RUNAWAY IN THE LANDSCAPE

STRINGS 07
MADRID JUNE 2007

MELANIE BECKER

RUNAWAY IN THE LANDSCAPE

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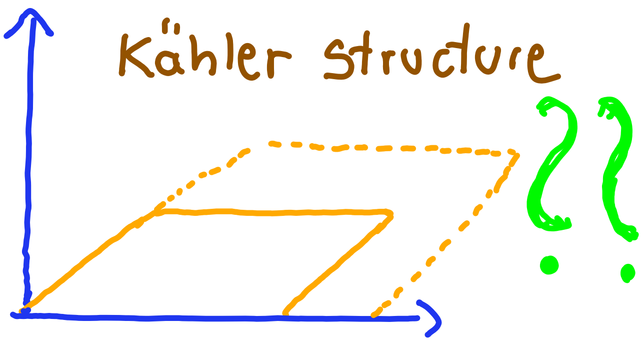
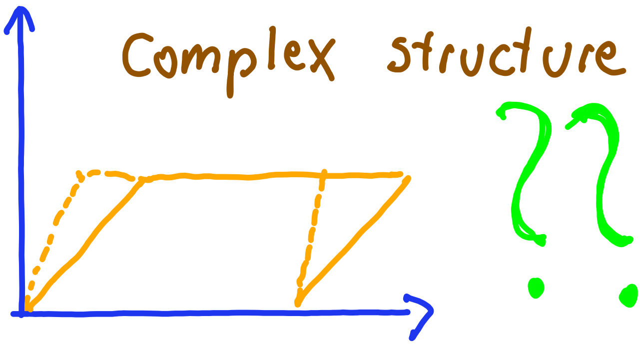
CALABI-YAU MANIFOLDS

MANY ASPECTS OF THE 4D THEORY CAN BE TRACED BACK TO THE TOPOLOGY OF THE INTERNAL MANIFOLD

MODULI FIELDS ⇒ FLUX COMPACTIFICATIONS !



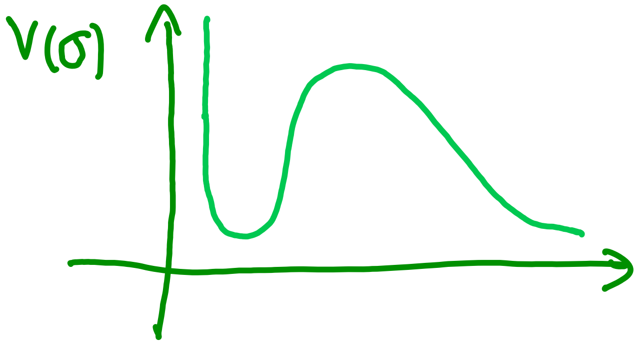


SCENARIOS

BEFORE OUR PAPER THERE WERE (ROUGHLY SPEAKING) 2 SCENARIOS:

Kachru
Kallosh
Linde + Trivedi

① KKLT LIKE SCENARIOS



- × fluxes (cplx. sf.)
- × np effects (kähler)
- × $\overline{D3}$'S ($\Lambda > 0$)

② STABILIZATION WITH ONLY FLUXES (GEOMETRIC)

MODULI STABILIZATION AT THE CLASSICAL LEVEL WITH FLUXES ONLY IN SUGRA APPROX.

MASSIVE IIA ON ORIENTIFOLD

$$AdS_4 \times T^6/\mathbb{Z}_3 \times \mathbb{Z}_3$$

De Wolfe
Siryavets
Kachru + Taylor

PARAMETRIC CONTROL: SMALL PARAMETER ε

$\boxed{\frac{1}{N} < \varepsilon}$ FLUX NUMBER $N \to \infty$

- GEOMETRIC DESCRIPTION
- IIA MODEL IS CONSTRAINT TO $\Lambda < 0$
- MASSES OF MODULI TOO SMALL

GOAL: CONSTRUCT A SIMPLE TYPE IIB MODEL IN WHICH MODULI STABILIZATION CAN BE ACHIEVED BEYOND THE SUGRA APPROXIMATION IN TERMS OF FLUXES ONLY

