Hierarchies and Inflation in the Mirror Quintic

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w/ Cabo-Bizet & Loaiza-Brito

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- Flux compactifications in type IIB theory
- Mirror quintic and its moduli space
- Type IIB orientifolds of the mirror quintic
  - PF equations and solutions
  - Vacua exploration: hierarchies and inflation
- Conclusions & Outlook

Introduction

$\mathcal{N} = 1$ string theory compactifications

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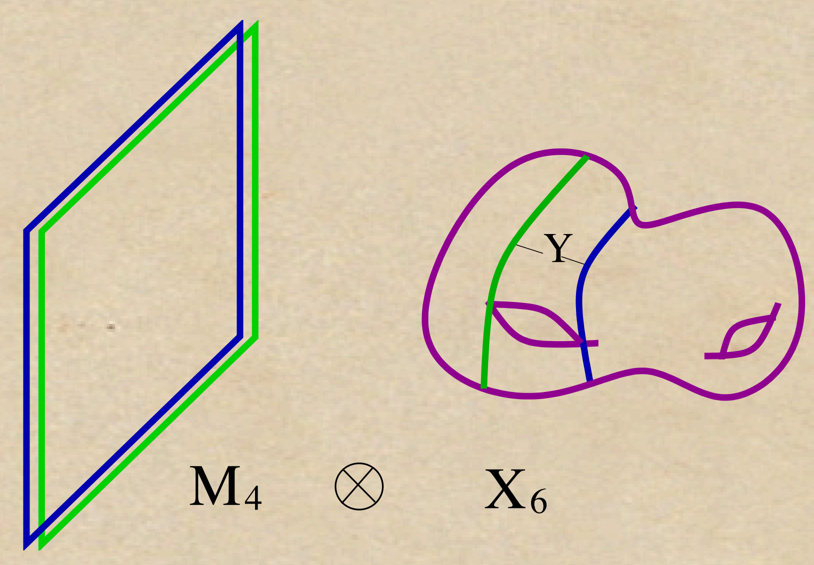
$\mathcal{N}=1$ string theory compactifications

- String Theory in 10D: compactify on a 6D compact manifold

  - Tori
  - Calabi-Yau



Introduction

Flux compactifications in string theory

[Giddings-Kachru-Polchisnki, ’01]

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Flux compactifications in string theory

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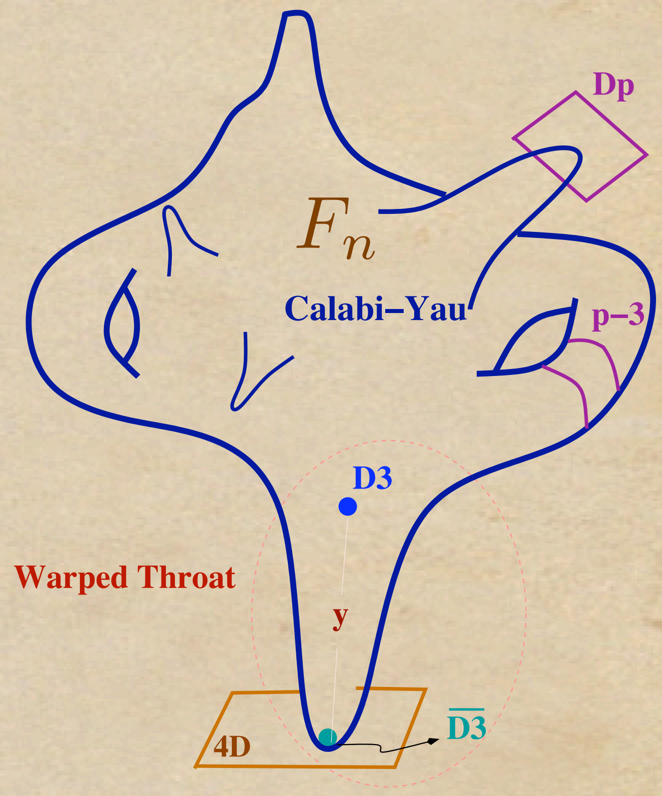
Introduce internal fluxes: F_n



- Fluxes backreact warping internal CY manifold: new avenues for *phenomenology and cosmology*!
- Stabilise some of the moduli: dilaton & complex structure
- Scale hierarchies á la Randall-Sundrum generated

[Randall, Sundrum, '99]

Type IIB flux compactifications

Consider type IIB string theory in 10D with localised sources: D-branes & Orientifolds

$$S_{\rm IIB} = \frac{1}{2{\kappa_{10}}^2}\int d^{10}x\sqrt{-g}\left\{\mathcal{R} - \frac{\partial_M\tau\partial^M\bar\tau}{2({\rm Im}\,\tau)^2} - \frac{G_{(3)}\cdot\bar G_{(3)}}{12\,{\rm Im}\,\tau} - \frac{\tilde F_{(5)}^2}{4\cdot 5!}\right\}$$
$$+\frac{1}{8i{\kappa_{10}}^2}\int\frac{C_{(4)}\wedge G_{(3)}\wedge\bar G_{(3)}}{{\rm Im}\,\tau} + S_{\rm loc}\ .$$

$\tau = C_{(0)} + ie^{-\phi}$ axio-dilaton

$G_{(3)} = F_{(3)} - \tau H_{(3)}$ 3-form potentials

$\kappa_{10}^2 = (2\pi)^7(\alpha')^4/2 \equiv \ell_s^8/4\pi$

$g_s = e^\phi$

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under $SL(2,\mathbf{Z})$ $\qquad \tau \to \dfrac{a\tau+b}{c\tau+d}\ ,$

together with $\qquad G_{(3)} \to \dfrac{G_{(3)}}{c\tau+d}$

$$ad - cb = 1$$

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$$ad - cb = 1$$

this includes a **shift symmetry** for τ

$$\tau \to \tau + b$$

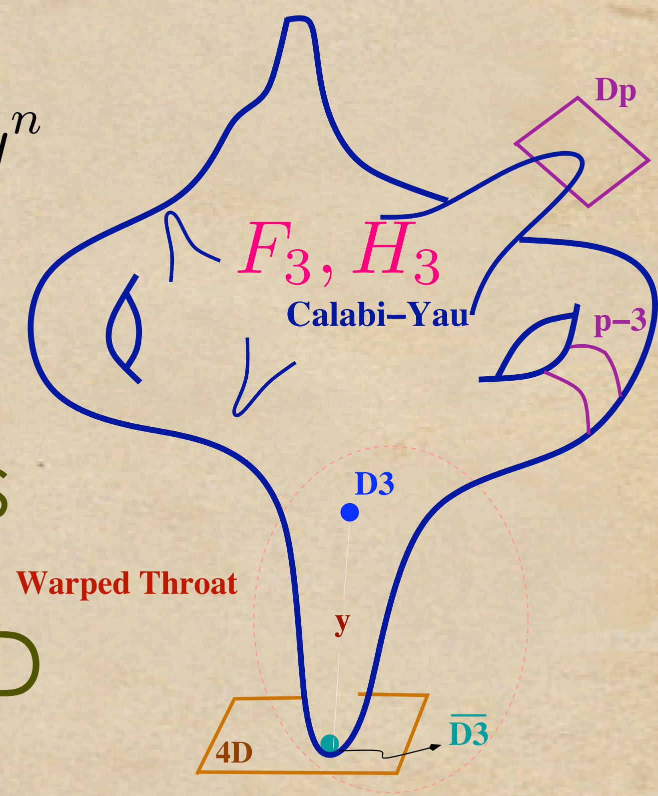
$$(c=0\,,\;\; a=d=1)$$

$G_3 \to G_3$ but

$$F_3 \to F_3 + bH_3$$

Compactify the internal 6D in some CY manifold

$$ds^2_{10} = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}dy^m dy^n$$



- Fluxes' backreaction ➠ warp throats
- Preserve $\mathcal{N} = 1$ supersymmetry in 4D
- RR&NSNS 3-form fluxes wrap internal 3-cycles and are quantised as

$$\frac{1}{2\pi\alpha'}\int F_{(3)} \in 2\pi\mathbf{Z}\ , \qquad \frac{1}{2\pi\alpha'}\int H_{(3)} \in 2\pi\mathbf{Z}$$

Tadpole cancelation

- The orientifold compactifications relevant for us contain O3/O7-planes. Need to cancel tadpoles

- Fluxes contribute to the D3-brane charge as well as D7-branes.

- Requiring to cancel total charges in the internal CY space from D-branes, O-planes and fluxes:

$$N_{flux} + N_{D3} = \frac{\chi}{24} - \frac{N_{O3}}{4}$$

$$N_{flux} \propto \int_{CY} F_3 \wedge H_3$$

4D $\mathcal{N} = 1$ Supergravity

The effective 4D action takes the form

$$S_4 = \int d^4x \sqrt{g} \left[\frac{M_{Pl}^2}{2} R - M_{Pl}^2 \, K_{a\bar{b}} \, \partial_\mu \Phi^a \partial^\mu \bar{\Phi}^{\bar{b}} + V(\Phi^l) \right]$$

$$M_{Pl}^2 = \frac{V_6}{\kappa_{10}^2 \, g_s^2}$$

$$\kappa_{10}^2 \;=\; (2\pi)^7 (\alpha')^4/2 \;\equiv\; \ell_s^8/4\pi$$

$$\Phi^a = \begin{cases} \text{axio-dilaton} \\ \text{complex structure} \\ \text{Kähler moduli} \end{cases}$$

where the flux potential is given by

$$V = \frac{1}{2\kappa_{10}^2} \int_{CY} d^6y \sqrt{\tilde{g}} \; \frac{G_{(3)} \cdot \bar{G}_{(3)}}{12 \, \mathrm{Im} \, \tau} - \frac{i}{4\kappa_{10}^2 \, \mathrm{Im} \, \tau} \int_{CY} G_3 \wedge \bar{G}_3$$

4D $\mathcal{N} = 1$ Supergravity

The potential can be written in $\mathcal{N} = 1$ form

$$V = \frac{1}{2\kappa_{10}^2 g_s} e^K \left[K^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right]$$

$$\Phi^a = \begin{cases} \text{axio-dilaton} \\ \text{complex structure} \\ \text{Kähler moduli} \end{cases}$$

with the Kähler potential

$$K = -\ln\left[-i\left(\tau - \bar{\tau}\right)\right] - \ln\left[-i\int_{CY} \Omega \wedge \bar{\Omega}\right] - 2\ln\left[\mathcal{V}\right]$$

and the *Gukov-Vafa-Witten flux superpotential*

[Gukov-Vafa-Witten, '99]

$$W = \int_{CY} G_3 \wedge \Omega$$

$\Omega =$ holomorphic (3,0)-form

No scale models

- In *no-scale* models the superpotential is independent of the Kähler moduli, T_i

- This is the case of the flux GVW superpotential (extra non-perturbative contributions needed to fix Kähler moduli)

$$V = \frac{1}{2\kappa_{10}^2 g_s} e^K \left[K^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right] \qquad a, b = \tau, z$$

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$$V = \frac{1}{2\kappa_{10}^2 \, g_s} e^K \left[K^{a\bar{b}} D_a W \overline{D_b W} \right] \geq 0 \qquad a, b = \tau, z$$

The periods of the CY

- The $h^{2,1}$ complex structure moduli are described in terms of the *periods* of Ω

$$\Pi = \begin{pmatrix} \mathcal{X}^I \\ \mathcal{F}_I \end{pmatrix} = \begin{pmatrix} \int_{A^I} \Omega \\ \int_{B_I} \Omega \end{pmatrix}$$

(A^A, B_B) symplectic basis for the $b_3 = 2h^{2,1} + 2$ 3-cycles, $H_3(CY)$

(α_I, β^I) its dual basis, $H^3(CY)$, and $\Omega = \mathcal{X}^I \alpha_I - \mathcal{F}_I \beta^I$

- In terms of the periods

$$K_{cs} = -\ln\left(-i\,\bar{\Pi}^T\,\Sigma\,\Pi\right) \qquad \Sigma = \begin{pmatrix} 0 & \mathbb{1}_{k\times k} \\ -\mathbb{1}_{k\times k} & 0 \end{pmatrix}$$

$$W = G\,\Sigma\,\Pi \qquad k = 1 + h^{2,1}$$

The quintic and its mirror I

[Candelas-de la Ossa-Green-Parkes, '91]

We consider type IIB orientifold compactification on the *mirror of the quintic* $\mathbb{P}^4$

- The quintic M_3 is given as the general quintic hypersurface in $\mathbb{P}^4$.
- It has 101 complex structure moduli and 1 Kähler. That is $h^{1,1} = 1\,,\;\; h^{2,1} = 101\,,\;\; \chi = -200$

The quintic and its mirror II

[Candelas-de la Ossa-Green-Parkes, '91]

- The mirror quintic threefold $\mathcal{W}$ is given as the hypersurface

$$P = \sum_k x_k^5 - 5\psi \prod x_k = 0$$

modded out by the $\mathbb{Z}_5^3$ symmetry: $M_3/\mathbb{Z}_5^3$
and ψ determines the complex structure of $\mathcal{W}$

- It has $h^{1,1} = 101\,,\ \ h^{2,1} = 1\,,\ \ \chi = 200$ and $b_3 = 4$

Critical points in the CS moduli space of $\mathcal{W}$

The mirror quintic has three critical points: *conifold, large complex structure and orbifold*

- The conifold and LCS arise when $P = 0$ and $dP = 0$
  - ➡ This restricts $\psi^5 = 1$ to a point, the *conifold* point.
  - ➡ The point $\psi^5 = \infty$, corresponds to the *large complex structure* point where the variety degenerates to

$$x_1 x_2 x_3 x_4 x_5 = 0$$

- The point $\psi = 0$ in moduli space is an *orbifold* singularity

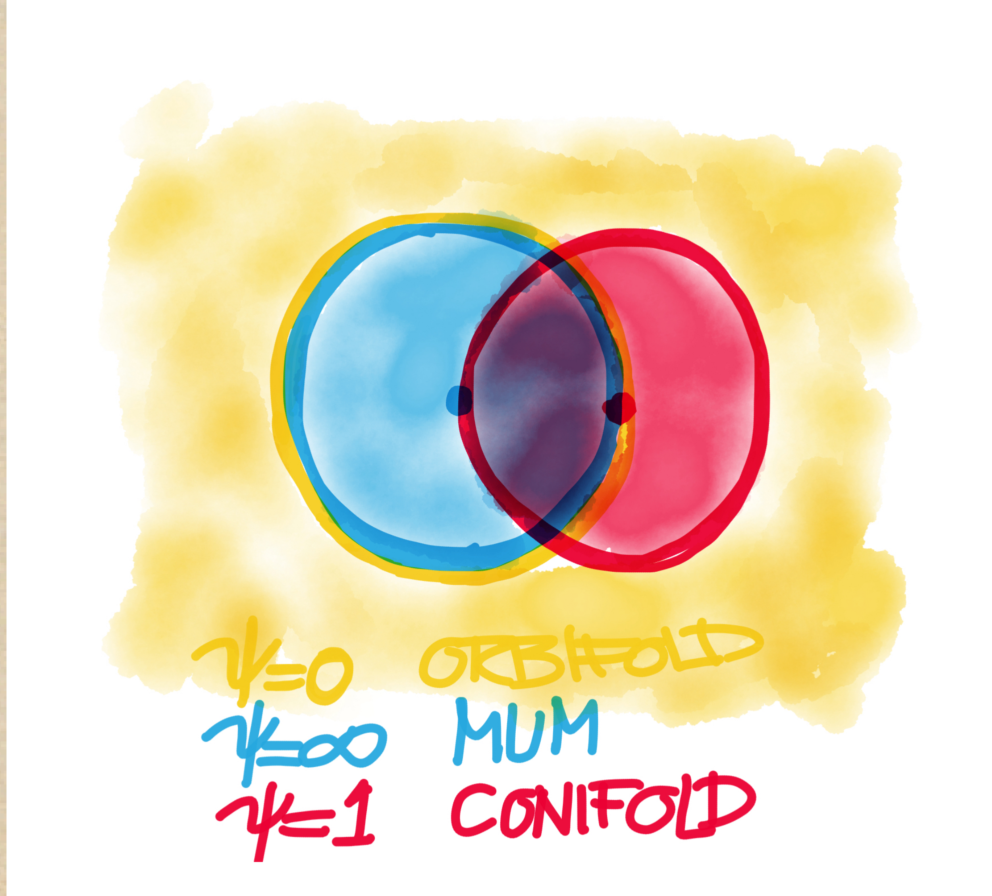
Critical points in the CS moduli space of

Parameterising the modulus ψ by the coordinate z_C as

$$z_C = 1 - \psi^{-5}$$

the singular points are located at:

- the conifold: $z_C = 0$
- the LCS: $z_C = 1$
- the orbifold: $z_C = \infty$



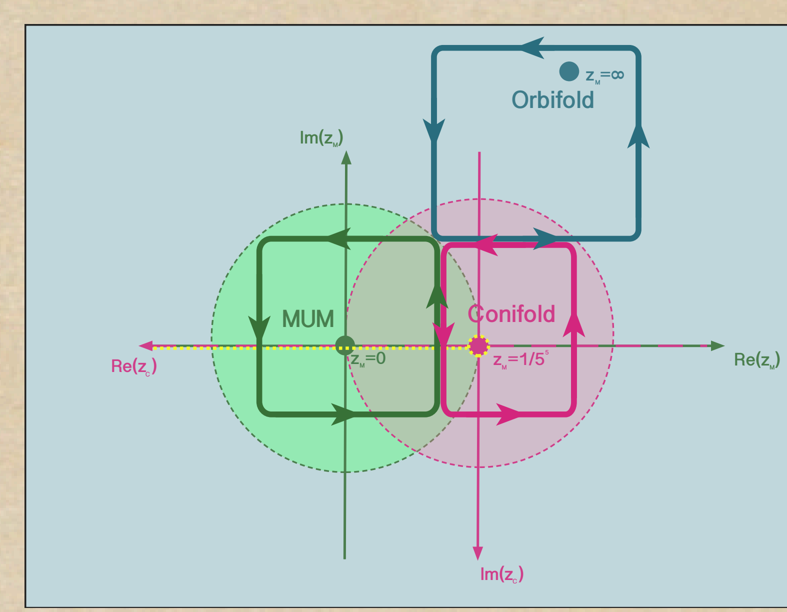
Monodromies

- Transport of the periods around the critical points lead to specific *monodromy* transformations:

$$\Pi \to \mu\Pi$$

$\mu =$ monodromy transformation matrix

- The monoromies around the singular points satisfy
  - the conifold: $(\mu_C - 1)^2 = 0$
  - the LCS: $(\mu_M - 1)^4 = 0,$
  - the orbifold: $\mu_O^5 = 1$



- The monodromies around the critical points satisfy

$$\mu_C \cdot \mu_M \cdot \mu_O^{-1} = \mathbb{1}.$$

Picard-Fuchs equations

The periods obey the differential *Picard-Fuchs* (PF) equations, which in coordinates $z_M = (5\psi)^{-5}$ near the LCS point take the form

$$(\theta^4 - z(\theta + a_1)(\theta + a_2)(\theta + a_3)(\theta + a_4))\Pi_i = 0, \qquad i = 1, 2, 3, 4,$$

where $\theta = z_M \partial_{z_M}$ and $a_k = k/5$. $k = 1, 2, 3, 4.$

- To explore the solutions near the orbiofold point, convenient to make change of variables $z_O = 1/z_M$

$$(-z_0/5^5\theta_O^4 + (a_1 - \theta_O)(a_2 - \theta_O)(a_3 - \theta_O)(a_4 - \theta_O))\Pi_i^O = 0.$$

- While near the conifold, convenient variables are $z_C = 1 - 5^5 z_M$

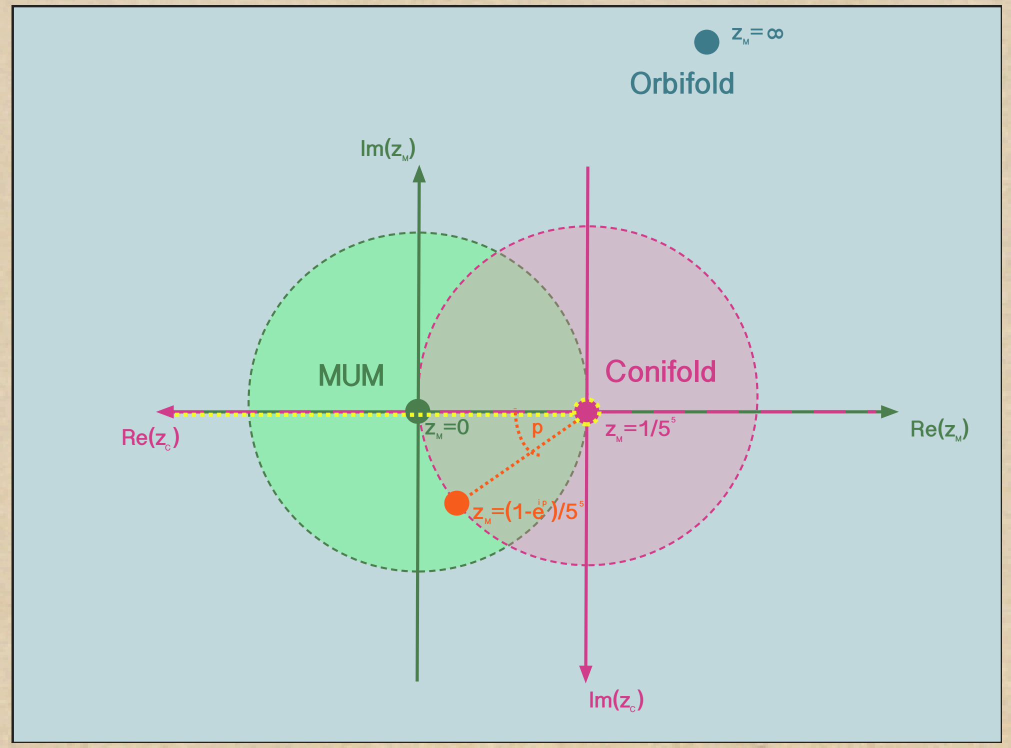
$$(\theta_C^4 - (1 - z_C)(a_1 - \theta_C)(a_2 - \theta_C)(a_3 - \theta_C)(a_4 - \theta_C))\Pi_i^C = 0.$$

(the convergence radii are 5^{-5}, 5^5, 1, respectively)

Picard-Fuchs equations

To explore the full moduli space we also study the PF equations in the vicinity of an arbitrary regular point on the boundary of the conifold convergence region

$$(\theta_\alpha^4 - (1 - z_\alpha - e^{i\alpha})(a_1 - \theta_\alpha)(a_2 - \theta_\alpha)(a_3 - \theta_\alpha)(a_4 - \theta_\alpha))\pi_i^\alpha = 0$$



$$z_C = z_\alpha + e^{i\alpha}$$

Power series solutions

Near the conifold the solutions are found by making a power series ansatz: $\Pi_{C,i} = z_C^x(c_0 + c_1 z_C + c_2 z_C^2 + \cdots + c_n z_C^n)$.

- The solutions for x are $x = 0, 1^2, 2$. We obtain three power series solutions for $x = 0, 1, 2$ and a logarithmic solution for $x = 1$. This vanishes when $z_C \to 0$

  One obtains a set of recursive equations for the coefficients to each order of the expansion.

- The case $x = 1$ serves to construct the logarithmic solution

$$\Pi_{C,4} = z_C(c_0 + c_1 z_C + c_2 z_C^2 + \cdots + c_n z_C^n) \ln z_C + z_C^{x_b}(b_0 + b_1 z_C + b_2 z_C^2 + \dots)$$

- The convergence of the power series is $\lim_{n\to\infty} |c_n/c_{n+1}| = 1$ and similarly for b_n

Power series solutions

In the sympectic basis the periods near the conifold take form

$$\Pi_C = \begin{pmatrix} \mathcal{X}^I \\ \mathcal{F}_I \end{pmatrix} = \begin{pmatrix} \Pi_1(z_C) \\ \Pi_2(z_C) \\ \frac{1}{2\pi i}\Pi_1(z_C)\ln z_C + Q(z_C) \\ \Pi_4(z_C) \end{pmatrix}$$

In a similar form, we find the periods $\Pi(z)$ in the vicinity of all special points $\psi = 0, 1, \infty$

We also determine the *transition matrices* to connect the convergence regions.

Find the periods in the full moduli space of $\mathcal{W}$ up to order 600.

[Candelas et al. '91]
[Greene, Plesser '89]
[Huang, Klemm, Quackenbush '06]

Mirror quintic vacua

- Flux compactification on the mirror quintic: *no-scale* model with a single complex structure z (and the axio-dilaton τ)

$$V = \frac{1}{2\kappa_{10}^2 g_s} e^K \left[K^{a\bar{b}} D_a W \overline{D_b W} \right]$$

$$\left(K = -\ln(-i\bar{\Pi}^T \Sigma \Pi) - \ln(-i(\tau - \bar{\tau})) - 2\ln \mathcal{V}\,; \qquad W = G\Sigma\Pi \right)$$

- To explore vacua, we want to map the full moduli space of CY, the mirror quintic: $D_\tau W = D_z W = 0$

- To map the *full CY moduli space* we solve the periods as functions of the CS near all the critical points as well as far from them

$$\Pi = \begin{pmatrix} \mathcal{X}^I \\ \mathcal{F}_I \end{pmatrix} = \begin{pmatrix} \int_{A^I} \Omega \\ \int_{B_I} \Omega \end{pmatrix}$$

$$(A^1, A^2, B_1, B_2)\,; \;\; (\alpha_A, \beta^A)$$

Symmetries of the potential I

The no-scale $\mathcal{N}=1$ sugra potential

$$V = \frac{e^K}{2\kappa_{10}^2\, g_s}\left[K^{a\bar{b}} D_a W \overline{D_b W}\right]$$

- K and W are invariant under a shift of the axion C_0

$$C_0 \to C_0 + b\,, \qquad G_3 \to G_3 \qquad (F_3 \to F_3 + bH_3) \qquad \tau = C_{(0)} + ie^{-\phi}$$

$$G_3 = F_3 - \tau H_3$$

broken spontaneously by the fluxes

Symmetries of the potential II

- Under a shift of the CS phase, monodromy, by n powers of μ_C

$$z = re^{i\theta}$$

$$\theta \to \theta + 2\pi n \,,$$

K remains invariant, since $\mu_C^T \Sigma \mu_C = \Sigma.$ while

$$\Pi_3 \to \Pi_3 - n\,\Pi_1$$

and therefore

$$W \to W - n\,G_1 \Pi_1$$

But shifting also the flux, $G_3 \to G_3 - n\,G_1$ the superpotential remains invariant

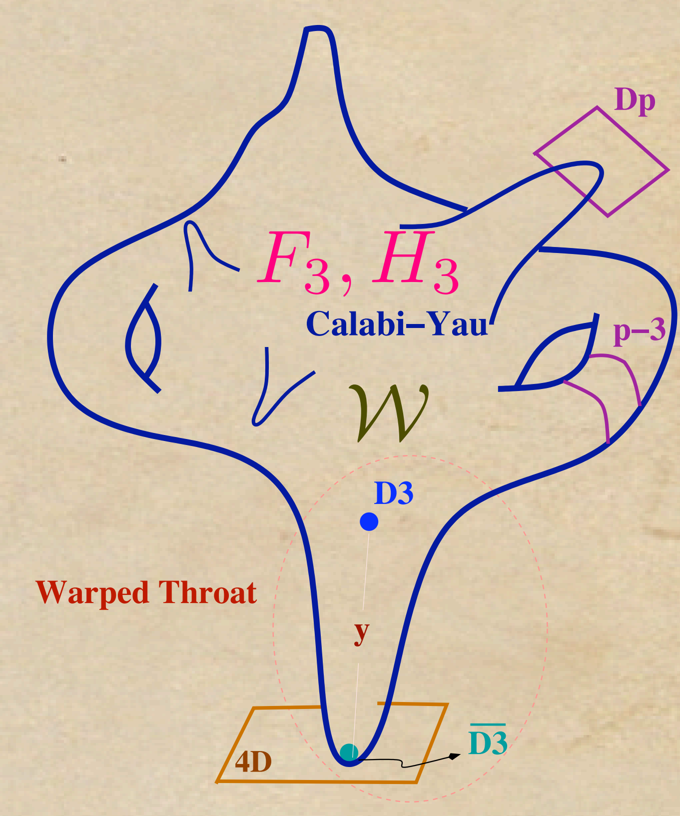
Hierarchies from fluxes revisited

In GKP only leading term in series of periods was kept. Assuming further $F_1, H_3, H_4 \neq 0,\ H_3 \gg H_4$ exponential hierarchies were found solving for $D_\tau W = D_z W = 0$

[Giddings-Kachru-Polchisnki, ’01]

$$e^{A_{min}} \sim z_C^{1/3} \sim e^{-2\pi H_3/H_4}$$

$$ds_{10}^2 = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}dy^m dy^n$$



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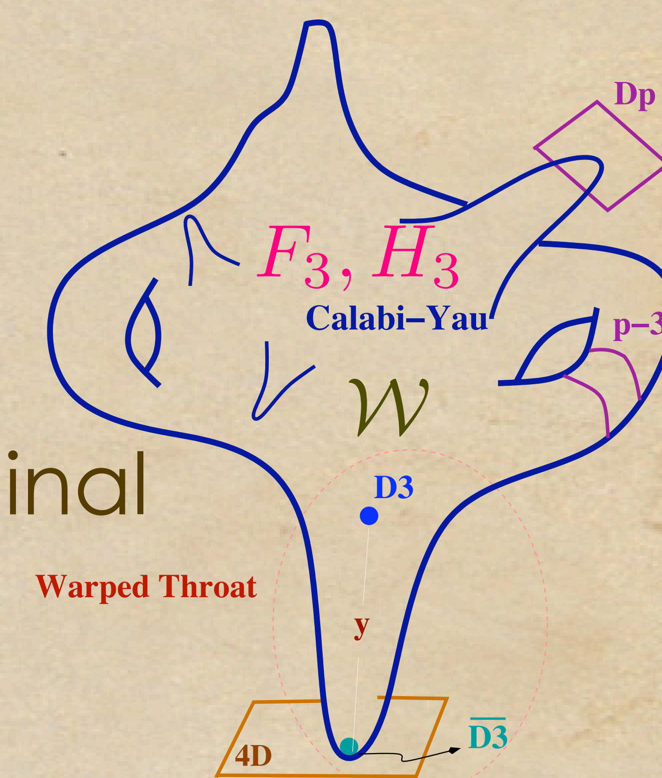
$$e^{A_{min}} \sim z_C^{1/3} \sim e^{-2\pi H_3/H_4}$$

$$ds^2_{10} = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}dy^m dy^n$$

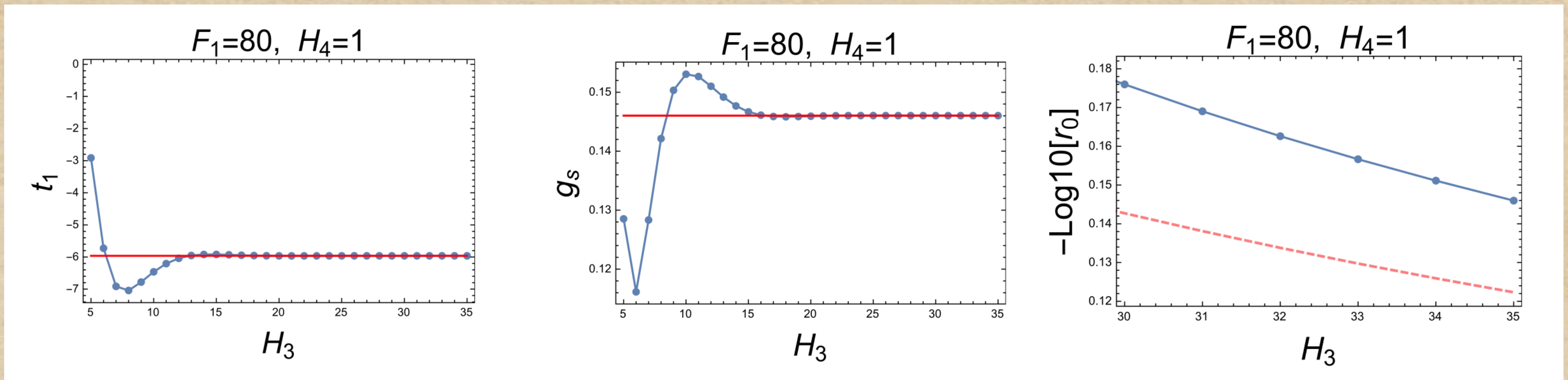


- We find an order one correction to original GKP result, at leading order, due to neglected terms in $D_z W = 0$

$$z_C \sim e^{-2\pi H_3/H_4 - \delta_0}\,, \qquad \delta_0 \sim \mathcal{O}(1)$$

[Blumenhagen et al. '16]

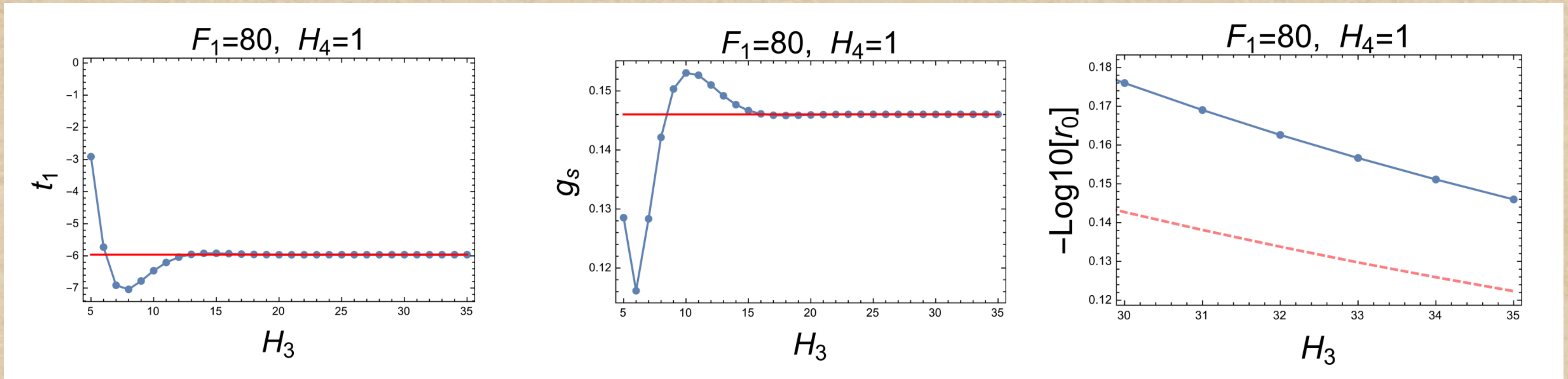
- We find vacua with hierarchies keeping up to oder 600 in the series and for *more general flux configurations*



GKP solution

Corrected solution

$$z_C \sim e^{-2\pi H/F-\delta_0}$$



GKP solution

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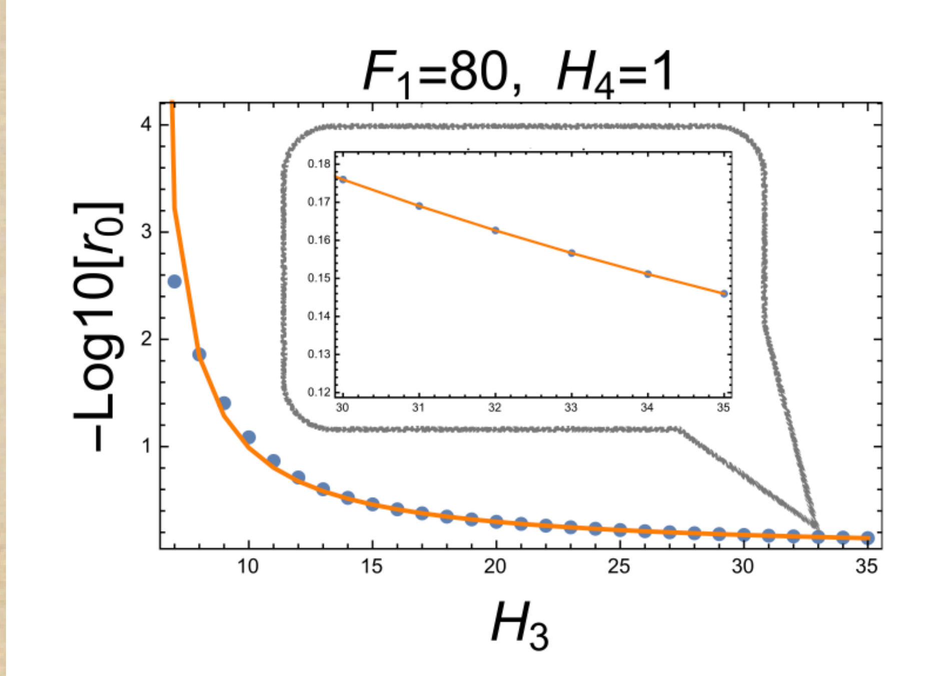
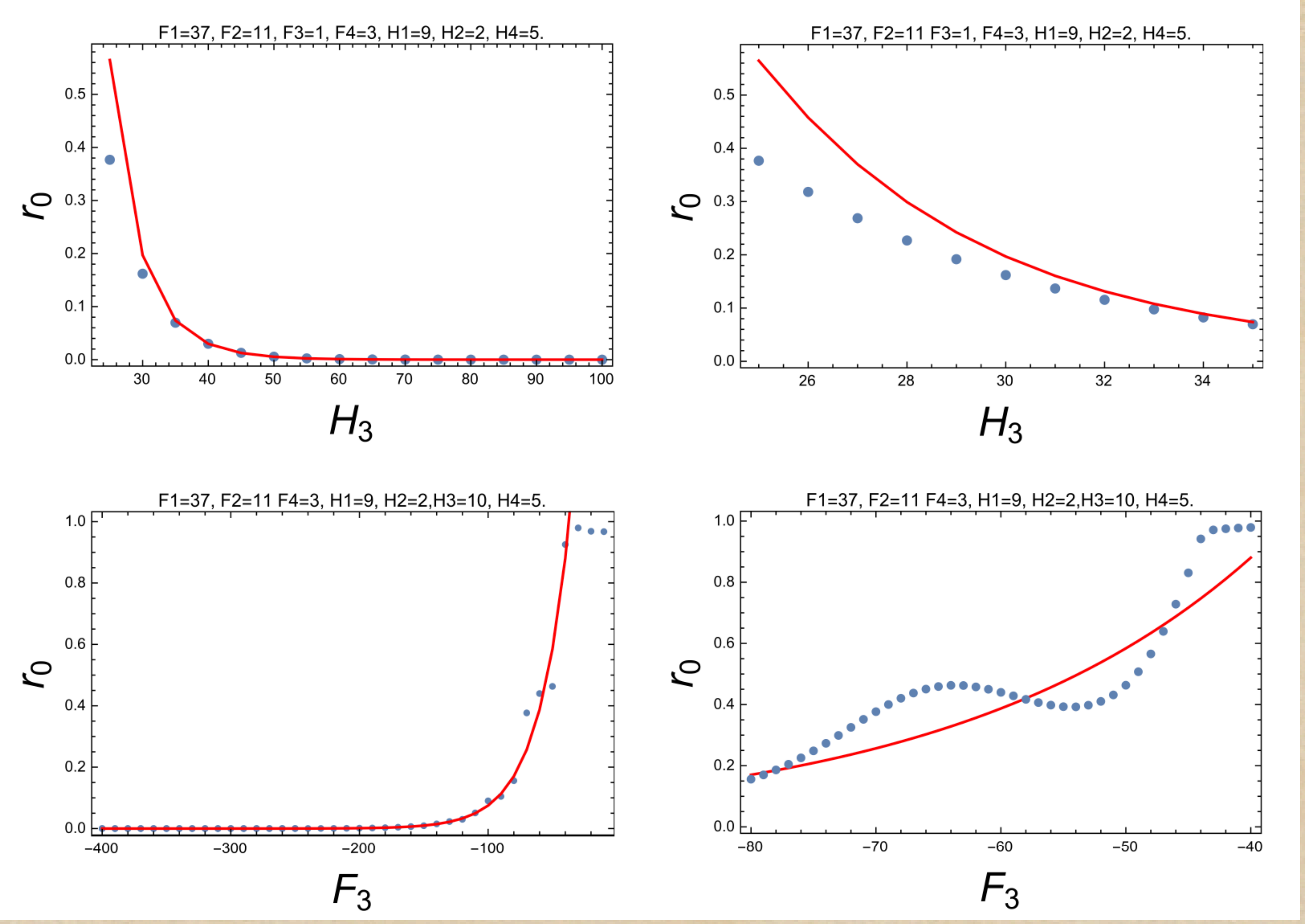


Corrected solution

Full solution (order 600)



Approximated solution near the conifold point

Full solution (order 600)

Quintic vacua

- Several stable Minkowski vacua at non-trivial monodromy close to the conifold, $r = |z| < 1$ (all have $g_s < 1$): $\theta \to \theta + 2\pi n\,,\ \ n > 1$

	r	θ	t_1	t_2	(F_1, H_1)	(F_2, H_2)	(F_3, H_3)	(F_4, H_4)
1	0.00387722	-7.01112	-2.965416	3.421883	(40,0)	(0,0)	(0,16)	(0,1)
2	0.289795	-3.90606	-7.0416876	7.0353577	(80,0)	(0,0)	(0,8)	(0,1)
3	0.289795	-3.90606	-176.04219	175.88394	(2000,0)	(0,0)	(0,8)	(0,1)
4	0.289795	-3.90606	-4.40105	4.3971	(50,0)	(0,0)	(0,8)	(0,1)
5	0.476018	-21.5600	-3.54466	5.02946	(9*10,1)	(0,0)	(27*10,16)	(0,2)
6	0.26791	-2.65769	-1.13736	2.11955	(20,0)	(0,0)	(0,8)	(0,1)
7	0.0038772	-7.01111	-4.44813	5.13282	(60,0)	(0,0)	(0,16)	(0,1)
8	0.0553517	-1.88428	-5.51566	20.8484	(200,1)	(30,1)	(2,10)	(2,1)
9	$2.07602 \cdot 10^{-6}$	-13.6039	-5.96259	6.84777	(80,0)	(0,0)	(0,30)	(0,1)
10	0.160500	1.7234	0.407671	0.81259	$(37, 9)$	$(11, 2)$	$(1, 31)$	$(3, 5)$
11	0.000301	7.2269	-1.22438	44.711	$(16, 2)$	$(7, 7)$	$(1, -8)$	$(4, -1)$
12	$6.28576 \cdot 10^{-8}$	-4.06	123.57	124.58	$(36, 2)$	$(107, 0)$	$(0, 5)$	$(0, 1)$
13	$8.91875 \cdot 10^{-7}$	-47.91	-4.75	1.56681	$(2, 0)$	$(4, -2)$	$(1, 3)$	$(1, 0)$
14	0.03351	6.28319	-3	3.71019	$(3, -1)$	$(3, 0)$	$(1, 1)$	$(0, 0)$

$$z = re^{i\theta}\,, \quad \tau = t_1 + it_2 = C_0 + ig_s^{-1}$$

- Several "fake" Minkowski vacua appear: moduli vevs depend on order of series.

Prospects for large field inflation

- Due to the shift symmetry in the CS moduli they have recently been used as potential inflatons in string theory:

  natural inflation & [Freese-Frieman-Linto, '90]

  axion monodromy [Silverstein et al. '08-'14] [Kaloper, Sorbo. '09]

  where the (discrete) shift symmetry for the CS is broken by fluxes

- *Most* works so far keep only *leading order* terms in periods' series expansion near the *large complex structure* point and freeze most moduli except the (shift symmetric) inflaton

Inflation in the mirror quintic

- We look for inflationary trajectories first along the shift symmetric directions, in the full 4D moduli space: C_0, θ $(\tau = C_0 + i g_s^{-1},\, z = r e^{i\theta})$

  keeping up to order 600 in the series expansions

- We do this by looking for regions where at the multifield slow roll conditions are satisfied:

$$\epsilon \ll 1 \qquad \eta \ll 1$$

where:

$$\epsilon = M_{Pl}^2 \frac{K^{i\bar{j}} \nabla_i V \nabla_{\bar{j}} V}{V^2}\,, \qquad \eta = \min \ \text{eigenvector} \left[\frac{K^{i\bar{j}} \nabla_i \nabla_{\bar{j}} V}{V} \right]$$

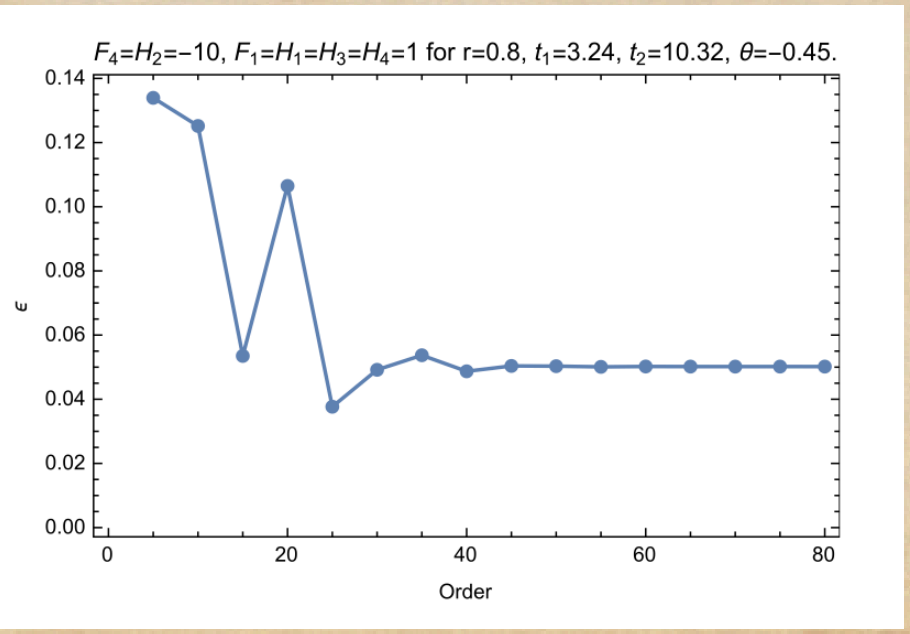
Inflation in the mirror quintic

- We look for inflationary trajectories first along the shift symmetric directions, in the full 4D moduli space: C_0, θ $\quad (\tau = C_0 + i g_s^{-1},\ z = r e^{i\theta})$

  keeping up to order 600 in the series expansions

- We do this by looking for regions where at the multifield slow roll conditions are satisfied:

  effect on expansion order on ϵ



Inflation in the mirror quintic

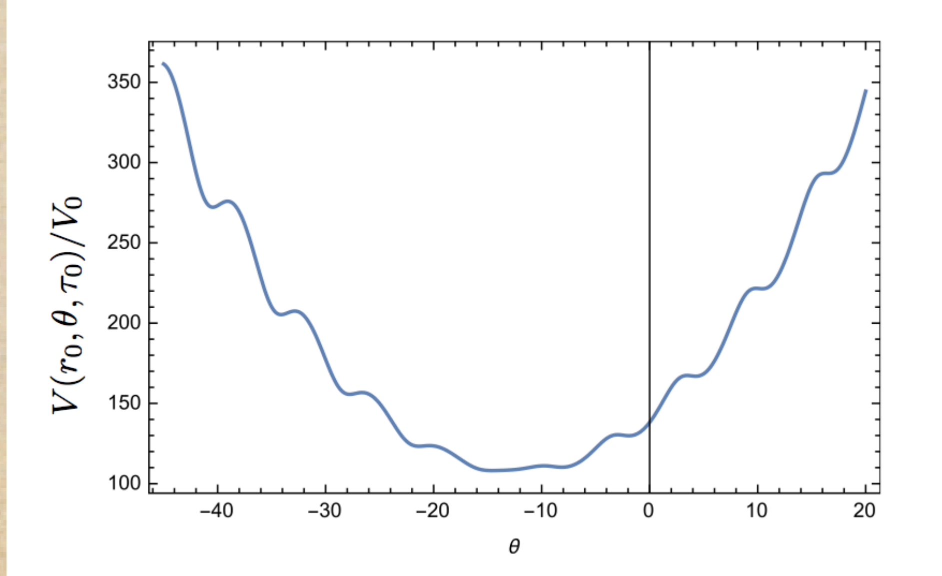
- In this case we did not find regions with small slow-roll parameters
- Scalar potential has generic form:

[Kobayashi,Oikawa,Otsuka,'15]

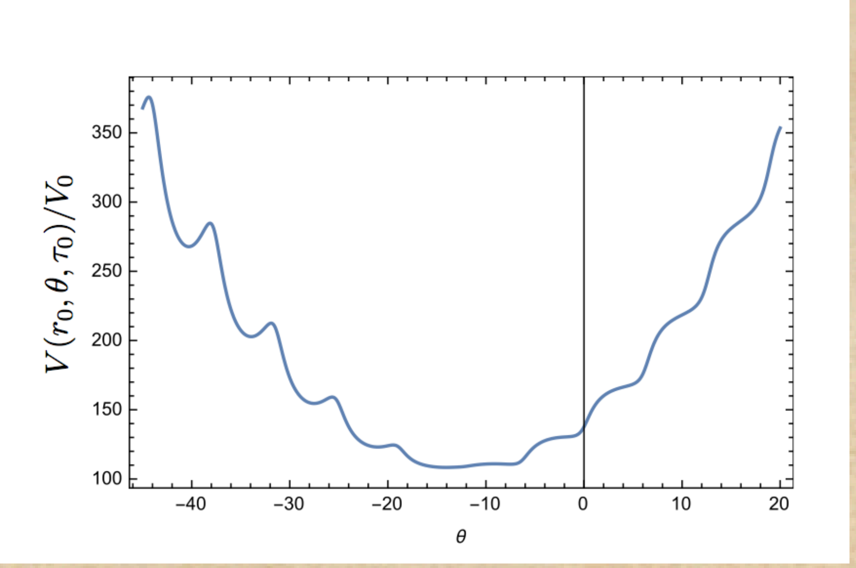
$$V(\theta) \sim A + B\,\theta^2 + C\,\theta\cos\theta + \ldots$$

$\Rightarrow$ oscillatory term generically too large

$$F_1 = H_1 = 1,\ F_4 = H_2 = -10,\ F_2 = F_3 = 0,\ H_3 = H_4 = 1$$



Order 1



Order 200

Inflation in the mirror quintic

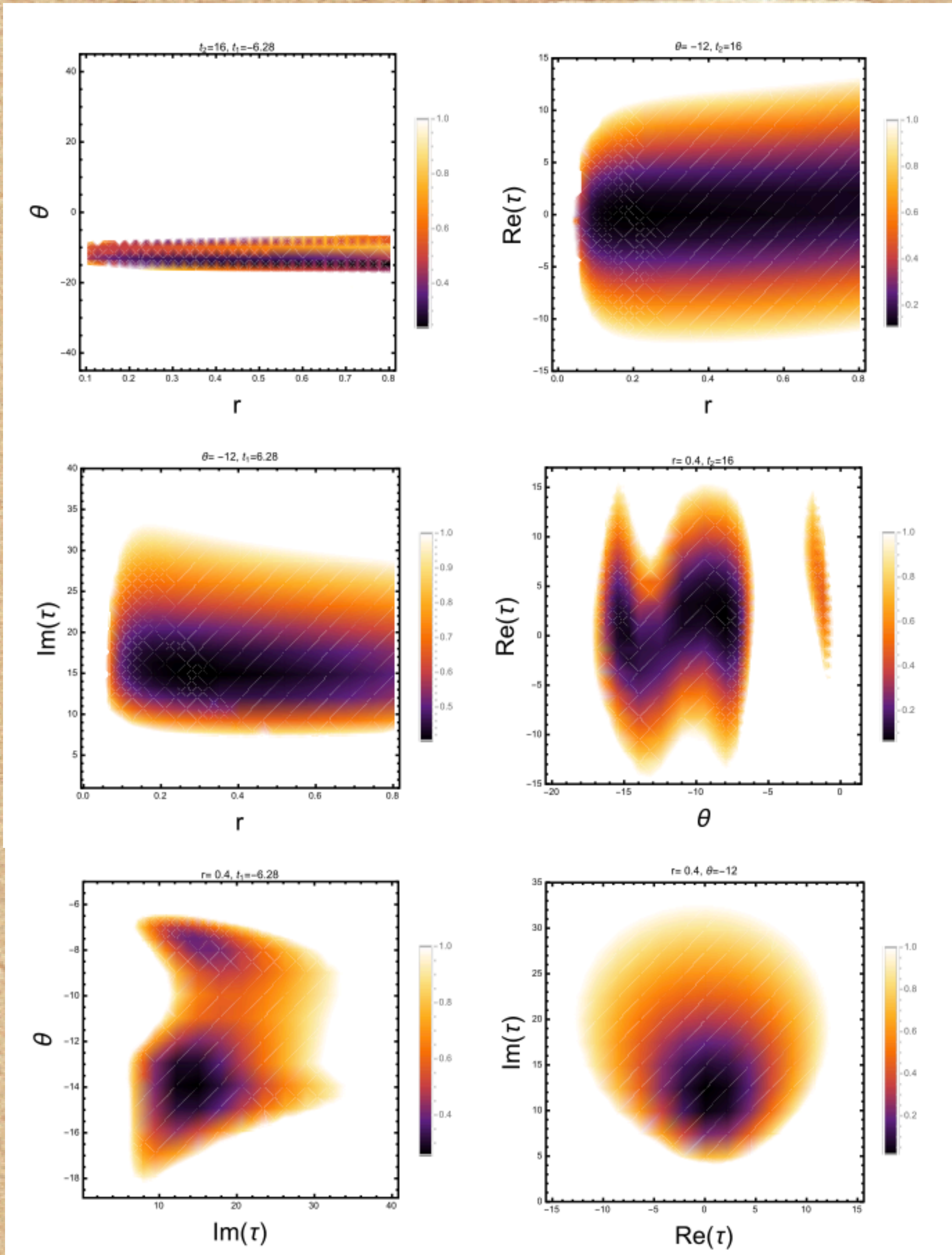
Explore scalar potential in all possible directions

- ