Recent Developments in LARGE Volume String Scenario

F. Quevedo, Cambridge/ICTP. Planck 2010, CERN, May-June 2010.

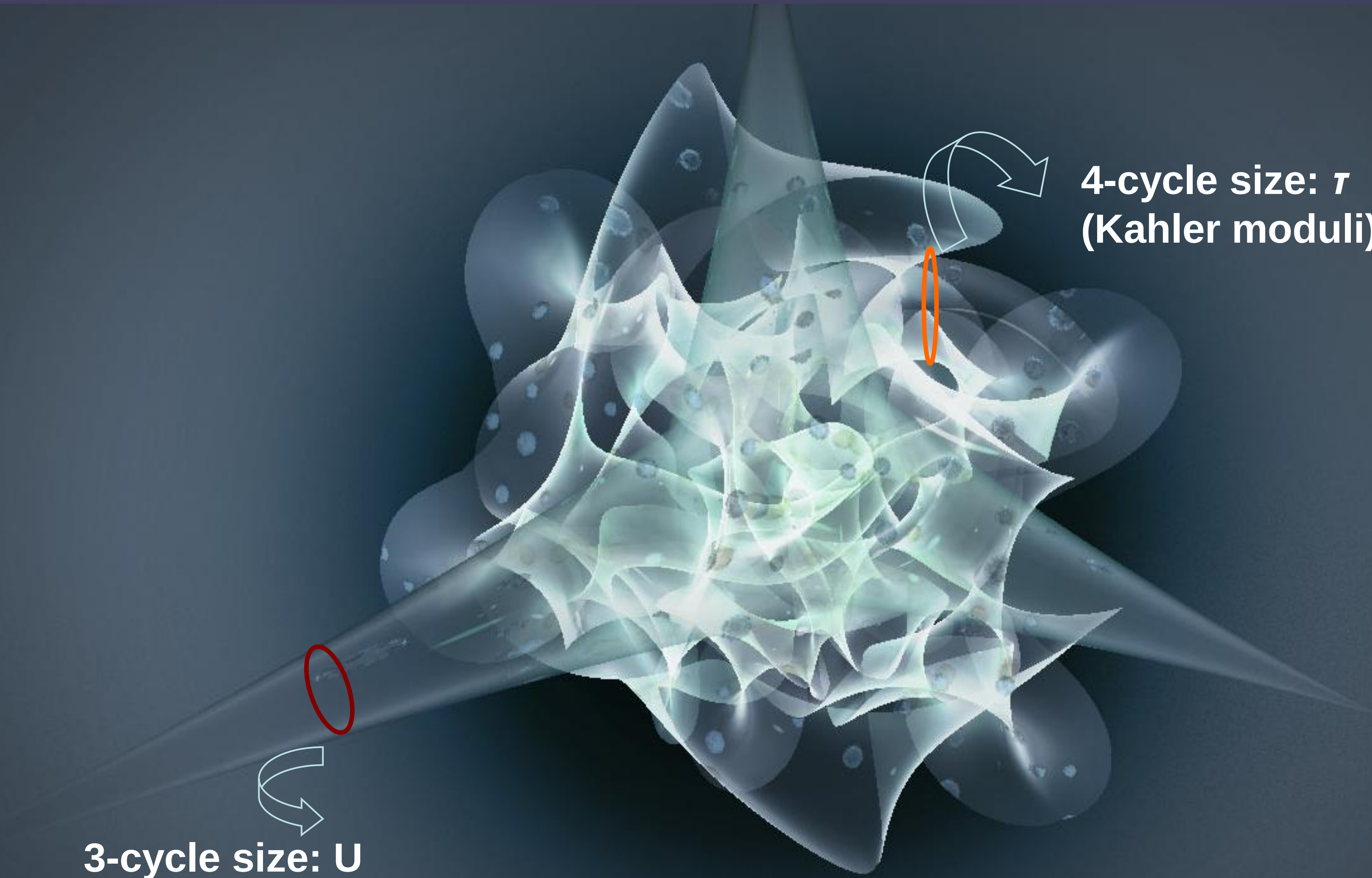
R. Blumenhagen, J. Conlon, S. Krippendorf, S. Moster, FQ; JHEP 0909:007,2009
S. Krippendorf, M. Dolan, A. Maharana, FQ; arXiv:1002.1790
C. Burgess, A. Maharana, FQ; arXiv:1005.1199
C. Burgess, M. Cicoli, M. Gomez-Reino, FQ, G. Tasinato, I. Zavala; arXiv1005.4840

String Phenomenologists:

Strategic (long term) Plan:

String theory scenario that satisfies all high energy and cosmological observations and hopefully lead to measurable predictions

MODULI STABILISATION



+ String Dilaton: S

LARGE Volume Scenario

IIB Moduli Stabilisation

…GKP, KKLT, …

Type IIB String on Calabi-Yau orientifold

Turn on Fluxes

$\int_a F_3 = n_a \qquad \int_b H_3 = m_b$

Size of cycle a = U_a

Superpotential $W = \int G_3 \wedge \Omega, \quad G_3 = F_3 - iS\, H_3$

Scalar Potential: $V = e^K \, |D_a W|^2$

Minimum $D_a W = 0$ Fixes U_a and S

T moduli unfixed: No-Scale models

GKP

Exponentially Large Volumes

BBCQ, CQS (2005)

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

Perturbative (alpha') corrections to K

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

Volume

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

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!!!