① MODULI STABILIZATION IN A NON-GEOMETRIC MODEL (MIGHT BE THE ONLY WAY TO STABILIZE SUSIC VACUA

② SUSIC VACUA OF AdS/MINKOWSKI TYPE WITH ALL MODULI STABILIZED

A NONGEOMETRIC TYPE IIB MODEL

IN THE TYPE IIB THEORY THERE IS A SUPERPOTENTIAL FOR COMPLEX STRUCTURE MODULI

Gukov, Vafa + Witten

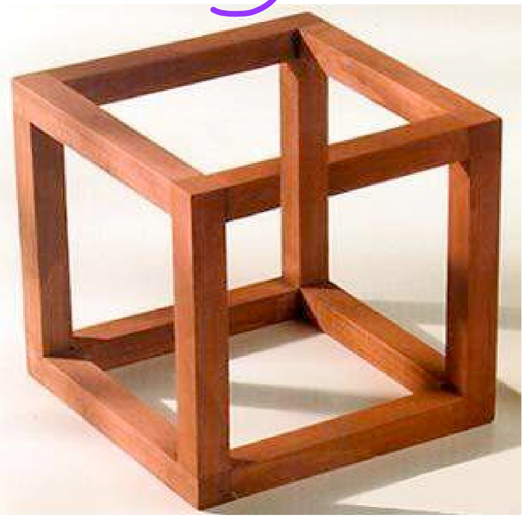
$$W = \int_{M_6} G \wedge \Omega \qquad G = H_{RR} - \tau H_{NS}$$

TAKE A MODEL WITH $h_{21} = 84$ cplx. str. $h_{11} = 0$ Kähler str.

NO RADIAL MODULUS ⇒ NON-GEOMETRIC !

NOT A CALABI-YAU (WHICH HAVE A SIZE)

$\mathcal{N} = 2$ SCFT ⇒ LANDAU-GINZBURG MODEL with $c = 9$ (ORIENTIFOLD)



Non-geometric cube ☺

GOAL : CONSTRUCT THIS MODEL

CONSTRAINTS ON THE MODEL

① SUPERSYMMETRY

UNBROKEN SUSY DEMANDS

$$\boxed{D_i W = \partial_i W + (\partial_i K) W = 0} \quad (*)$$

$i = \tau$, cplx. structure moduli

$$K(\tau) = -4 \log(\tau - \bar{\tau}) \;;\; K(z_a) = -\log\left(i \int \Omega \wedge \bar{\Omega}\right)$$

$$W = \int G \wedge \Omega = W_{RR} - \tau W_{NS}$$

space-time superpotential

$$D_\tau W = -\frac{1}{\tau - \bar{\tau}} \int (3G + \bar{G}) \wedge \Omega = 0 \Rightarrow \tau = \frac{W_{RR}}{2 W_{NS}} (3 - e^{i\varphi})$$

$$D_i W = \int G \wedge \chi_i = 0$$

χ_i : harmonic (2,1) forms

$$\boxed{G = A^i \chi_i + A^0 (-3\Omega + \bar{\Omega})}$$

3-FORM FLUX

MINKOWSKI $W = 0$

AdS_4 $W \neq 0$

② TADPOLE CANCELLATION

FOR A COMPACT MODEL THE TOTAL CHARGE HAS TO CANCEL. CONSIDER FOR NOW MINKOWSKI VACUA

$$\int H_{RR}\wedge H_{NS} = \frac{1}{(\tau-\tau^*)}\int G\wedge G^* = -Q(O_3)$$

O3 - PLANE CHARGE

NEGATIVE O3 PLANE CHARGE IS PROVIDED BY ORIENTIFOLDS OF LANDAU - GINZBURG MODELS

Brunner, Hori
Hosomichi
Walcher ...

LANDAU GINZBURG ORIENTIFOLDS

THE LANDAU GINZBURG MODEL IS CONSTRUCTED IN TERMS OF 9 COPIES OF C = 1 MINIMAL MODELS

$$W = \sum_{i=1}^{9} X_i^3$$

WORLDSHEET SUPERPOTENTIAL AT FERMAT POINT

DIVIDED BY THE ORBIFOLD PROJECTION

$$\mathbb{Z}_3 : \quad X_i \rightarrow \omega X_i \quad \text{with} \quad \omega = e^{\frac{2\pi i}{3}}$$

MODULI FIELDS CORRESPOND TO PRIMARY FIELDS IN THE CONFORMAL FIELD THEORY.

