LARGE VOLUME STRING SCENARIO AND COSMOLOGY

F. Quevedo, Cambridge/CERN. Zurich RTN September 2009.

J. Conlon, FQ hep-th/0509012
M. Cicoli, J. Conlon, FQ, 0805.1029[hep-th]
J. Conlon, R. Kallosh, A. Linde, FQ, arXiv:0806.0809 [hep-th]
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J.P. Conlon, A. Maharana, FQ arXiv:0810.5660 [hep-th]
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R.Blumenhagen, J. Conlon, S. Krippendorf, S. Moster, FQ arXiv:0906.3297 [hep-th]

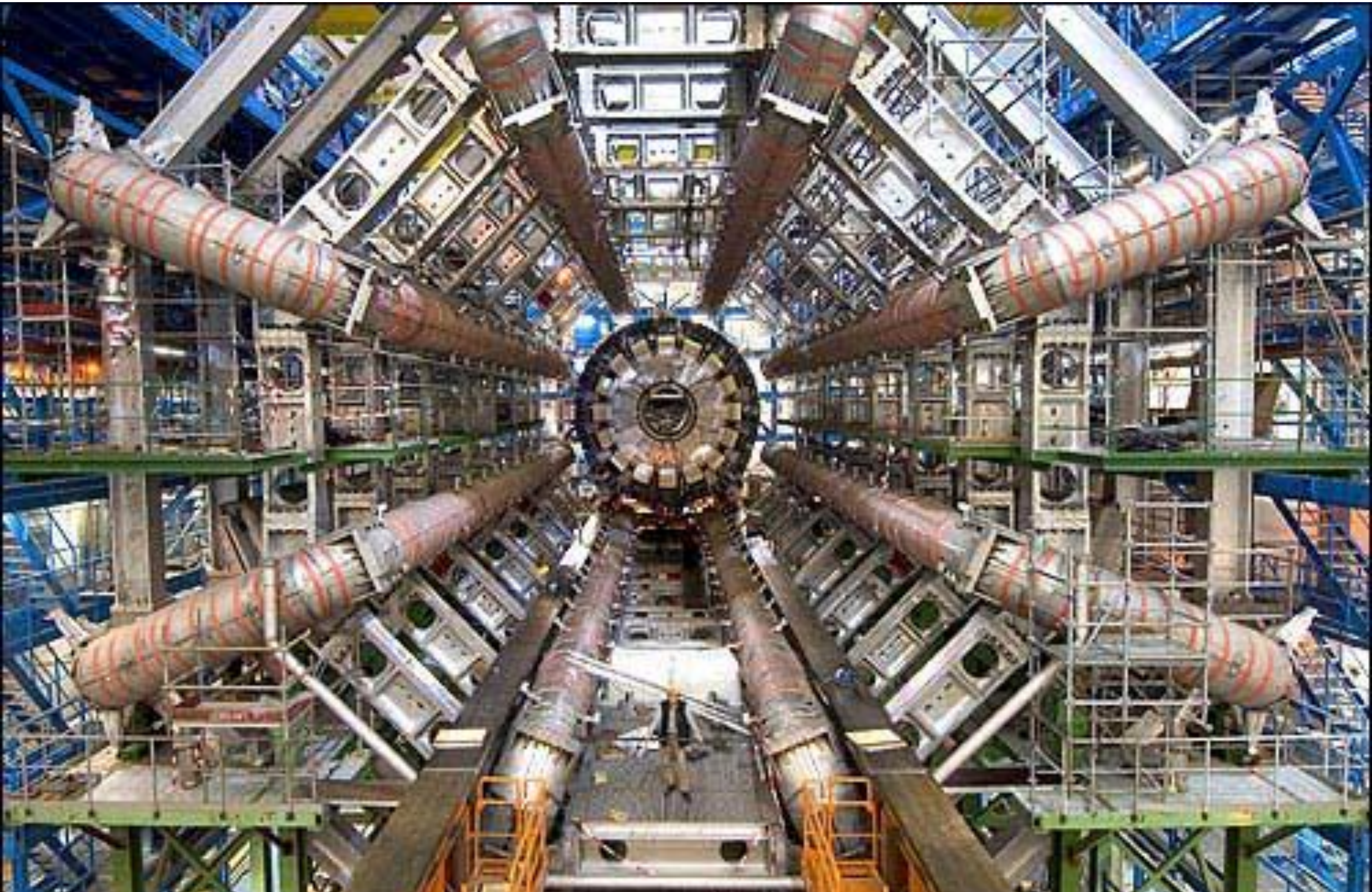
STRING PHENOMENOLOGY/ COSMOLOGY

Phenomenology

String Theory

String Phenomenology

THE LHC IS COMING!



DISCOVERIES BSM?

- **Nothing**
- **Low-energy SUSY**
- **Large extra dimensions**
- **Technicolor/Warping**
- **New Higgses, generations, Z’s, W’s, etc**
- **All of the above**
- **None of the above**
- **….**

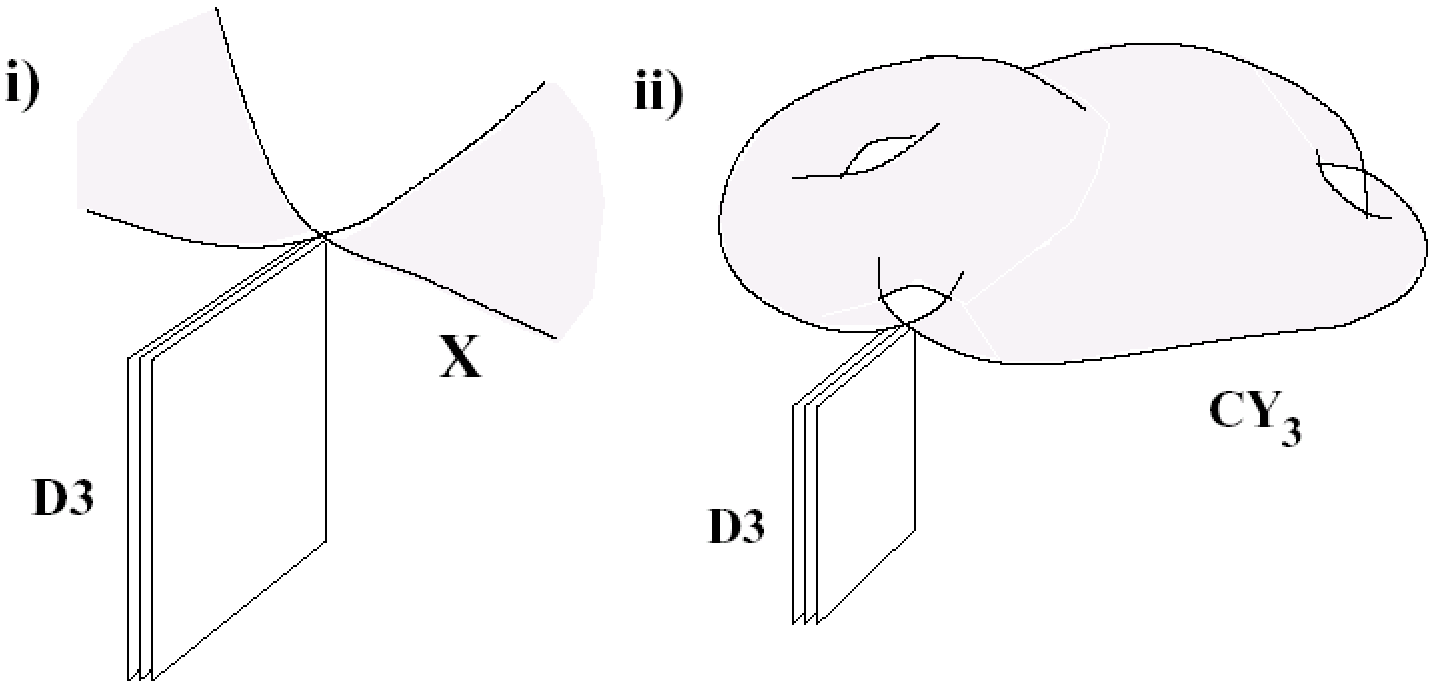
COSMOLOGY vs LOW-ENERGY SUSY

- **GOOD:**
  - ► **Cold Dark Matter** **(in some models, need R-parity)**

- **BAD:**
  - ► **Gravitino problem,**
  - ► **Cosmological moduli problem,**
  - ► **Thermal destabilisation,**
  - ► **Overshooting,**
  - ► **Gravitino mass,**
  - ► **eta-problem, scale of inflation,…**