De Sitter?: anti D3 or D,F uplifing

Model dependent e.g.:

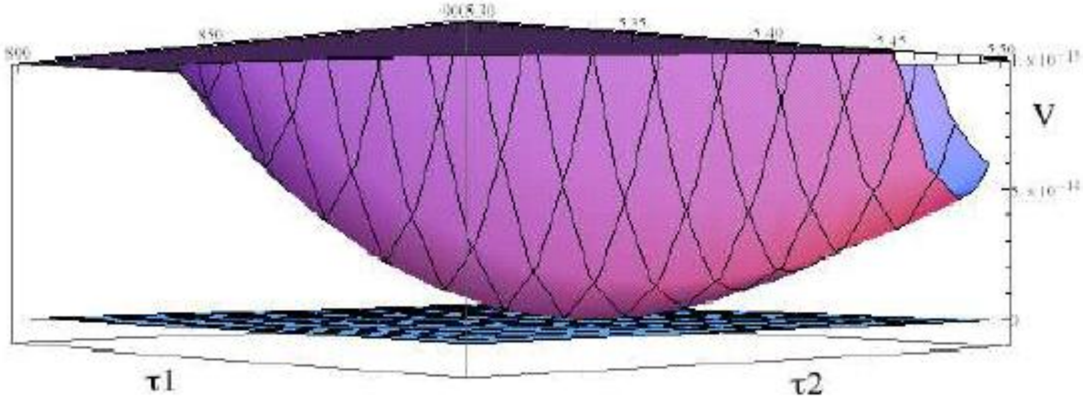
$$K = -2M_P^2 \log\left(\tau_1^{3/2} - \tau_2^{3/2} + \frac{\xi}{g_s^{3/2}}\right) + \frac{g_s^n \tau_2^n}{g_s \tau_1}\left(|p|^2 + |q|^2 + |\rho|^2 + |\Phi|^2\right),$$

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

(Or $W \sim W_0 + \varphi_1\varphi_2 e^{-aT2}$)

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

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

$\mathbb{P}_{[1,3,3,3,5]}[15]$ $\mathbb{P}^4_{1,2,2,10,15}(30)$ $\mathbb{P}^4_{1,1,2,2,6}(12)/\mathbb{Z}_2$ $\mathbf{M}_{\mathbf{n}}^{(\mathrm{dP}_{\mathbf{8}})^{\mathbf{n}}}$

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

Relevant Scales

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

General Scenarios

- $M_{String} = M_{GUT} \sim 10^{16}$ GeV (V~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….)
- $M_{String} = M_{int.} \sim 10^{12}$ GeV (V~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~10^{30})
  - $W_0 \sim 1$
  - Most exciting, but 5th Force (volume modulus m~10^{-15} eV)??

Model Building

LARGE Volume Implies

Standard Model is localised !

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

→ 'Bottom-up'

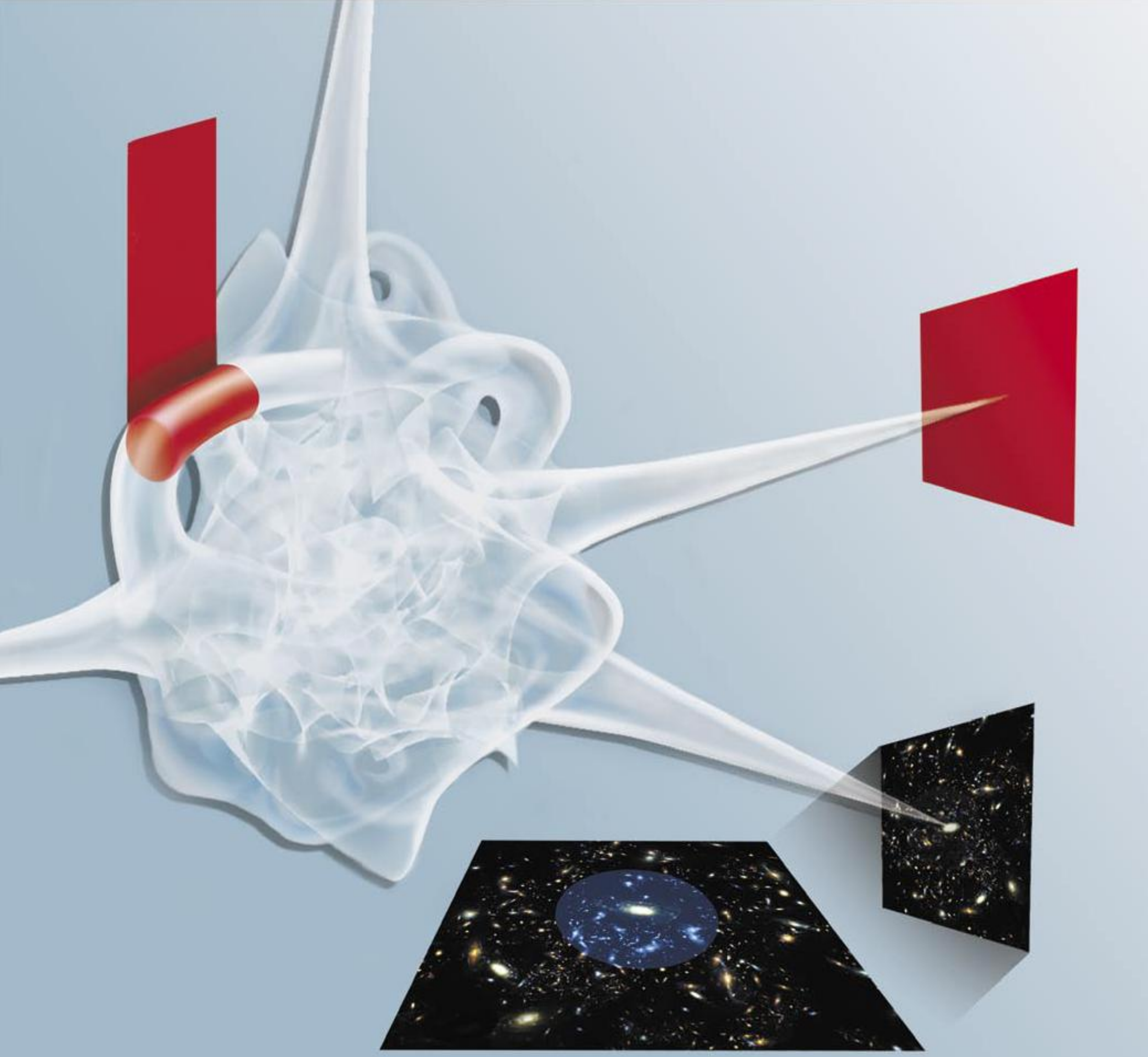
Aldazabal et al.

- 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, …



Universe

D3 Brane

or

D7 Brane

D3 Branes at Singularities

- Orbifolds
- Del Pezzos 0-8
- Larger class: Toric singularities

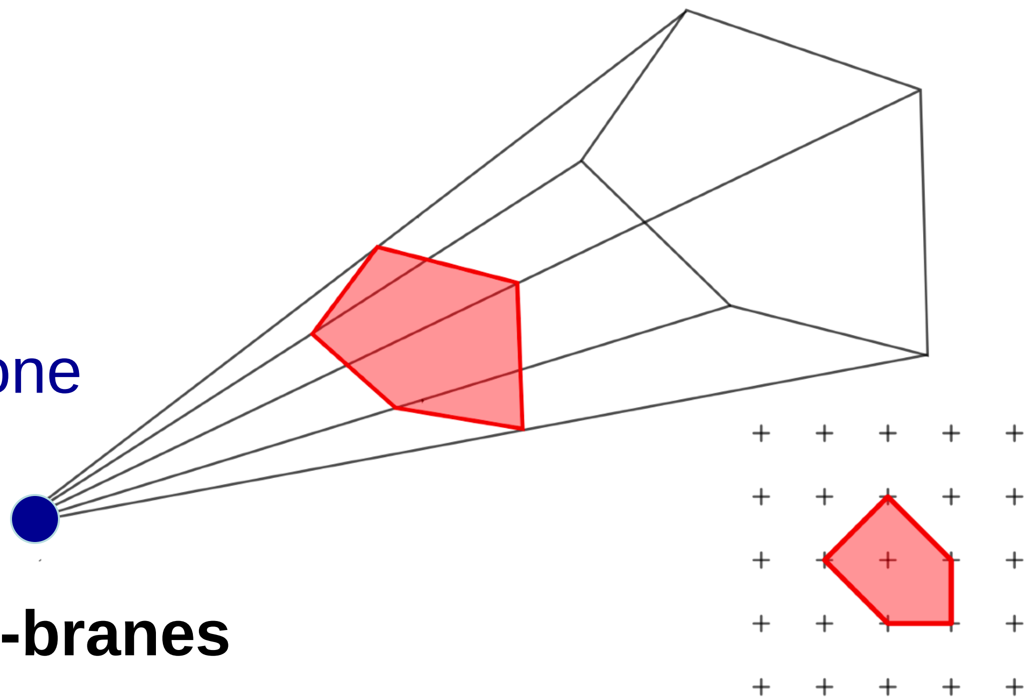
(infinite class of models!!!)

Toric Singularities

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

Einstein-Sasaki

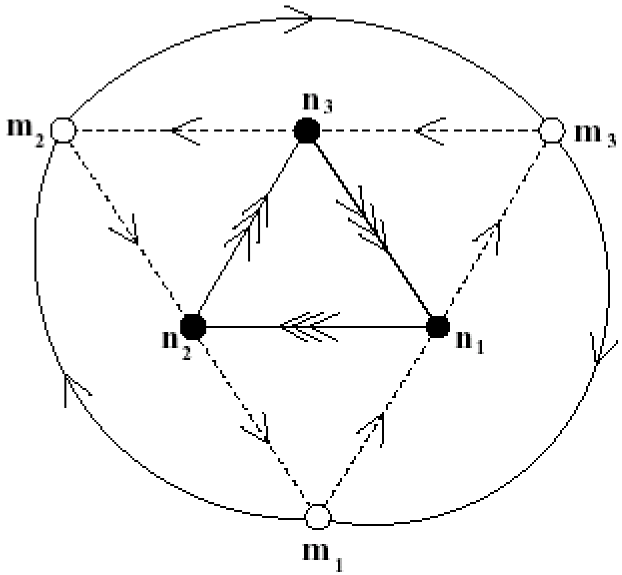
T^3 Fibration
Over rational
polyhedral cone



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

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

3 Families!

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

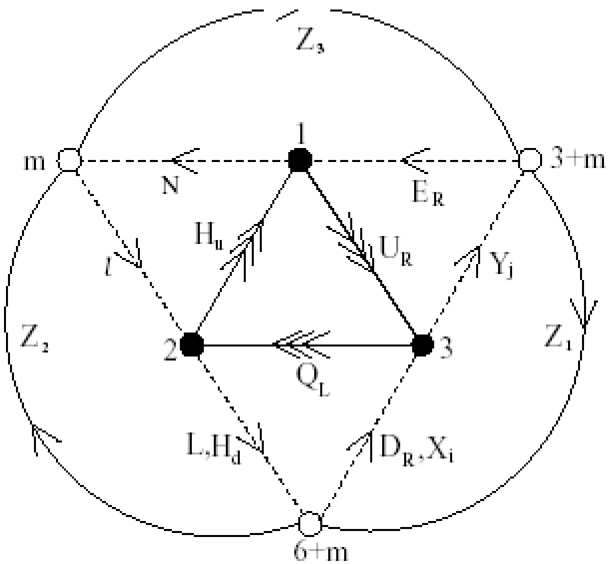
Anomaly/tadpole cancelation

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

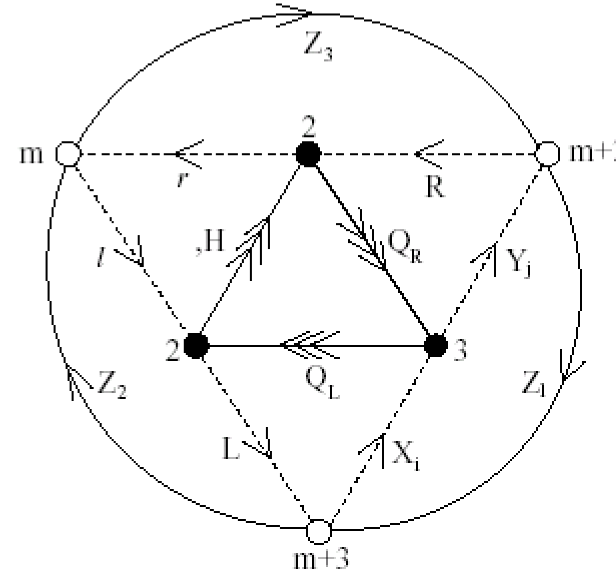
Hypercharge ($n_i \neq n_j$)