HOW DO THESE LOOK PRECISELY?

COMPLEX STRUCTURE DEFORMATIONS

NS-SECTOR

CORRESPOND TO PRIMARY FIELD OF THE (c, c) RING AND ARE DESCRIBED IN TERMS OF THE JACOBIAN RING

1 $\qquad h_{30} = 1$

$x_i \, x_j \, x_k$ $\qquad h_{21} = 84$

$x_{i1} \, x_{i2} \, x_{i3} \, x_{i4} \, x_{i5} \, x_{i6}$ $\qquad h_{12} = 84$

$x_1 \, x_2 \cdots\cdots x_8 \, x_9$ $\qquad h_{03} = 1$

KÄHLER STRUCTURE DEFORMATIONS

NS-SECTOR

CORRESPOND TO PRIMARY FIELDS IN THE (a, c) RING AND COME FROM THE TWISTED SECTORS OF THE ORBIFOLD

$h_{00} = 1 \qquad h_{33} = 1 \qquad (\mathbb{Z}_3 \text{ orbifold})$

R-R GROUNDSTATES (Spectral flow)

ORIENTIFOLD ACTION?

ORIENTIFOLD ACTION

SOURCES OF NEGATIVE CHARGE ARE OBTAINED BY ORIENTIFOLDING

WORLDSHEET PARITY

$$X(\tau,\sigma) \simeq \underset{\uparrow}{P} X(\tau, \overset{\downarrow}{-}\sigma)$$

INVOLUTION $P^2 = 1$

WHAT ARE THE ALLOWED INVOLUTIONS?

THE WORLDSHEET ACTION HAS AN F-TERM

$$\int d\theta^+ d\theta^- W(x) \xrightarrow[P\Omega]{} - \int d\theta^+ d\theta^- \underbrace{W(PX)}$$

$$W(X) \simeq - W(PX)$$ SHOULD BE ODD

INVOLUTIONS

THERE ARE 5 CHOICES OF INVOLUTIONS WHICH CONSIST IN AN OVERALL SIGN FLIP AND PAIRWISE EXCHANGE OF L6 COORDINATES

$$(x_1 x_2 \cdots x_8 x_9) = -(x_1 x_2 \cdots x_8 x_9)$$

P1 : $(x_1 x_2 \cdots x_8 x_9) = -(x_2 x_1 x_3 x_4 \cdots x_8 x_9)$

O3 PLANE

• • •

STATES SHOULD BE INVARIANT UNDER ORIENTIFOLD ACTION (UP TO A SIGN)

$x_i x_j x_k$ (84 states) $\Longrightarrow$

$x_1 x_2 x_j$	7
$x_i x_j x_k$	30
$x_1 x_i x_j + x_2 x_i x_j$	21
states	63

SUSIC CYCLES IN LANDAU-GINZBURG

Iqbal, Hori + Vafa

FLUXES NEED TO BE INTEGRATED OVER SUSIC CYCLES TO CHECK TADPOLE CANCELLATION

WE ARE CONSIDERING AN $N=2$ LG THEORY ON A MANIFOLD WITH BOUNDARY. THE SUPERPOTENTIAL W IS AN F-TERM THAT UNDER SUSY GIVES A TOTAL DERIVATIVE. BOUNDARY TERM $=0$

① A-CYCLES (SLAGs)

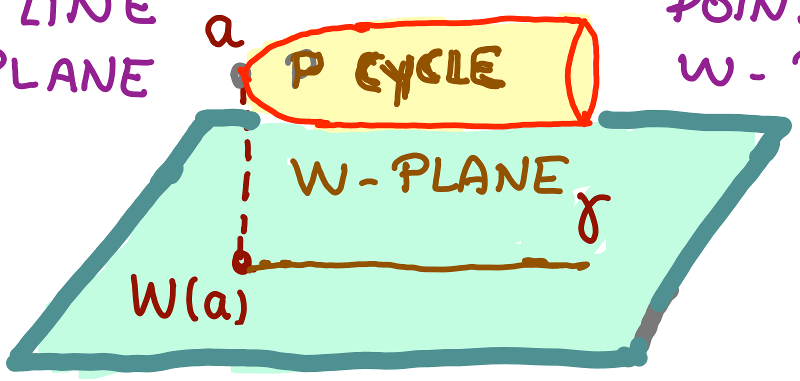
$\operatorname{Im} W = 0$ (odd)