String Model Building:

- Global Models (e.g. Heterotic)
- Local Brane Models (e.g. IIB) ⬅



Bottom-up Approach

Aldazabal, Ibanez, FQ, Uranga 2000

Local (brane) issues

- Gauge group
- Chiral spectrum
- Yukawa couplings
- Gauge couplings
- Proton stability
- Flavour symmetries

Global (bulk) issues

- Moduli Stabilisation
- Cosmological constant
- SUSY Breaking
- Scales (unification, axions,…)
- Inflation, Reheating
- Cosmological moduli problem

Model Degeneracy (IIB)

- **Choice of closed string backgrounds:** g_{mn} (Calabi-Yaus), Fluxes H_3, F_3; F_5 (fix U, S; warping, 10^{500} landscape)

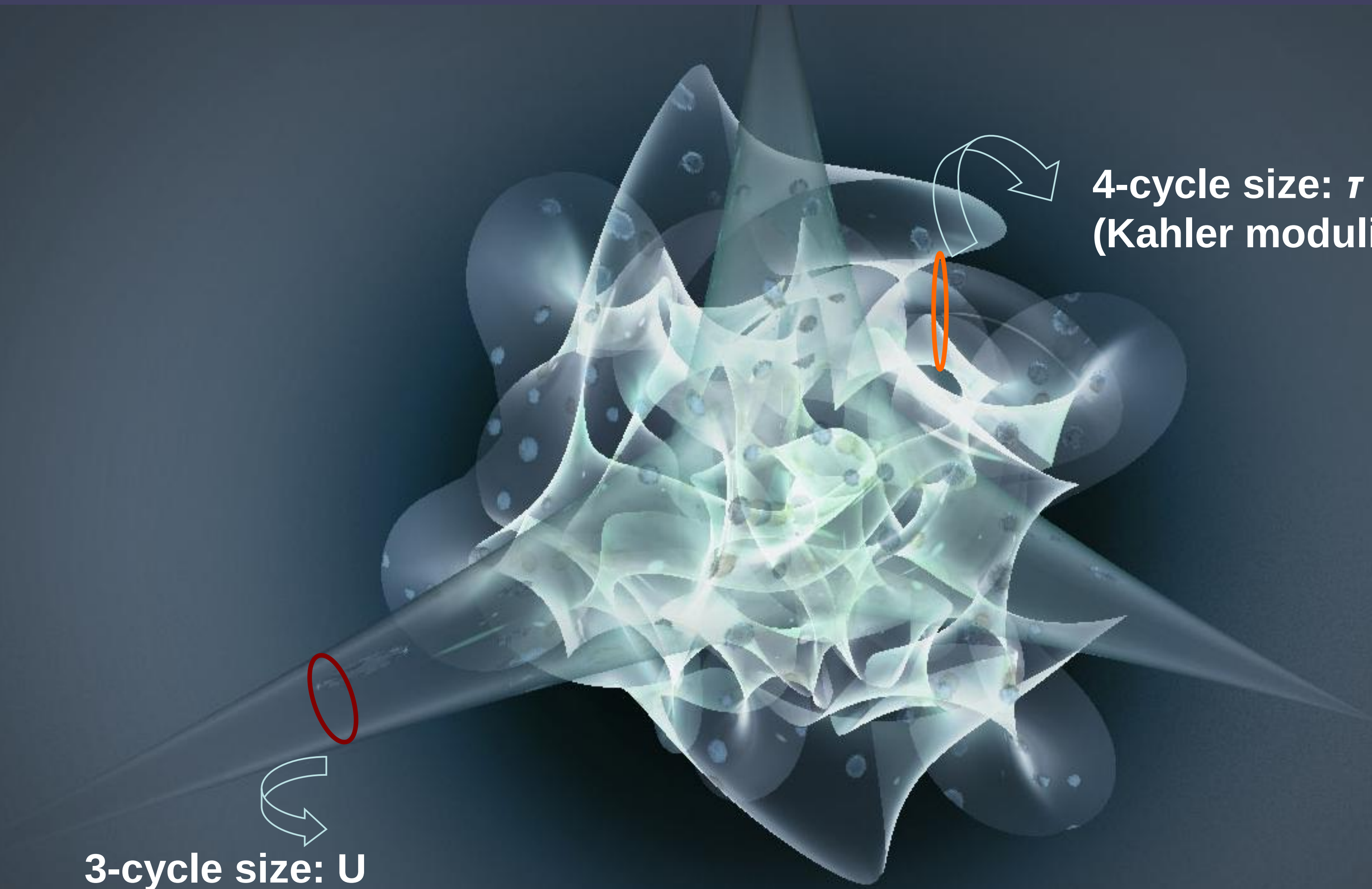
- **Open string sector: Brane set-up**

Hidden Sector: number of D7 branes; E3 branes, gaugino condensation

SM sector: magnetised D7 (F_2 background), D3 at singularity (choice of singularities)

GLOBAL ISSUES

MODULI STABILISATION



+ String Dilaton: S

LARGE Volume Scenario

Perturbative vs Non perturbative :

- **In general:**

$$\mathcal{K} = \mathcal{K}_0 + \mathcal{K}_p + \mathcal{K}_{np} \approx \mathcal{K}_0 + J,$$
$$W = W_0 + W_{np} \approx W_0 + \Omega,$$

$$V = V_0 + V_J + V_\Omega + \cdots,$$

- **Then:**

$$V_0 \sim W_0^2, \quad V_J \sim J W_0^2, \quad V_\Omega \sim \Omega^2 + W_0 \Omega,$$

- **Usually V_0 dominates but $V_0=0$ (no-scale $G^{-1}_{i\bar{k}}\mathcal{K}_i\mathcal{K}_{\bar{k}} = 3$)**
- **Dominant term is V_J unless $W_0<<1$ (e.g. KKLT)**

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

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

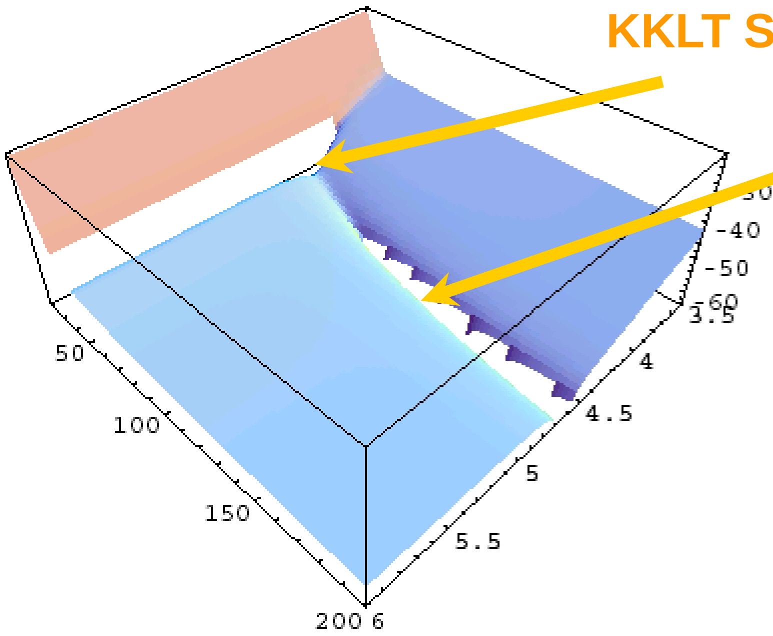
$$\Rightarrow \quad \mathcal{V} \sim e^{a_s\tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

Exponentially large volumen + Broken SUSY!!!

KKLT SUSY AdS

Large volume

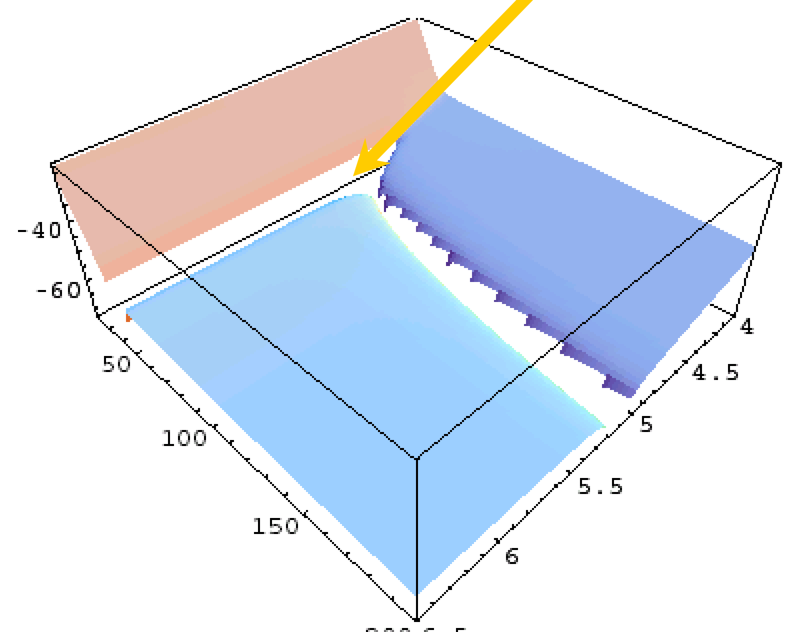
Non-SUSY AdS



Both minima close

$W_0 \sim 10^{-10}$

$W_0 < 10^{-11}$



For de Sitter: Anti D3 Branes (KKLT)

D-terms (BKQ, …, CGQS, KQ)

e.g.Hidden sector W chiral matter

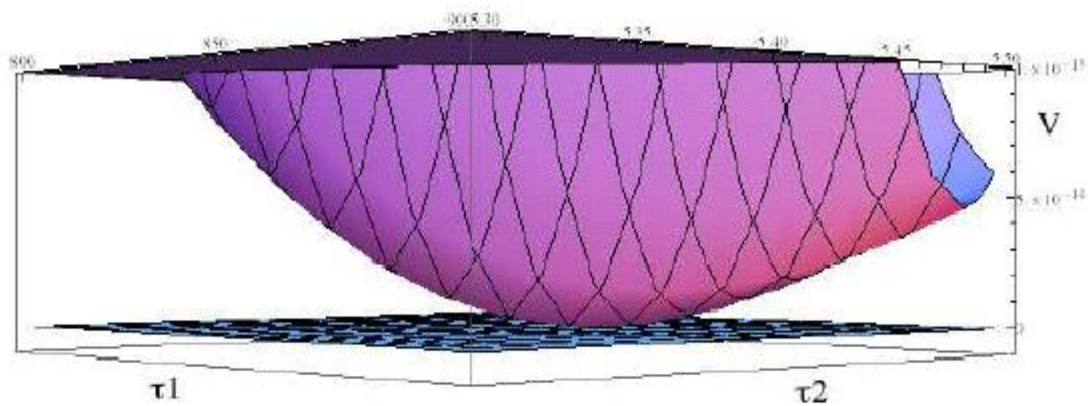
$$K = -2M_P^2 \log\left(\tau_1^{3/2} - \tau_2^{3/2} + \frac{\xi}{g_s^{3/2}}\right) + \frac{g_s^n \tau_2^n}{g_s \tau_1}(|p|^2 + |q|^2 + |\rho|^2 + |\Phi|^2)\,,$$

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

(Or W~ $\varphi_1\varphi_2 e^{-aT2}$)

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

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
- For N_{small} blow-up modes, there are $L=h_{11}-N_{small}-1$ flat directions at tree-level
- These directions are usually lifted by perturbative string effects

Swiss Cheese Calabi-Yau's

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

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

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

But also K3 fibrations, etc.

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** $m_{3/2} = W_0\, M_P/\mathcal{V}$

General Scenarios (before 2009)

- $M_{String} = M_{GUT} \sim 10^{16}$ GeV   ($V \sim 10^{4-5}$)

- $W_0 \sim 10^{-11} << 1$ (or $W_0 \sim 1$ plus warping)
- Fits with coupling unification
- Natural scale of most (all?) string inflation models.
- Axi-volume quintessence scale (w=-0.999….)
- Cosmological moduli problem!

- $M_{String} = M_{int.} \sim 10^{12}$ GeV ($V \sim 10^{15}$)

- $W_0 \sim 1$ (no tuning here)
- $m_{3/2} \sim 1$ TeV
- QCD axion scale
- Neutrino masses LLHH
- Cosmological moduli problem

- $M_{String} = 1$ TeV   ($V \sim 10^{30}$)

- $W_0 \sim 1$
- Most exciting, but 5th Force (volume modulus $m \sim 10^{-15}$ eV)??

INFLATION

String Inflation Motivation

- **Inflation: very successful but is only ad-hoc scenario in search of a theory**

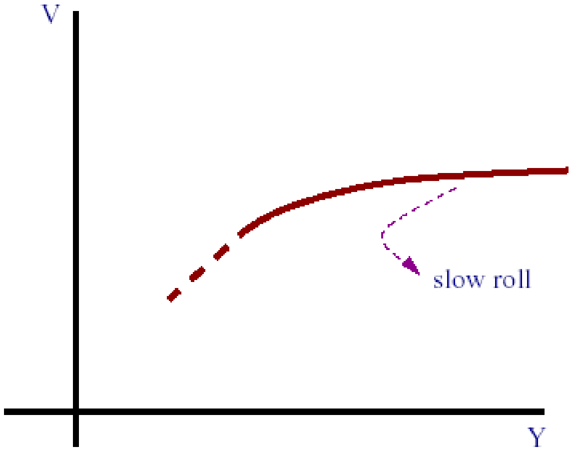
- **String theory: fundamental theory but lacks experimental tests.**

- **Is it possible to ‘derive’ inflation from string theory?**

Need to compute scalar potential from String theory satisfying slow-roll conditions:

$$\epsilon \equiv \frac{M_{Planck}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,,$$

$$\eta \equiv M_{Planck}^2\frac{V''}{V} \ll 1\,.$$



Number of e-folds N>50

$$N(t) \equiv \int_{t_{init}}^{t_{end}} H(t')dt' = \int_{\psi_{init}}^{\psi_{end}} \frac{H}{\dot\psi}d\psi = \frac{1}{M_{Planck}^2}\int_{\psi_{end}}^{\psi_{init}} \frac{V}{V'}d\psi\,.$$

Density perturbations

$$\delta_H = \frac{2}{5}\mathcal{P}_{\mathcal{R}}^{1/2} = \frac{1}{5\pi\sqrt{3}}\frac{V^{3/2}}{M_p^3 V'} = 1.91\times 10^{-5}\,,$$

$$n-1 = \frac{\partial \ln \mathcal{P}_{\mathcal{R}}}{\partial \ln k} \simeq 2\eta - 6\epsilon\,, \qquad \frac{dn}{d\ln k} \simeq 24\epsilon^2 - 16\epsilon\eta + 2\xi^2\,.$$

$$n_{grav} = \frac{d\ln \mathcal{P}_{grav}(k)}{d\ln k} = -2\epsilon\,. \qquad (r=16\,\varepsilon)$$

Two General Classes of String Inflation

- Open String Inflaton

- Closed String Inflaton

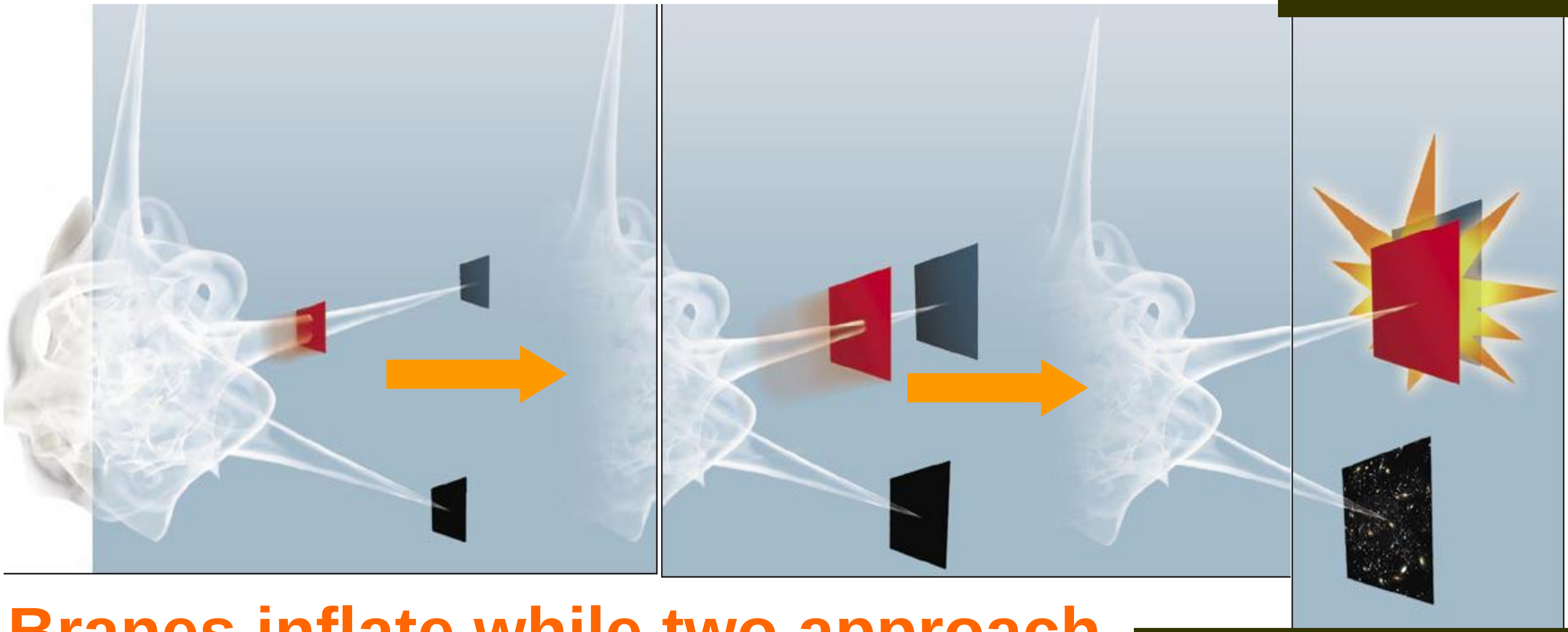
OPEN STRING INFLATON

Dvali+Tye

BMQRZ

Dvali, Shafi, Solganik

KKLMT



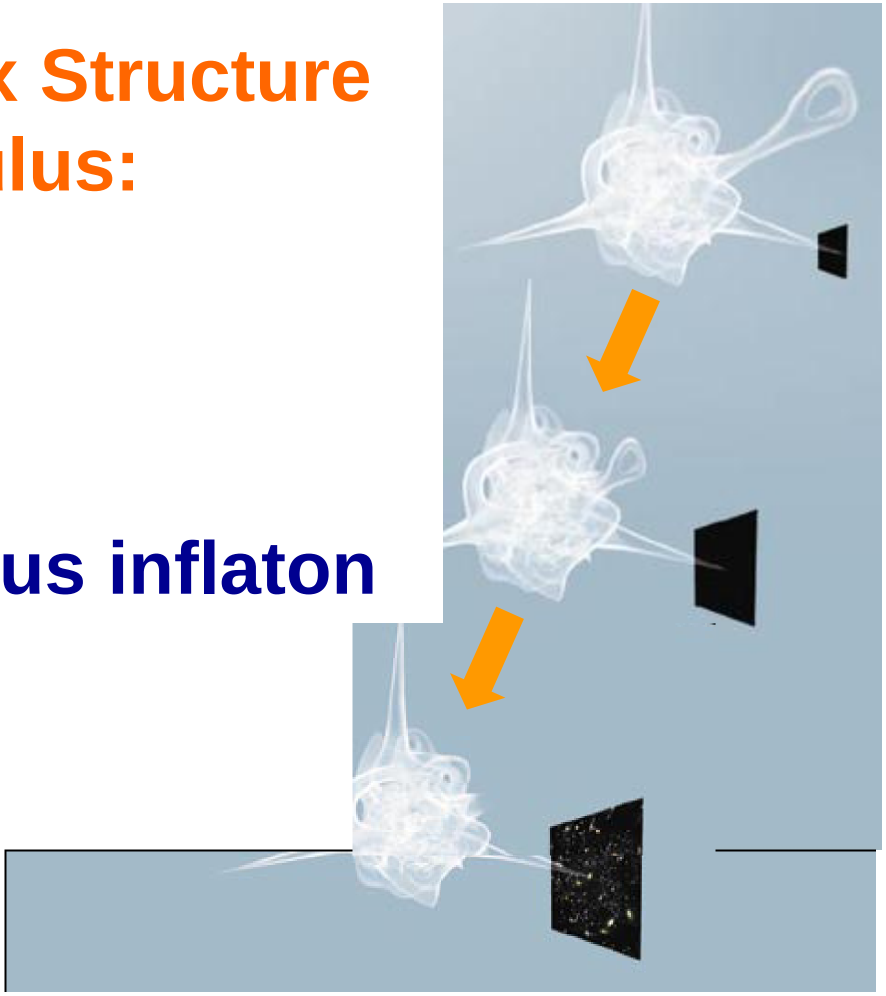
Branes inflate while two approach

Also D3/D7, Wilson-line

Slow-roll or DBI (need tuning but tunable, r~0,Tachyon condensation:~hybrid inflation + cosmic strings)

CLOSED STRING INFLATON

Dilaton, Complex Structure or Kahler Modulus:



- **Axion Inflaton**
- **Blow-up modulus inflaton**
- **Fibre inflaton**
- **Volume**

KAHLER INFLATONS

- **Blow-up modes**
- **Fibration modes**
- **Volume modulus**

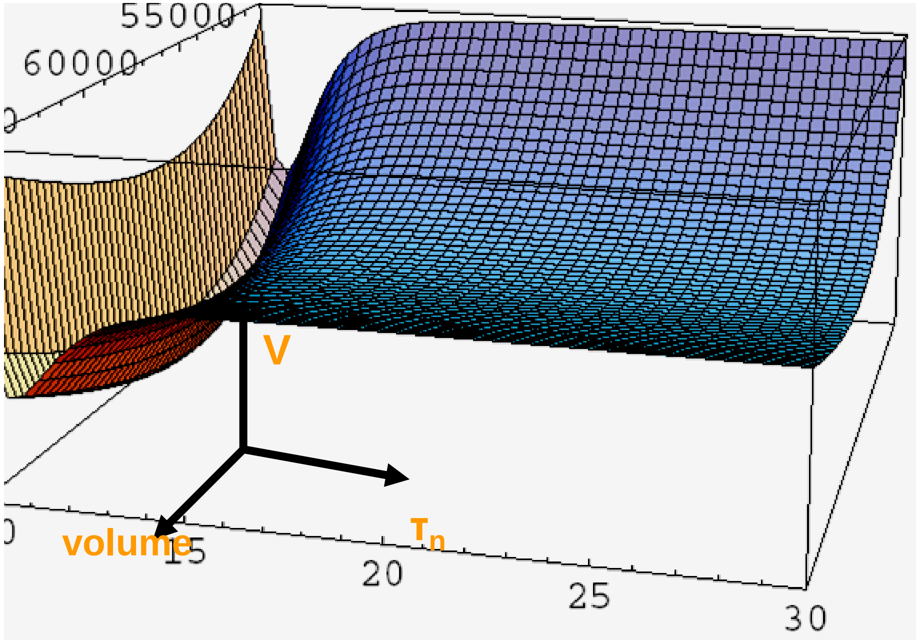
Kähler Moduli Inflation (Blow-up)

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

Conlon-FQ
Bond et al.
…

$$V \cong V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}^2} \left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3} (\tau_n^c)^{4/3} \exp\left[-a_n \left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3} (\tau_n^c)^{4/3}\right].$$

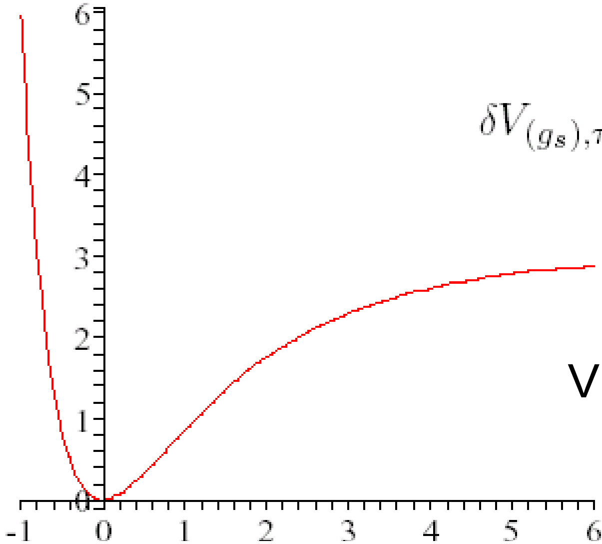
Calabi-Yau: $h_{21}>h_{11}>2$



Small field inflation (r<<<1)
10^5<Volume<10^7
No fine-tuning!!
0.960<n<0.967
Loop corrections??

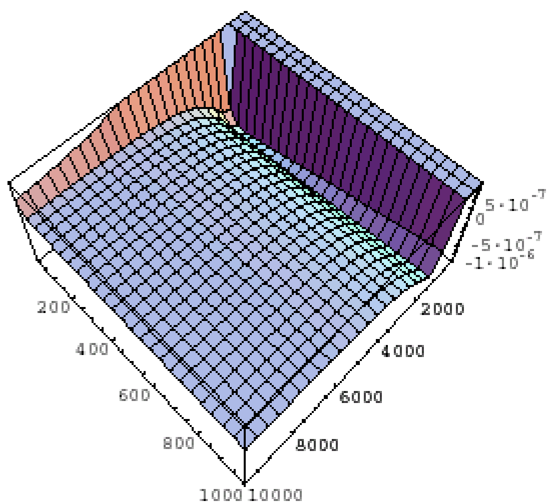
Fibre Inflation

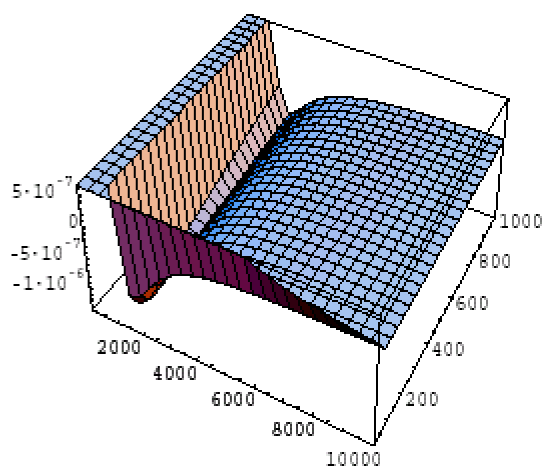
$$\mathcal{V} = \alpha \left[\sqrt{\tau_1}(\tau_2 - \beta \tau_1) - \gamma \tau_3^{3/2} \right],$$



$$\delta V_{(g_s),\tau_1} + \delta V_{(g_s),\tau_2} = \frac{A}{\tau_1^2 \mathcal{V}^2} + \frac{B\sqrt{\tau_1}}{(\tau_2 - 2\tau_1)\mathcal{V}^3} + \frac{C}{\sqrt{\tau_1}\mathcal{V}^3} + \frac{D\tau_1}{\mathcal{V}^4}.$$

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

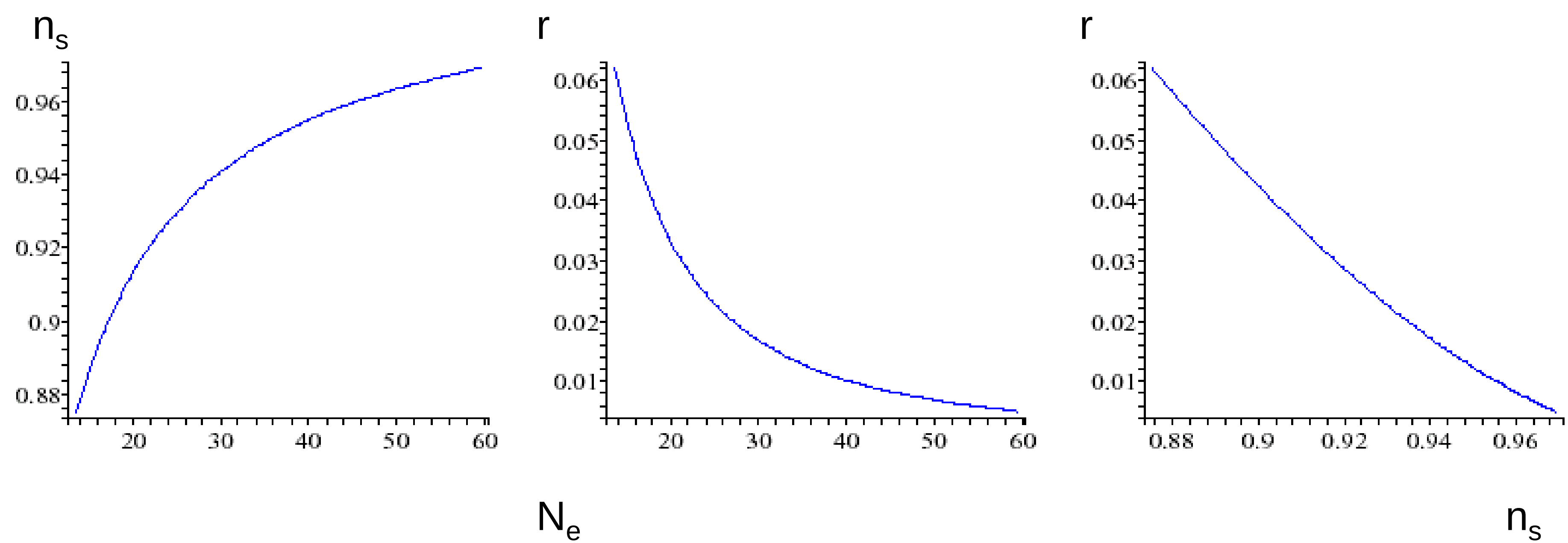




$$\varepsilon \simeq \frac{8}{3\left[3\, e^{\kappa\hat{\varphi}/2} - 4\right]^2},$$

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

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



No tuning but initial conditions close to bdry of Kahler cone

Observable gravity waves !

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

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

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

LOCAL ISSUES

LARGE Volume Implies

Standard Model is localised !