D7s:Franco-Uranga

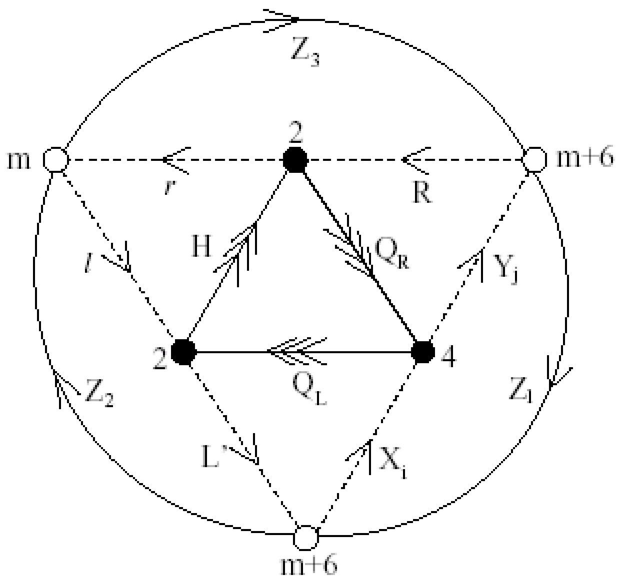
Standard Models



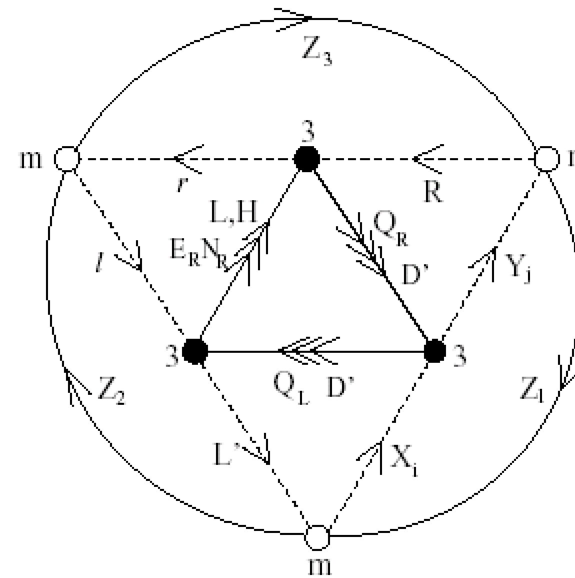
LR-Symmetric Models



Pati-Salam Models



Trinification Models



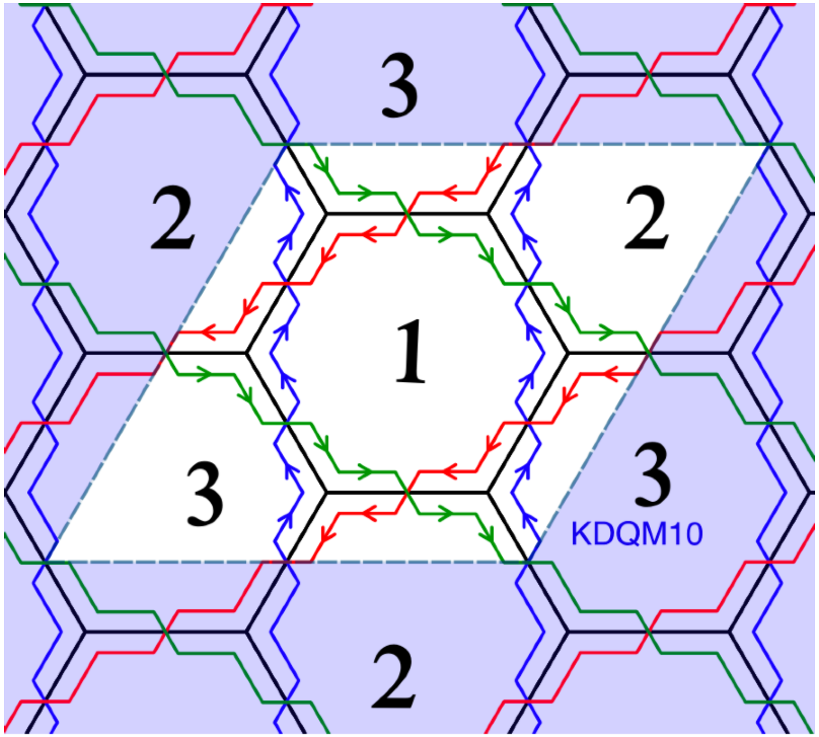
Relevant Questions

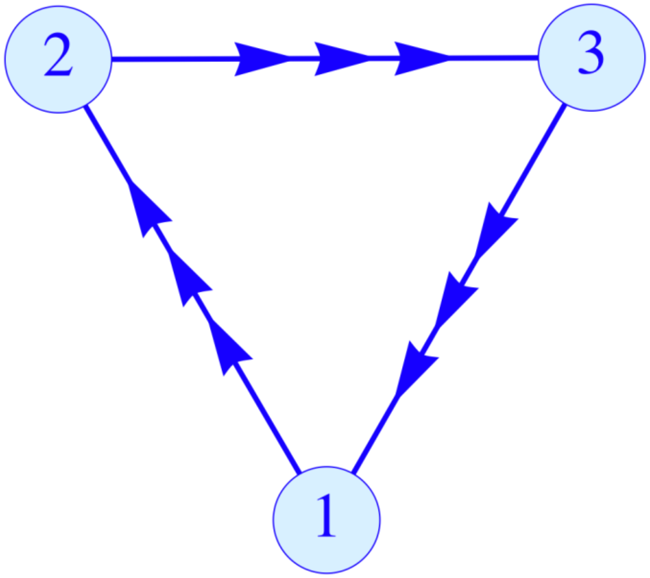
1. Quiver: Matter content + superpotential

2. Given a singularity find the quiver theory

Answer to Question 1:

Dimer Diagrams (e.g. dP0)

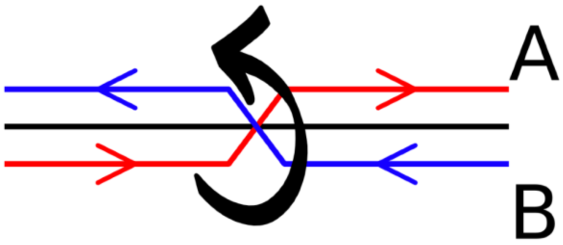




DIMERS

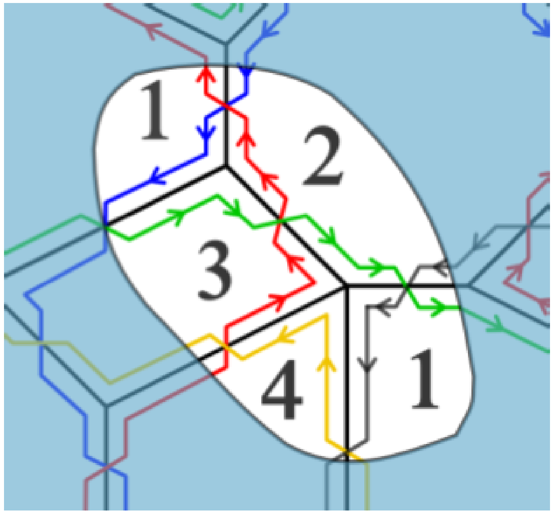
•**Faces**

= **gauge groups**



•**Intersection of zigzag paths**
fundamental matter

•**Vertices (faces orbited by zigzag paths)** = **superpotential terms, e.g.:**



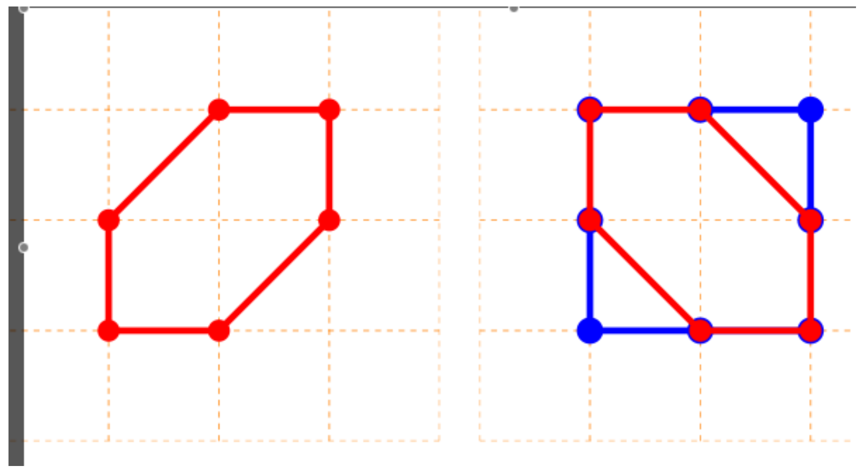
Superpotential for these two vertices:

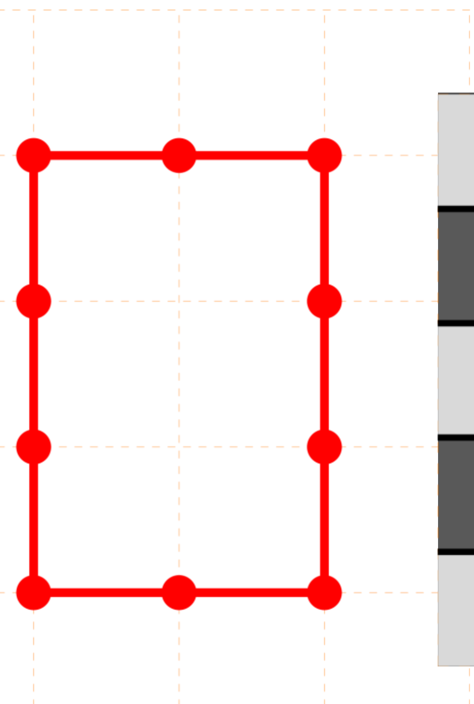
$$W = X_{13}X_{32}X_{21} - X_{14}X_{43}X_{32}X_{21}$$

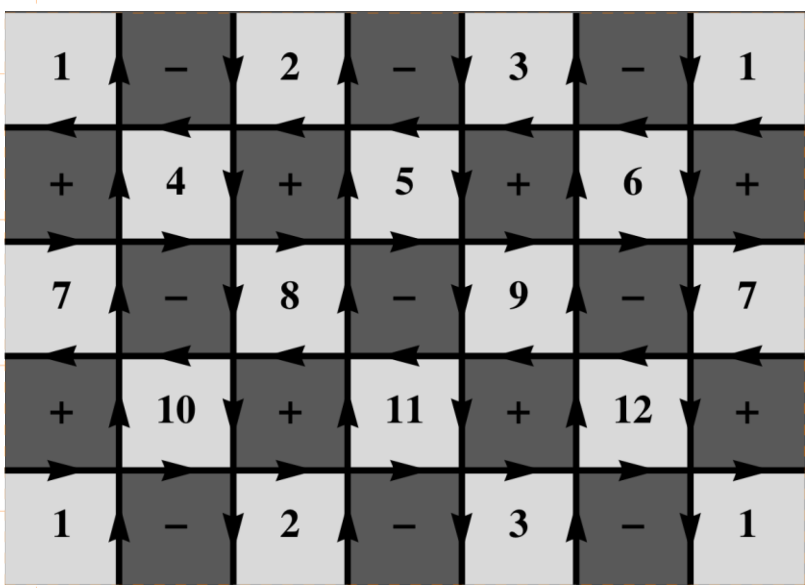
Answer to Question 2

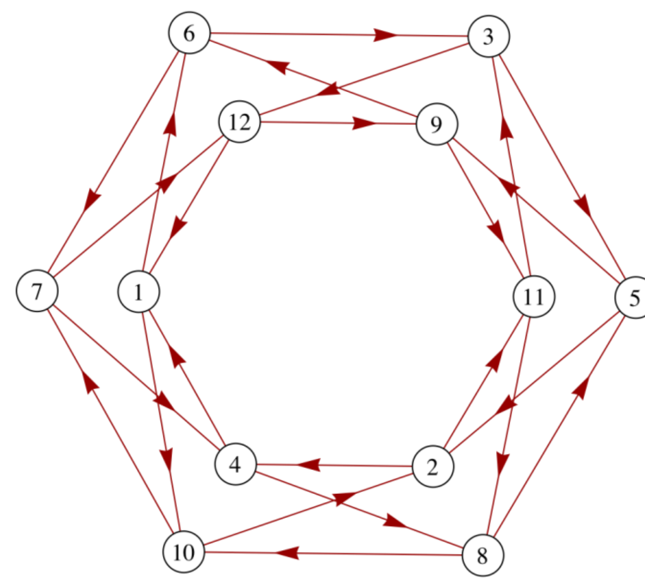
Gulotta's Algorithm:

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)

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

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

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

Works due to SU(2)xU(1) isometry

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

4. CP violation

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

D3D3 case (similar for D3D3/D3D7)

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

SUSY BREAKING

SUSY Breaking

- **Approximate Universality**

$$\Psi \Longleftrightarrow \text{Kähler moduli},$$
$$\chi \Longleftrightarrow \text{Complex structure moduli.}$$

$$\Phi = \Psi_{\text{susy-breaking}} \oplus \chi_{\text{flavour}}.$$

CAQS, Conlon (Mirror Mediation)

- **Two cases:**
  - **$T_{SM} \neq 0$ soft terms $\sim m_{3/2}$**
    $Ms \sim 10^{12}$ GeV
  - **$T_{SM} = 0$ soft terms $\ll m_{3/2}$**

Local/Global Mixing

- **Standard Model in small cycle**
- **SM cycle NOT fixed by non-perturbative effects:**

- **SM chiral implies:** $W_{np} = \left(\prod_i \Phi_{hidden,i}\right)\left(\prod_j \Phi_{MSSM,j}\right) e^{-aT_{MSSM}}.$

Blumenhagen et al.2007

$$D_a \sim \sum_i \left(|\Phi|^2 - \xi\right)^2, \quad \xi = (\partial_{V_a} K)|_{V_a=0}$$

MSSM: <Φ>=0, so W_{np}=0, $\xi = 0.$
(singularity)? Or <|Φ|²>= ξ

SM Cycle does not break SUSY!

'Fayet-Iliopoulos' →0

$$K_{T_a} = 0 \qquad \tau_a \to 0$$

$$F_a = e^{K/2}\left(W_{T_a} + W K_{T_a}\right)$$

$$F^a = 0$$

'Sequestered moduli/gravity mediated SUSY Breaking'

$$|F^{T_b}| \sim \frac{M_P^2}{\mathcal{V}}, \qquad |F^{T_s}| \sim \frac{M_P^2}{\mathcal{V}^{3/2}}, \qquad |F^S| \sim \frac{M_P^2}{\mathcal{V}^2}$$

No-scale (vanishing soft terms)

Suppressed !

Different Scenarios

- Scalars $1/V^{3/2}$, others $1/V^2$
- All $a/V^{3/2}$
- All $1/V^2$
- Loop corrections ~ $b/V^{5/3}$
- $M_{string} \sim 10^{13}$-10^{15} GeV
- Gauge mediation? ($F_X/x > m \ll M_{3/2}$?) but with heavy gravitino!

General Properties

- **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

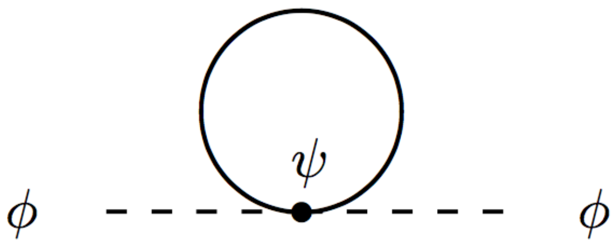
Question:

Unnaturally light scalars?

Loop induced heavy masses

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

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

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

With SUSY

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

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

Übernaturalness

Implications

- **Intermediate scale scenario**

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

- **GUT scale scenarios**

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

- **TeV Scenario**

SUSY broken on the brane:

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

But potential distabilisation of LV minimum

Cosmological Inflation

Kähler Moduli Inflation (Blow-up)

$$V=\sum_i \frac{8(a_iA_i)^2\sqrt{\tau_i}}{3\mathcal{V}\lambda_i\alpha}e^{-2a_i\tau_i}-\sum_i 4\frac{a_iA_i}{\mathcal{V}^2}W_0\tau_i e^{-a_i\tau_i}+\frac{3\xi W_0^2}{4\mathcal{V}^3}.$$

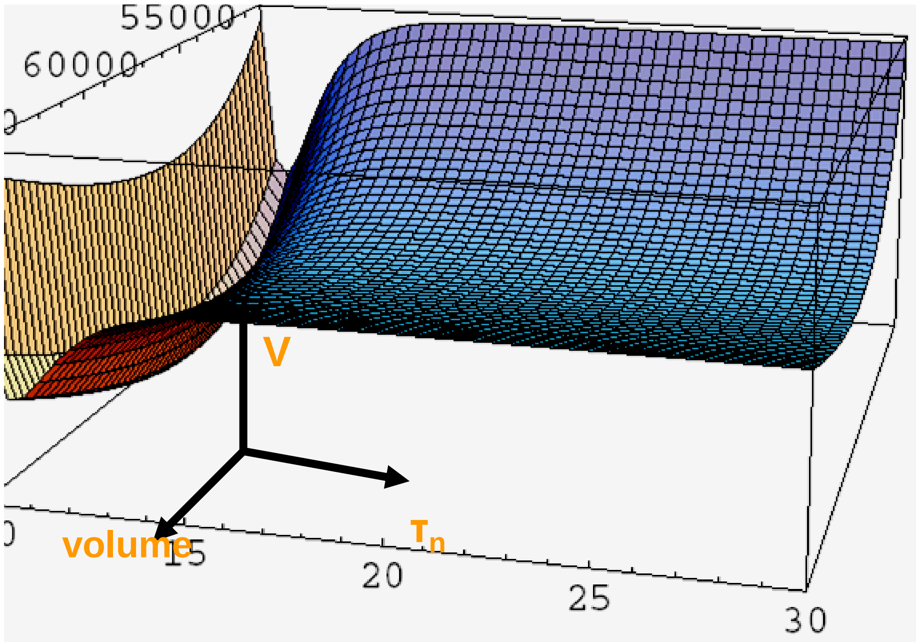
Conlon-FQ

Bond et al.

…

$$V\cong V_0-\frac{4W_0a_nA_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\exp\left[-a_n\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\right].$$

Calabi-Yau: $h_{21}>h_{11}>2$



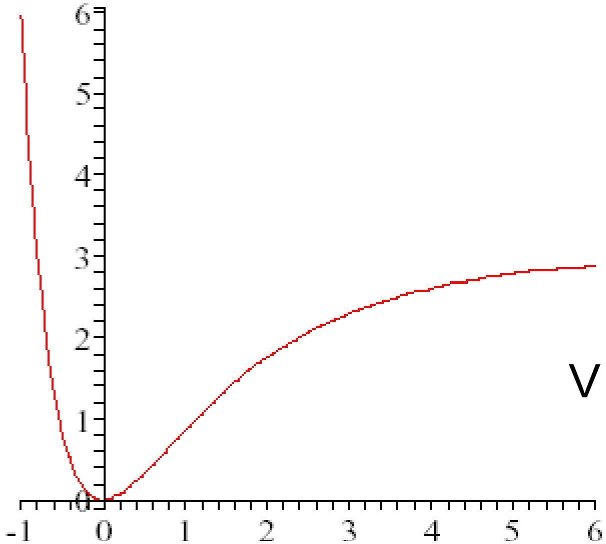
Small field inflation (r<<<1)

No fine-tuning!!

0.960<n<0.967

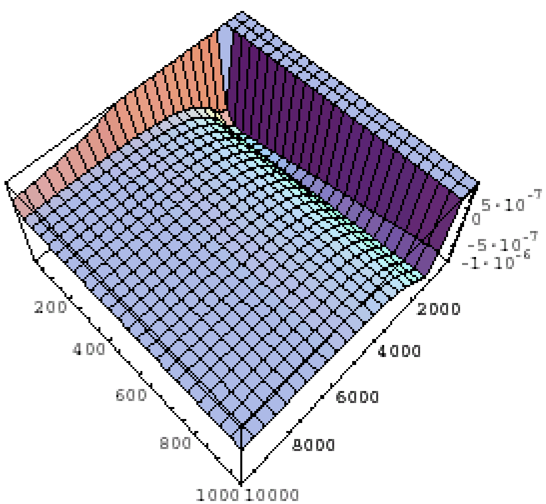
Loop corrections??

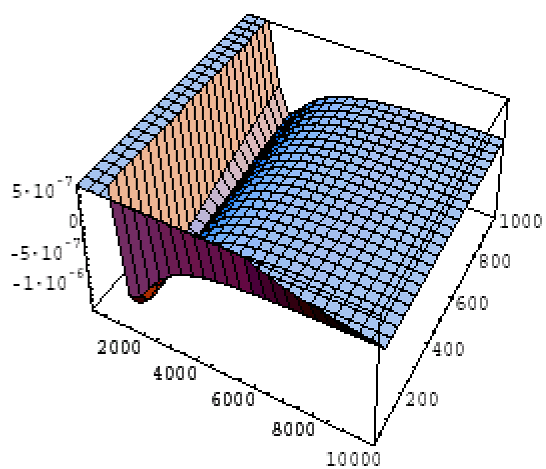
Fibre Inflatons



$$\mathcal{V} = \alpha\left[\sqrt{\tau_1}(\tau_2-\beta\tau_1)-\gamma\tau_3^{3/2}\right],$$

$$V = \frac{m_{\varphi}^2}{4}\left(3-4\,e^{-\kappa\hat{\varphi}/2}+e^{-2\kappa\hat{\varphi}}\right) \qquad \kappa = \frac{2}{\sqrt{3}}\,.$$

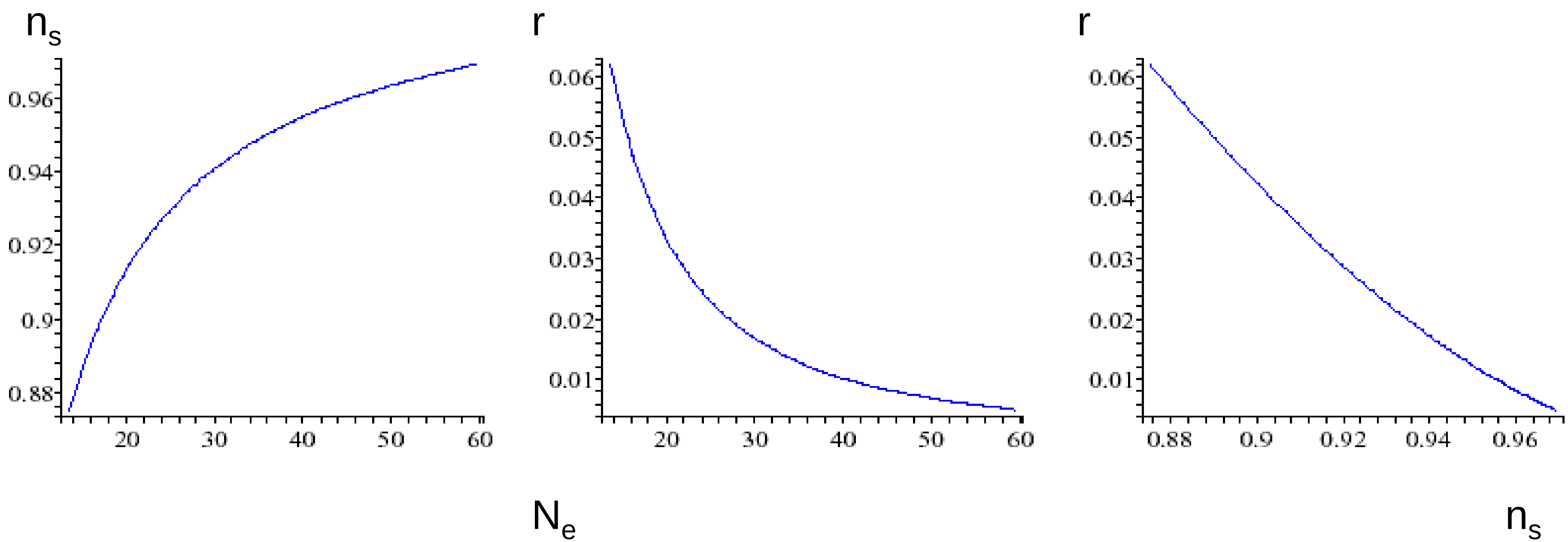




$$\varepsilon \simeq \frac{8}{3\left[3\,e^{\kappa\hat{\varphi}/2}-4\right]^2},$$

$$\eta \simeq -\frac{4}{3\left[3\,e^{\kappa\hat{\varphi}/2}-4\right]},$$

$$\varepsilon \simeq \frac{3\,\eta^2}{2}\,.$$



$$r \simeq 6(n_s - 1)^2 \,,$$

$$n_s \simeq 0.970, \qquad r \simeq 4.6 \cdot 10^{-3} \,,$$

Observable gravity waves !

(can be ruled out by Planck if they observe them and CMBpol… if they do not observe them)

Stringy Curvaton Scenario

$$\mathcal{V} = \alpha \left(\sqrt{\tau_1}\tau_2 - \sum_{i=3}^{4} \gamma_i \, \tau_i^{3/2} \right) .$$

$$W \simeq W_0 + A_3 e^{-a_3 T_3} + A_4 e^{-a_4 T_4} ,$$

$$V_{inf}(\phi_4) \simeq V_0 - \frac{g_s \, W_0 a_4 A_4}{2\pi \, \mathcal{V}^2} \left(\frac{3\mathcal{V}}{4\alpha\gamma_4} \right)^{2/3} \phi_4^{4/3} \exp \left\{ - \left[a_4 \left(\frac{3\mathcal{V}}{4\alpha\gamma_4} \right)^{2/3} \phi_4^{4/3} \right] \right\}$$

$$V_{cur}(\hat{\chi}_1) = \frac{g_s \, W_0^2}{8\pi \, \mathcal{V}^{10/3}} \left[C_0 \, e^{\frac{2}{\sqrt{3}} \hat{\chi}_1} - C_1 \, e^{-\frac{1}{\sqrt{3}} \hat{\chi}_1} + C_2 \, e^{-\frac{4}{\sqrt{3}} \hat{\chi}_1} \right]$$

Curvaton Mass:

$$m^2_{\chi 1} \simeq \frac{g_s C_t W_0^2}{4\pi \mathcal{V}^{\frac{10}{3}}} \ll H_\star^2 \simeq \frac{3 g_s \beta \hat{\xi} W_0^2}{32\pi \mathcal{V}^3},$$

Non-Gaussianities

$$\zeta = \zeta_G + \frac{3}{5} f_{NL} \zeta_G^2,$$

Examples

$\mathcal{V}$	a_4	ξ	g_s	n	W_0	α	A_4	γ_4
10^3	$\frac{1}{2}$	0.1	0.3	$\frac{1}{16}$	1	0.1	1	0.1

$$f_{NL} \simeq 56.$$

$\mathcal{V}$	a_4	ξ	g_s	n	W_0	α	A_4	γ_4
10^6	0.85	1	10^{-2}	$\frac{1}{16}$	40	10^{-2}	1	10^{-2}

$$f_{NL} \simeq 2.5,$$

CONCLUSIONS

- Continuous progress on LARGE volume scenario
- Several SUSY breaking scenarios
  ($m \sim m_{3/2}$, $m_{3/2}^{3/2}/M_p^{1/2}$, $m_{3/2}^2/M_p$), ($M_s \sim 10^3 - 10^{16}$ GeV)
- Local model building(3-families, mass hierarchies (M,m,0), CKM,…)
- 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?...)