STRAIGHT LINE IN W-PLANE

② B-CYCLES (Cplx)

$W = 0$ (even)

POINT IN W-PLANE



SIMPLE EXAMPLE

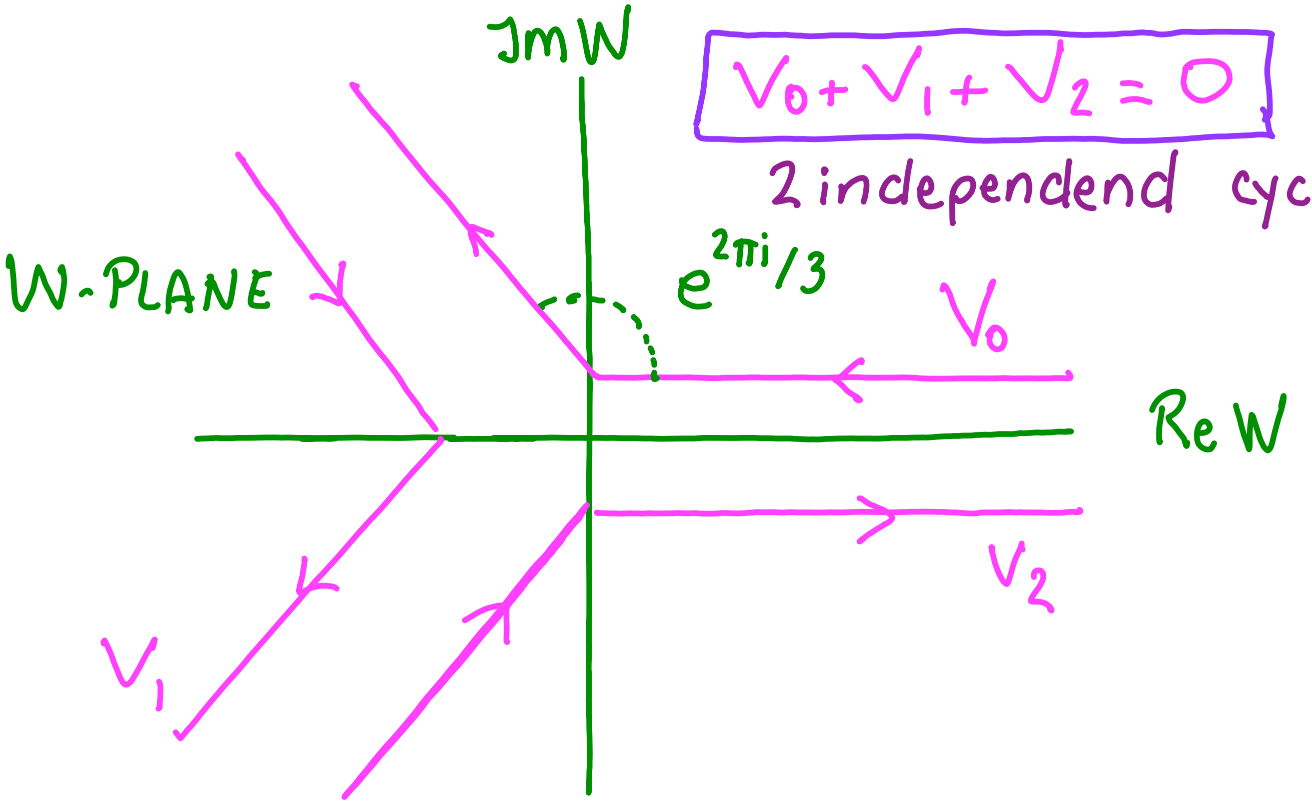
CONSIDER ONE $c=1$ MINIMAL MODEL

$W(x) = x^3$

$\mathrm{Im}\, W = 0$

$$\boxed{V_0 + V_1 + V_2 = 0}$$

2 independend cycles



WE NEED TO BUILD A $\mathbb{Z}_3$ INVARIANT COMBINATION OF THE TWO CYCLES AND CONSIDER 9 MINIMAL MODELS

WE WOULD LIKE TO INTEGRATE THE R-R GROUNDSTATES (BASIS)

