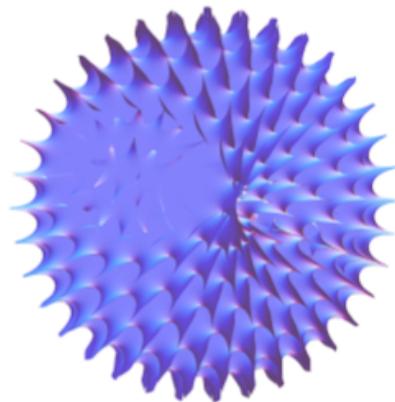


Exponentially Large Volumes

BBCQ, CQS (2005)

Example :

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



*From P. Berglund!

Perturbative (alpha') corrections to K

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

$$W = \underbrace{W_0}_{\text{Fluxes}} + A_s e^{-a_s T_s}.$$

Volume

Nonperturbative corrections to W

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



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

Exponentially large volumen + Broken SUSY!!!

De Sitter?: anti D3 or D,F uplifting

Model dependent e.g.:

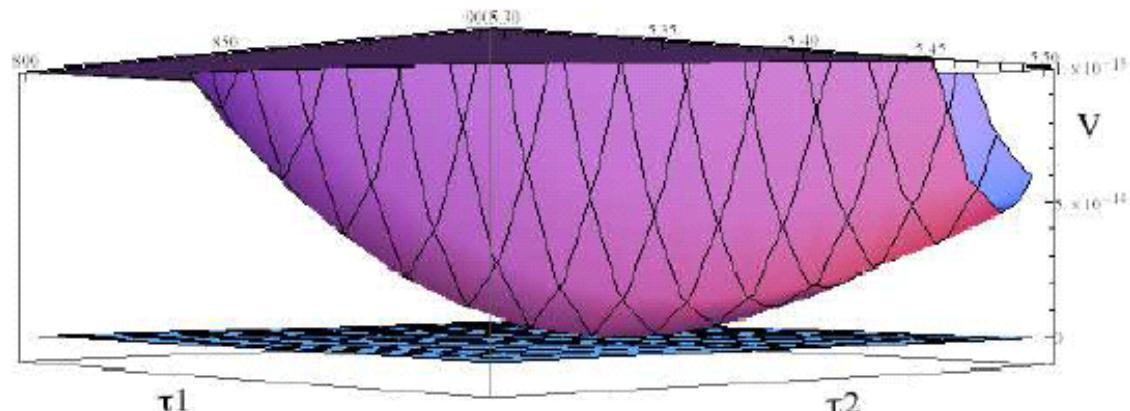
$$K = -2M_P^2 \log \left(\tau_1^{3/2} - \tau_2^{3/2} + \frac{\xi}{g_s^{3/2}} \right) + \frac{g_s^n \tau_2^n}{g_s \tau_1} (|p|^2 + |q|^2 + |\rho|^2 + |\Phi|^2),$$

$$W = M_P^3 g_s^{3/2} W_0 + \alpha M_P g_s^{1/2+n} e^{-aT_2} \left(\frac{p\Phi q}{\mu} + \Phi \rho \right).$$

(Or $W \sim W_0 + \varphi_1 \varphi_2 e^{-aT_2}$)

$$V = g_s M_P^4 \left(\frac{A e^{-2a\tau_2}}{\tau_1^{5/2} \tau_2^{1/6}} - \frac{B e^{-4/3a\tau_2} \tau_2^{14/9}}{\tau_1^{11/3}} + \frac{C}{\tau_1^{9/2}} \right) \rightarrow$$

LARGE volume de Sitter!



S. Krippendorf, FQ 2009

General Conditions for LARGE Volume

Cicoli, Conlon, FQ

- $h_{12} > h_{11} > 1$
- At least one blow-up mode (point-like singularity)
- Blow-up mode fixed by non-perturbative effects, volume by alpha' corrections, other (fibre) by loop corrections.

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

$$\mathbb{P}_{[1,3,3,3,5]}[15]$$

$$\mathbb{P}_{1,2,2,10,15}^4(30)$$

$$\mathbb{P}_{1,1,2,2,6}^4(12)/\mathbb{Z}_2$$

$$\mathbf{M}_{\mathbf{n}}^{(\mathrm{dP}_8)^n}$$

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

LARGE Volume Implies

Standard Model is localised !

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



‘Bottom-up’

Aldazabal et al.

- Fractional D3/D7 Brane at a singularity
(collapsed cycle)
- Magnetised D7 - Brane wrapping a ‘small’ four-cycle
Blumenhagen et al.
- Local F-Theory
Donagi, Wijnholt; Vafa, Heckman, ...

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

- $M_{\text{String}} = M_{\text{GUT}} \sim 10^{16} \text{ GeV}$ ($V \sim 10^5$)
 - $W_0 \sim 10^{-11} \ll 1$ (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 ($w = -0.999\dots$)
- $M_{\text{String}} = M_{\text{int.}} \sim 10^{12} \text{ GeV}$ ($V \sim 10^{15}$)
 - $W_0 \sim 1$
 - $m_{3/2} \sim 1 \text{ TeV}$ (solves hierarchy problem!!!)
 - QCD axion scale
 - neutrino masses LLHH
- $M_{\text{String}} = 1 \text{ TeV}$ ($V \sim 10^{30}$)
 - $W_0 \sim 1$
 - Most exciting, but 5th Force (volume modulus $m \sim 10^{-15} \text{ eV}$)??

SUSY BREAKING

Several Scenarios

- F-term of volume modulus \sim approximate no-scale ($M_{\text{soft}} (\sim F_T/M_p)$) \sim vanish!

1. SM cycle breaks SUSY:

$M_{\text{soft}} \sim 1 \text{ TeV}$ ($\sim F_T/M_{\text{string}} \sim M_p/V \sim M_{3/2}$)

Volume $\sim 10^{15}$ and $M_{\text{string}} \sim 10^{12} \text{ GeV}$.

2. SM cycle does not break SUSY

$M_{1/2} \sim F_s/M_p \sim M_p/V^2 \ll M_{3/2}$

Extreme case: $V \sim 10^7$, $M_{\text{string}} \sim 10^{15} \text{ GeV}$

Scenario 2.

- Uplifting to de Sitter important De Alwis 2006
- Gravitino very heavy $M_{3/2} > 10^8 \text{ GeV} !!$
- Generically no CMP! ($M_{\text{volume}} > M_{\text{soft}}$)
- Minimal volume $V \sim 10^{6-7}$.
 - ★ TeV soft terms and $M_{\text{string}} \sim 10^{15} \text{ GeV}$
 - ★ Unification scale $M_X \sim M_{\text{string}}$ $V^{1/6} \sim 10^{16} \text{ GeV} !$
 - ★ Right scale for inflation! Conlon+Palti
 - ★ No CMP !!!

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

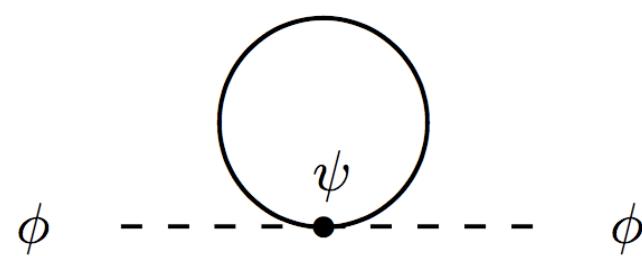
Question:

Unnaturally light scalars?

Loop induced heavy masses

$$-\mathcal{L}(\phi, \psi) := \frac{1}{2}[(\partial\phi)^2 + (\partial\psi)^2] + \frac{1}{2}[m^2\phi^2 + M^2\psi^2] + \frac{1}{24}[\lambda_\phi\phi^4 + 6g^2\phi^2\psi^2 + \lambda_\psi\psi^4]$$

where $M^2 \gg m^2 > 0$.


$$\delta m_\phi^2 \simeq \left(\frac{gM}{4\pi} \right)^2,$$

In Extra Dimensions:

$$-\frac{\mathcal{L}_2}{\sqrt{-g_{(4)}}} \simeq (\partial\phi)^2 + M_{KK}^2 \phi^2$$

$$-\frac{\mathcal{L}_3}{\sqrt{-g_{(4)}}} \simeq \frac{1}{M_p} \phi (\partial\phi)^2 + \frac{M_{KK}^2}{M_p} \phi^3$$

and $-\frac{\mathcal{L}_4}{\sqrt{-g_{(4)}}} \simeq \frac{1}{M_p^2} \phi^2 (\partial\phi)^2 + \frac{M_{KK}^2}{M_p^2} \phi^4,$

Without SUSY

$$M_{\text{mod}} \simeq M_{KK}^2/M_p.$$

With SUSY

$$\delta m^2 \simeq g (m_B^2 - m_F^2) \lesssim \left(\frac{M_{KK}^2}{M_p^2} \right) M_{3/2}^2 \simeq \left(\frac{1}{\mathcal{V}^{4/3}} \right) \frac{M_p^2}{\mathcal{V}^2},$$

$$\boxed{\delta m \simeq M_{KK} M_{3/2} / M_p \simeq M_p / \mathcal{V}^{5/3} \lesssim M_V \simeq M_p / \mathcal{V}^{3/2}}$$

Übernaturalness

Implications

- **Intermediate scale scenario**

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

- **GUT scale scenarios**

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

- **TeV Scenario**

SUSY broken on the brane:

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

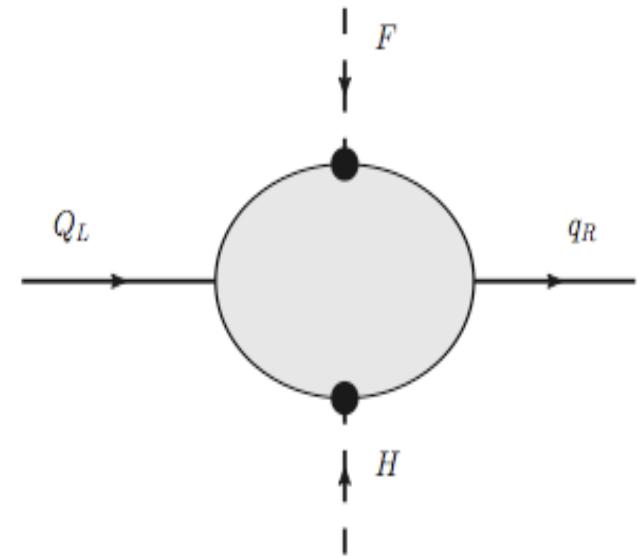
But potential destabilisation of LV minimum

Perturbative quark masses

- Ibanez 1982

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

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



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

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

CONCLUSIONS

- Continuous progress on **LARGE volume scenario**
- Several **SUSY breaking scenarios**
 $(m \sim m_{3/2}, m_{3/2}^{3/2}/M_p^{1/2}, m_{3/2}^2/M_p)$, $(M_s \sim 10^3 - 10^{16} \text{ GeV})$
- Local model building (3-families, mass hierarchies
 $(M, m, 0)$, CKM, Realistic models,...)
- Concrete models of inflation (gravity waves
and non-gaussianities)
- Many open questions
(More explicit SUSY breaking. Reheating (Bond et al, Cicoli+Mazumdar)
A fully realistic model? Testable model independent predictions?...)