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

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

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

Blumenhagen et al. 08

- Local F-Theory

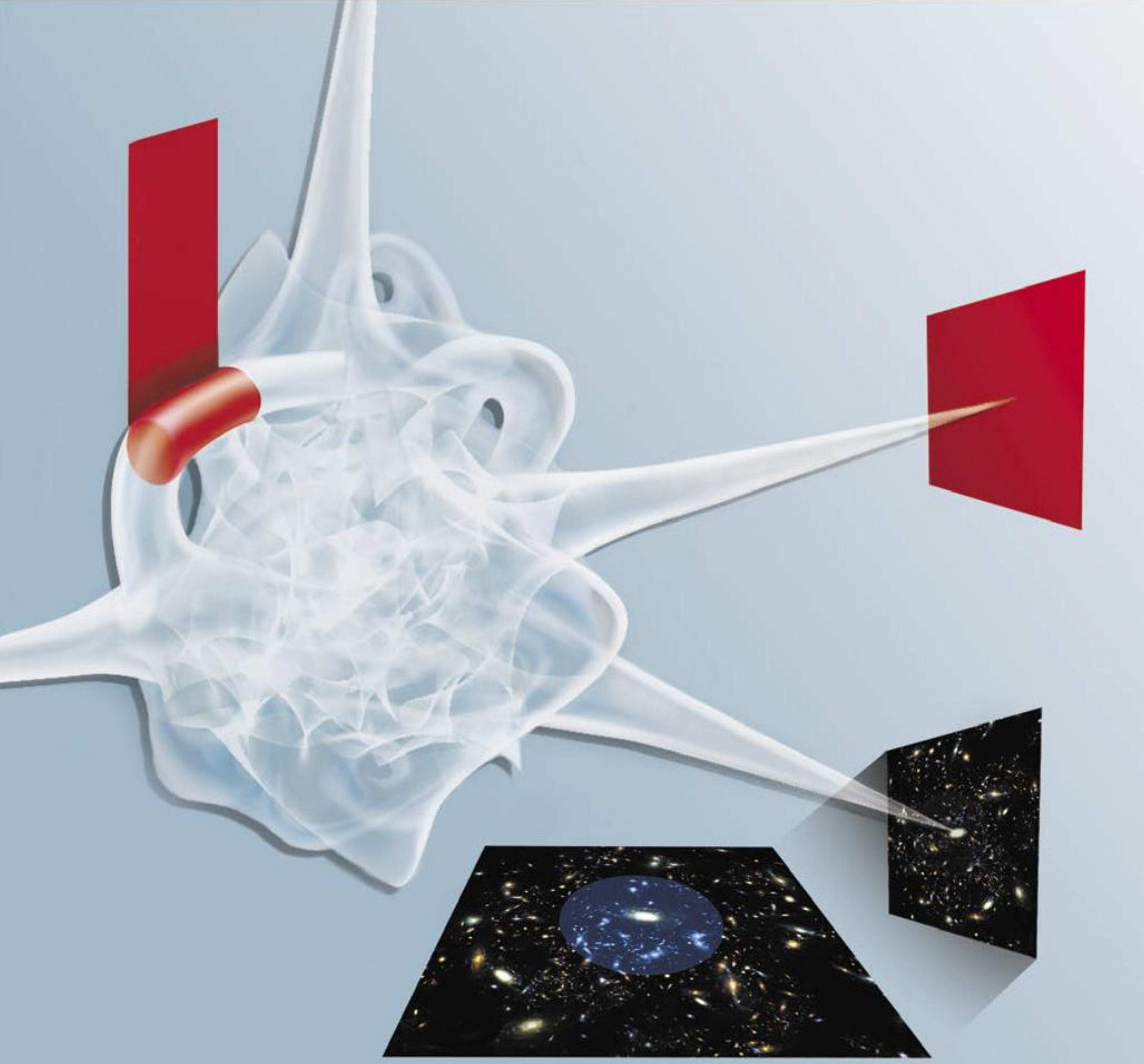
Donagi, Wijnholt; Vafa et al. 08

Modular Model Building

(Bottom up approach)

Aldazabal,Ibanez, FQ, Uranga 2000

Verlinde,Wijnholt 2006, Vafa et al 08



Universe

D3 Brane

or

D7 Brane

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

★ **Collapsing single 4-cycle:**

del Pezzo surfaces dP_n, n=0,1, …,8 ⬅

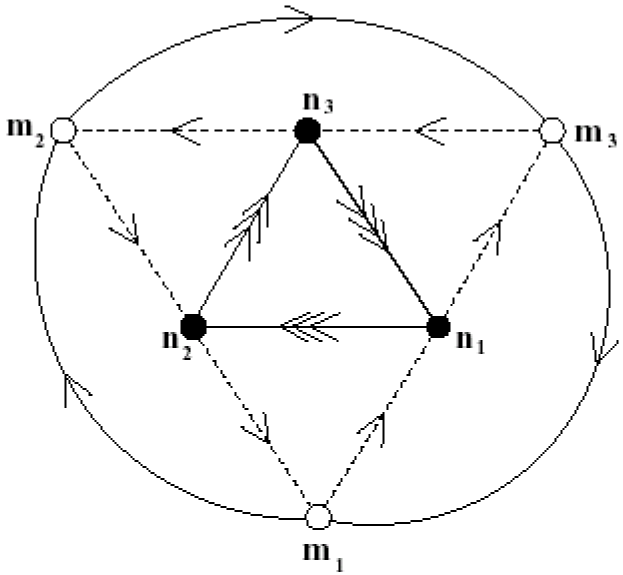
(P^2 blown-up at n arbitrary points

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

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

Simple Singularities/Quivers

Douglas,Moore; Hanany; Uranga et al



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

W=closed arrows loop

(=0 in smooth P2, Conlon, Maharana, FQ)

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

3 Families!

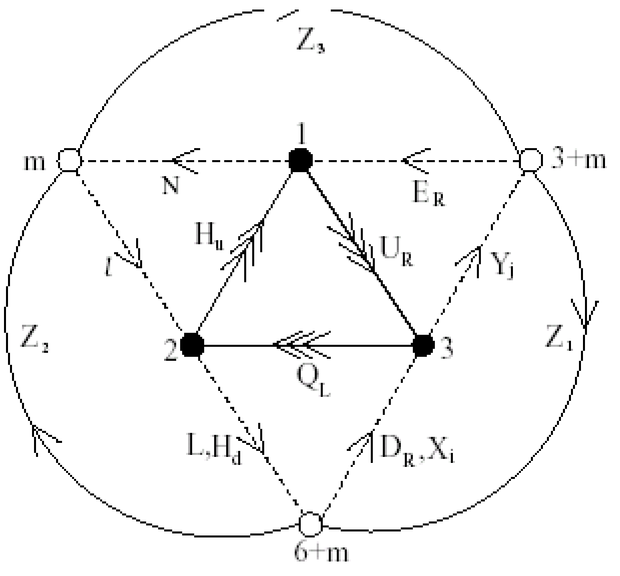
$$m_2=3\,(n_3-n_1)+m_1 \qquad m_3=3\,(n_3-n_2)+m_1$$

Anomaly/tadpole cancellation

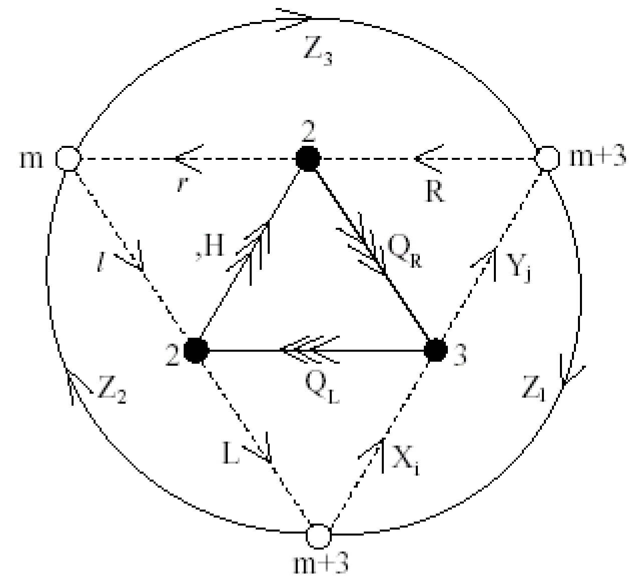
$$Q_{anomaly-free}=-\sum_{i=1}^{3}\frac{Q_i}{n_i},$$

`Hypercharge' ($n_i \neq n_j$)

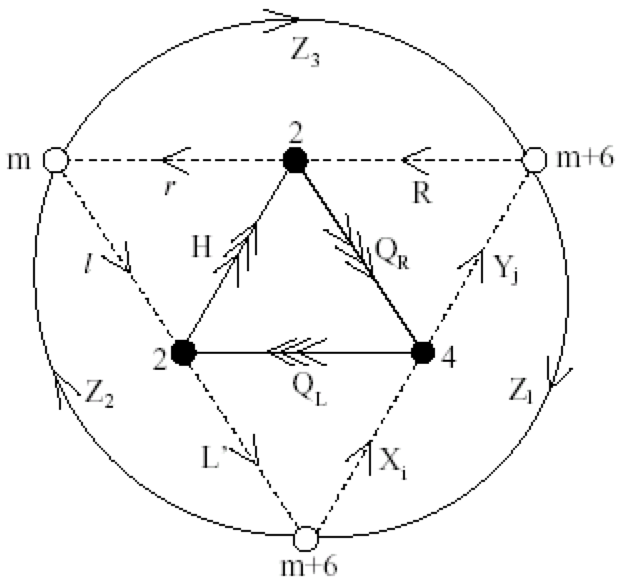
Standard Models



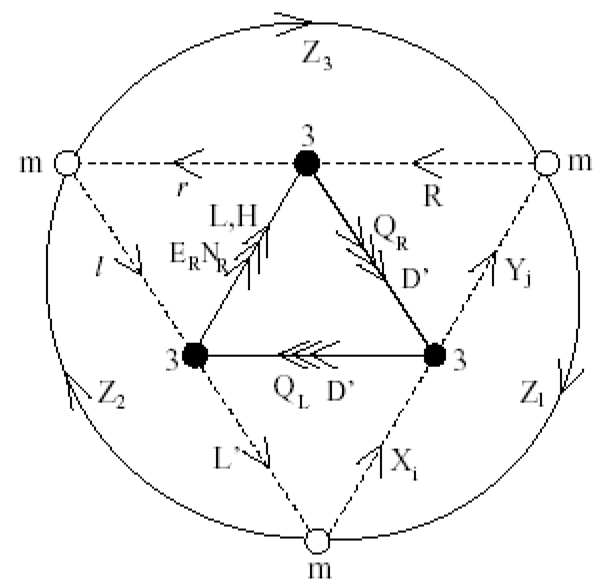
LR-Symmetric Models



Pati-Salam Models



Trinification Models



Problem for dP_0: Yukawa couplings

Conlon, Maharana, FQ

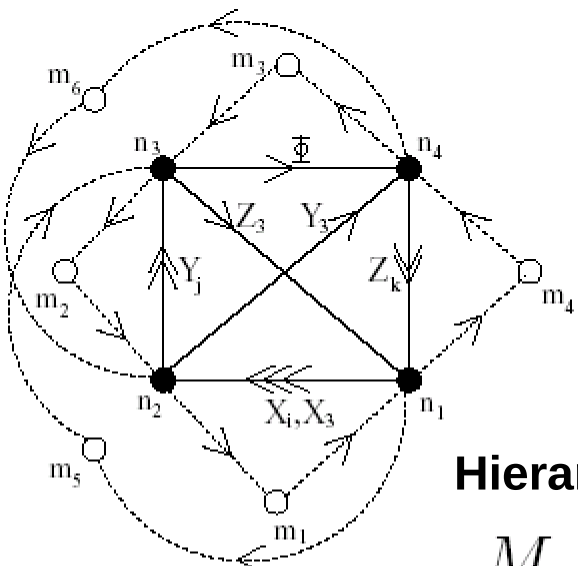
$$W = \epsilon_{ijk}\Phi^i_{33}\Phi^j_{33}\Phi^k_{33} + \sum \Phi^i_{33}\Phi_{37_i}\Phi_{7_i3},$$

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

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!!!!

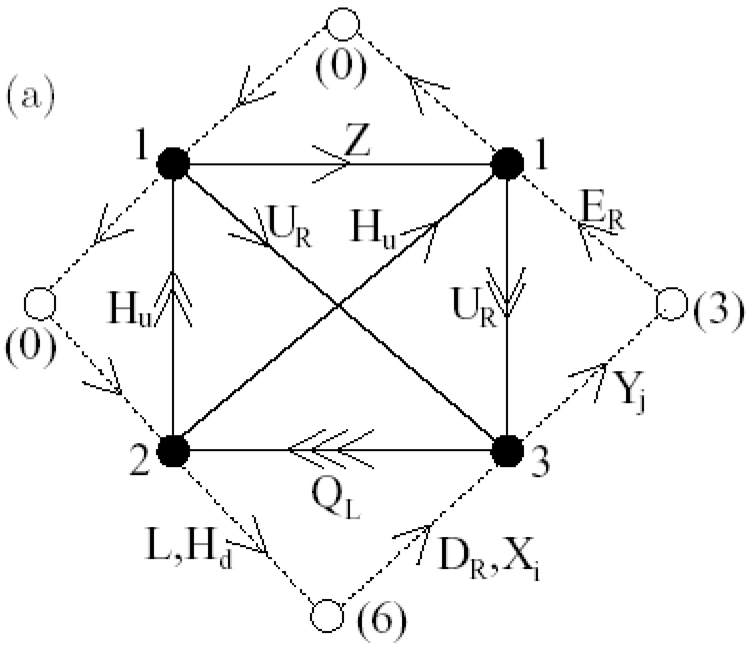
$$M \gg m \qquad \frac{\langle\Phi\rangle}{\Lambda} \ll 1$$

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

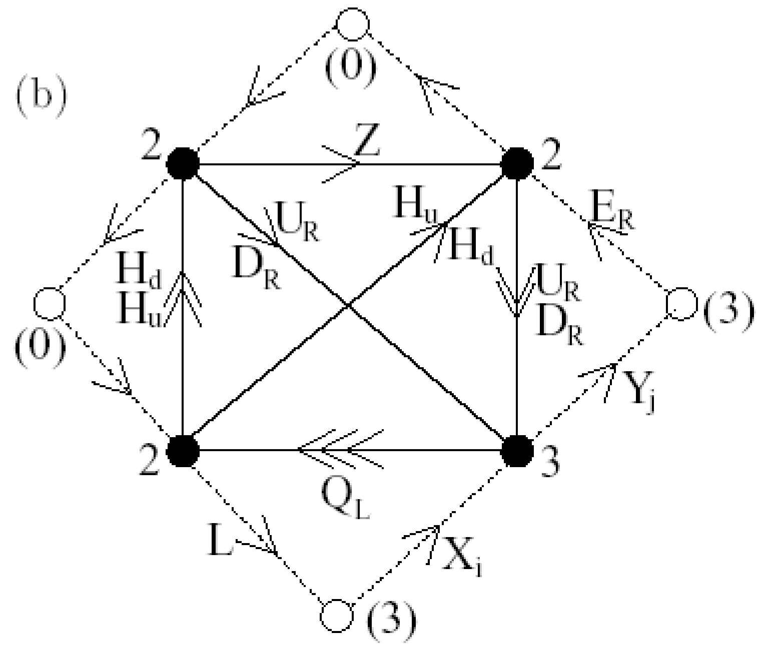
Higgsing gives back dP_0!!!

e.g. Realistic dP_1 Models

Standard Model



LR Symmetric Model



Higher del Pezzos

singularity	flavour symmetry
dP_0	SU(3)
dP_1	SU(2) × U(1)
dP_2	$U(1)$
$dP_{n>2}$	none

Triplication of families very limited

In general most quivers k<4 arrows

For dP8 model, see

H.Verlinde, M.Wijnholt (+Buican, Malyshev, Morrison) 06,07

LOCAL/GLOBAL MIXING

Local/Global Mixing

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

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

Blumenhagen et al.

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

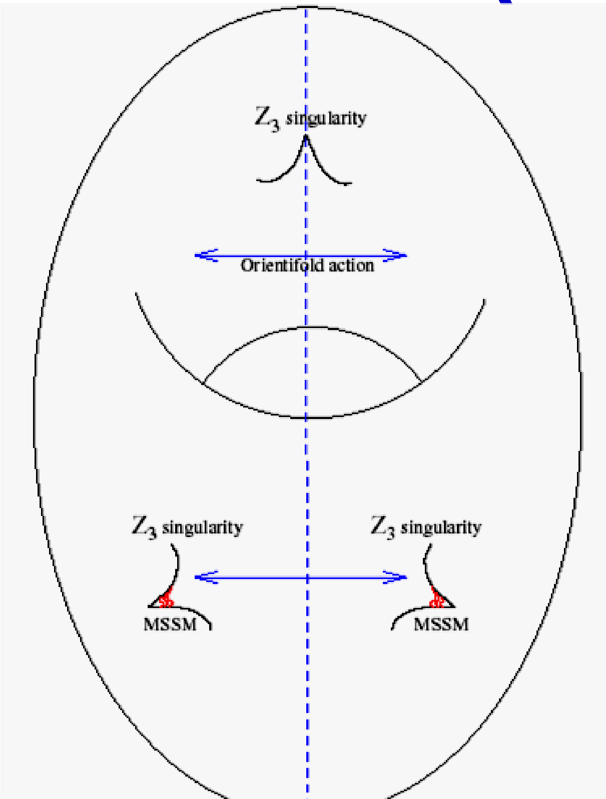
MSSM: <Φ>=0, so W=0, $\xi = 0.$
(singularity)? Or <|Φ|²>= ξ

$F_{SM}=K_{TSM}$ W=0
or $F_{SM} \neq 0$

Towards a Compact Model

- $h_{21} > h_{11} > 3$ (e.g. $h^{+}_{11}=3$, $h^{-}_{11}=1$)
- At least one blow-up
- Tadpole cancellation (D7s, Fluxes)

$$h^{+}_{1,1} \quad T_{\Sigma} + iC_4$$
$$h^{-}_{1,1} \quad B_2 + iC_2.$$



Generic Features

- **Aproximate Flavour Symmetries**

  (Approximate isometries)

- **Hyperweak Interactions**

  (SM fields charged under D7 gauge interactions $g^2=1/\mathcal{V}^{2/3} <<<1$, CDF?)

Burgess et al. 2008

Conlon, Maharana, FQ

SUSY Breaking

- **Approximate Universality**

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

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

CAQS, ConIon (Mirror Mediation)

- **Two cases:**
  - **$F_{SM} \neq 0$ soft terms $\sim m_{3/2} \sim 1/V$**
  - **$F_{SM} = 0$ soft terms $\ll m_{3/2}$**
    $\Delta m \sim 1/V^2 \sim m^2_{3/2}/M_{planck}$

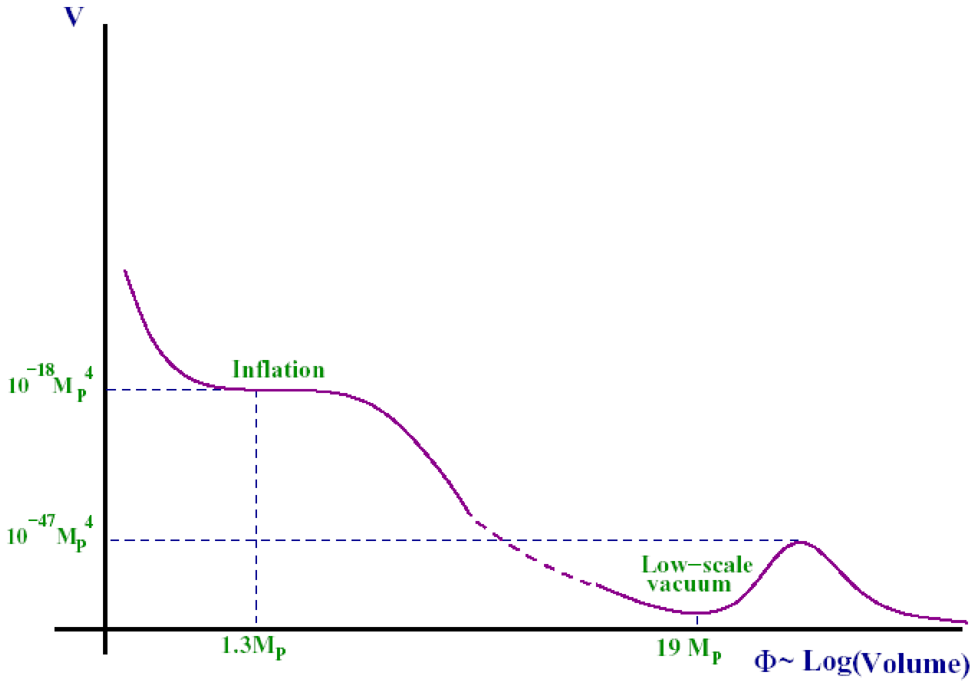
Phenomenology vs Cosmology!

Gravitino mass 1 TeV/Gravitino mass >> 1 TeV ??
(string scale 10^{11} GeV/ string scale ~ GUT scale)

- **Low scale inflation?**

- **Volume Inflation?**

Conlon, Kallosh, Linde, FQ



New Scenario $F_{SM}=0$

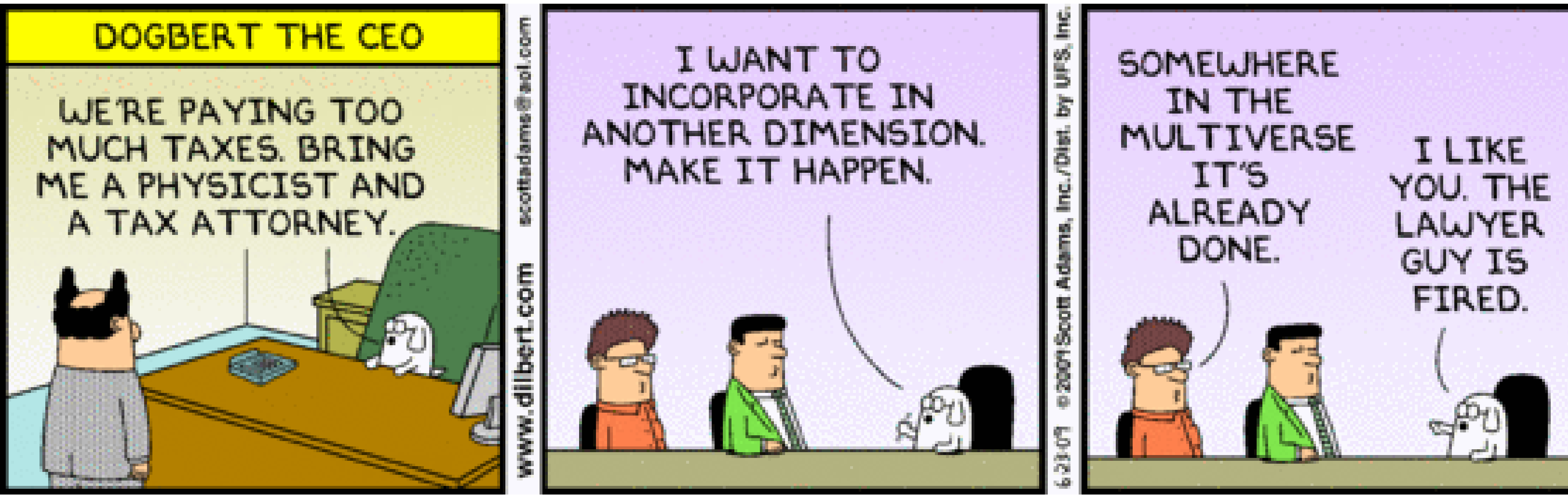
Blumenhagen, Conlon, Krippendorf, Moser, FQ

- $M_s \sim M_p/V^{1/2}$, $M_{KK} \sim Mp/V^{2/3}$
- $M^{3/2} \sim M_p/V$ (no gravitino problem)
- $\Delta m > M_p/V^2 \sim 1TeV$ (smallest volume $V \sim 10^6$)
- Lightest modulus $m \sim M_p/V^{3/2}$ (no CMP!)
- String/KK scales closer to standard inflation scale
- $M_{GUT} \sim M_s V^{1/6} \sim 10^{16}$ GeV (GUT scale and solves hierarchy problem!)
- Other contributions to SUSY breaking?

Conclusions

- Continuous progress in this `Decade of Applied String Theory'
- Bottom-up (Local Model Building) fits with Large Volume
- Realistic models at singularities: powerful quiver/dimer constructions (Modular road towards the stringy SM)
- General features (hyperweak interactions, approximate flavour symmetries, massive U(1)'s)
- Realistic cosmology (Models of inflation, no CMP, etc.)
- Open challenges (compact CY, detailed susy breaking, gauge unification(?), EFT in F-theory models, (compact CY, detailed susy breaking, (p)reheating

(see Barnaby, Bond, Kofman Friday's paper))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