$$x^{\ell-1} \equiv |\ell\rangle \qquad \ell = 1,2$$

OVER A-CYCLES $\langle V_m|$

THERE IS A NATURAL PAIRING THAT DEFINES THE INTEGRATION OF STATES OVER CYCLES

Cecotti, Hori + Vafa

$$\langle V_m|\ell\rangle = \int_{V_m} x^{\ell-1} e^{-x^3} dx \qquad \ell = 1,2$$

TADPOLE:

intersection matrix

$$\frac{1}{\tau-\tau^*}\int G\wedge G^* = \frac{1}{\tau-\tau^*}\langle \ell|V_m\rangle I^{mm}\langle V_m|\ell'\rangle$$

THESE ARE ALL THE TOOLS WE NEED!

SUMMARY OF CONDITIONS

CONSIDER MINKOWSKI SOLUTIONS FOR NOW

① SUPERSYMMETRY $G = H_{RR} - \tau H_{NS} \in H^{2,1}$

$$\int G\wedge\Omega = \int G\wedge\Omega^* = \int G\wedge \chi_{2,1} = 0$$

② TADPOLE CANCELLATION

$$\int H_{RR}\wedge H_{NS} = \frac{1}{\tau-\tau^*}\int G\wedge G^* = 12 - \cancel{N_{D3}}$$

③ FLUX QUANTIZATION

$\vec{m} = (m_1 \cdots m_g)$

$$\int_{\Gamma_{\vec{m}}} G = N^{\vec{m}} - \tau M^{\vec{m}} \leftarrow \text{NS flux XX}$$

$\Gamma_{\vec{m}}$ ← cycles

$N^{\vec{m}}$ — RR-flux XX

TAKING THIS INTO ACCOUNT WE OBTAIN A LARGE SYSTEM OF DIOPHANTINE EQS.

HARD TO SOLVE !

SAMPLE STRONG COUPLING SOLUTION

ALL MINKOWSKI SOLUTIONS EMERGE AT STRONG COUPLING ! (ADS SOLUTIONS ALSO EXIST)
(NOT IN THIS MODEL THOUGH)

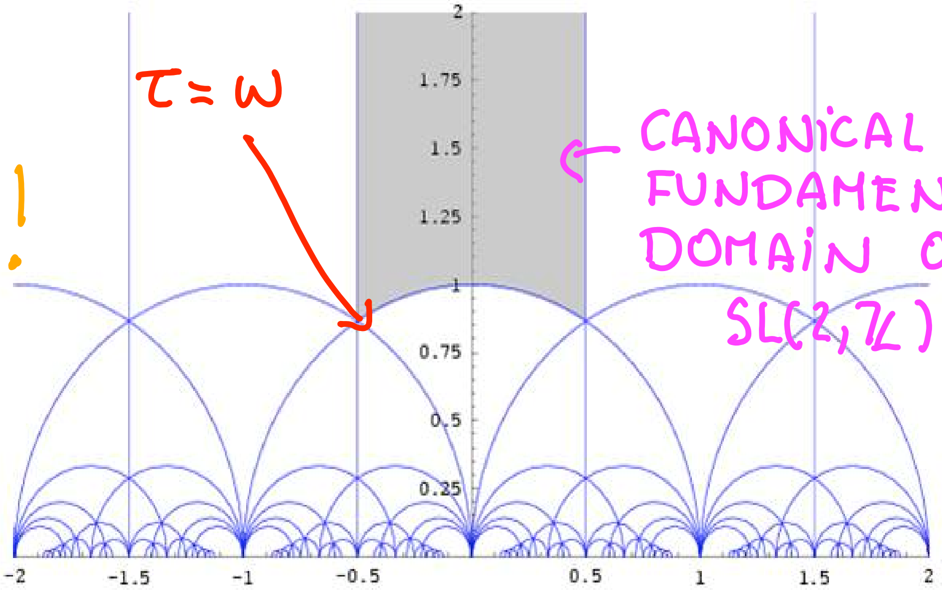
$$G = |111122121\rangle - |111122112\rangle - |111121221\rangle + |111121212\rangle$$

$$|e\rangle = |\ell_1 \ell_2 \dots \ell_g\rangle \text{ with } |\ell\rangle = x^{\ell-1}$$

$$\ell = 1, 2$$

$$\tau = \omega = e^{\frac{2\pi i}{3}}$$

↑ WEAK COUPLING (NORTH)



$\tau = \omega$

STRONG COUPLING !

CANONICAL FUNDAMENTAL DOMAIN OF $SL(2,\mathbb{Z})$

NON-RENORMALIZATION THEOREM

THE TYPE IIB FLUX SUPERPOTENTIAL DOES NOT RECEIVE ANY CORRECTIONS IN g_s

$\uparrow$ string coupling

$$W_{IIB} = \int G \wedge \Omega$$

Vafa

Dijkgraaf + Vafa

Burgess, Escoda + Quevedo

① PERTURBATIVE CORRECTIONS

THE N=1 ACTION STILL HAS FEATURES OF THE N=2 THEORY

(NO COUPLING BETWEEN HYPERS + VECTORS)

② NON-PERTURBATIVE CORRECTIONS:

NO CANDIDATE INSTANTON AVAILABLE

THIS ENSURES THE EXISTENCE OF VACUA!

MASSES OF MODULI?? SUSY BREAKING?.

TYBE IIB FLUX VACUA AT WEAK COUPLING

GOAL : SEARCH FOR VACUA IN THE LARGE COMPLEX STRUCTURE AND SMALL g_s LIMIT

MIRROR TO MASSIVE IIA MODEL OF DGKT (LARGE RADIUS, SMALL g_s)

$$W = \sum_{i=1}^{9} x_i^3 + a_1 x_1 x_2 x_3 + a_2 x_4 x_5 x_6 + a_3 x_7 x_8 x_9 + \dots$$

BULK MODULI : $t_1 t_2 t_3$ RELATED TO a_i
COMPLEX STRUCTURE OF $T^6 = (T^2)^3$

BLOW UP MODES : STABILIZED

FLUX SUPERPOTENTIAL AND MODULI

WE WOULD LIKE TO DERIVE $W_{IIB}(t_1 t_2 t_3)$.

$$\boxed{W_{IIB} = \int (H_R - \tau H_{NS}) \wedge \Omega}$$

$H_{NS} = N^a \alpha_a - \tilde{N}_a \beta^a$

$H_R = M^a \alpha_a - \tilde{M}_a \beta^a$

SYMPLECTIC BASIS

SPECIAL GEOMETRY

$$z_I = \oint_{A_I} \Omega \qquad \frac{\partial \mathcal{F}}{\partial z_I} = \oint_{B_I} \Omega$$

PREPOTENTIAL

$$\mathcal{F}(z) = -\frac{1}{3!} \kappa_{IJK} \frac{z^I z^J z^K}{z^0} \quad ; \quad \kappa_{123} = \kappa = 1$$

$t_1 = t_2 = t_3 = t$

$$\boxed{\begin{aligned} W_{RR} &= -t^3 M_0 + 3t^2 M_2 + 3t M_4 + M_6 \\ W_{NS} &= -t^3 N_0 + 3t^2 N_2 + 3t N_4 + N_6 \end{aligned}}$$

$$W_{IIB} = W_{RR} - \tau W_{NS}$$

MODULI [FLUX XX] THEN EASILY FOLLOWS BY SOLVING TADPOLE AND

$$\begin{cases} D_t W = D_\tau W = 0 \\ W = 0 \quad (\text{MINKOWSKI}) \end{cases}$$

WHAT DID WE SEE ??

① MINKOWSKI SOLUTIONS ARE CONFINED TO STRONG COUPLING

② AdS SOLUTIONS EXIST FOR LARGE t AND SMALL g_s

WE WORKED OUT SPECIFIC EXAMPLES

EXAMPLE: MIRROR OF MASSIVE IIA

A SIMPLE SOLUTION WHICH IS MIRROR TO THE MASSIVE TYPE IIA MODEL IS

$W_{NS} = N_6$ $\quad W_{RR} = -t^3 M_0 + 3t^2 M_2 + 3t M_4 + M_6$

TADPOLE $\quad \int H_{RR} \wedge H_{NS} = -M_0 N_6$

$M_2, M_4, M_6 \to \infty$ NOT BOUNDED !

PARAMETRIC CONTROL!

SOLUTION

$$t_1 = \frac{M_2}{M_0} \qquad t_2 = \sqrt{-\frac{M_2^2}{M_0^2} - \frac{M_4}{M_0}} \qquad t = t_1 + i t_2$$

$$\tau_2 \approx \frac{M_0}{N_6} (t_2)^3$$

t IS LARGE, $g_s = \frac{1}{\tau_2}$ IS SMALL !

A CONJECTURE

A SURPRISE ARRIVED FROM THE MASS MATRIX

$$M_{ij}(t_i,\tau) \sim \Lambda_{Ads}\, O_{ij}(1)$$

MASSES ARE OF THE ORDER OF THE 4D COSMOLOGICAL CONSTANT !

SITUATION IS RATHER GENERIC FOR ALL TYPE IIB SOLUTIONS AS WELL AS FOR THE MASSIVE IIA MODEL OF DGKT

Gukov, Ooguri + Vafa

CONJECTURE

"ANY SEQUENCE OF SUPERSYMMETRIC WEAKLY COUPLED STRING VACUA HAS SOME MODULI FIELDS WITH MASSES OF THE ORDER OF THE COSMOLOGICAL CONSTANT ... "

FOR SUSIC VACUA MODULI MIGHT ONLY BE STABILIZED IN THE NON-GEOMETRIC PHASE ! ! !

UPLIFTING TO DE SITTER

Kallosh + co
Saueressig
Theis +
Vandoren

THE SITUATION MAY IMPROVE ONCE WE UPLIFT TO DE SITTER SPACE AND MODULI MIGHT BE HEAVY

- * WE CAN UPLIFT WITH $\overline{D3}$s (KKLT)
- * SUSY BREAKING WITH FLUX ONLY

ONCE SUSY IS BROKEN AND IN MODELS WITH A RICHER STRUCTURE THERE MIGHT BE AN ALTERNATIVE TO $\overline{D3}$'s INVOLVING ONLY FLUX.

Aganagic, Beem
Heckman + Vafa
(non-compact)

INGREDIENTS:

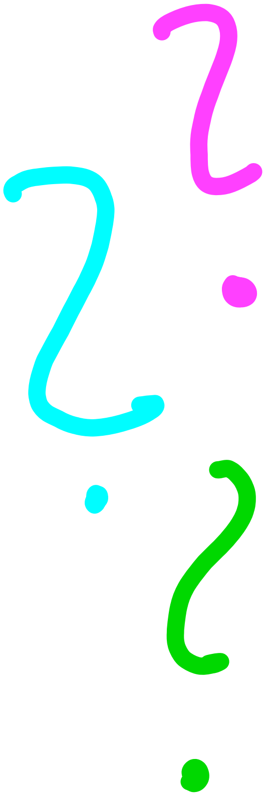
- * PERTURBATIVE CORRECTIONS TO $K(\Phi)$
- * NON-PERTURBATIVE CORRECTIONS TO $W(\Phi)$, WHICH ARE ALLOWED IN MORE COMPLICATED MODELS ONCE SUSY IS BROKEN.

NOT A FREE LUNCH THOUGH!

CONCLUSION

IT IS OF GREAT IMPORTANCE TO UNDERSTAND MODULI STABILIZATION IN THE NON-GEOMETRIC PHASE !

SOME RATHER INTERESTING QUESTIONS NEED TO BE SOLVED:



- * STRONG COUPLING SOLUTION:
  IS THERE A DUAL CFT ???
- * WEAK COUPLING SOLUTION:
  INSTANTON CORRECTIONS TO W,
  PERTURBATIVE CORRECTIONS TO K
- * FLUXES IN CFT AND LANDAU-GINZBURG ?
- * IMPLICATIONS OF LIGHT MODULI FOR SWAMPLAND

AN EXCITING TRIP THROUGH THE NON-GEOMETRIC LANDSCAPE IS AHEAD OF US ! ☺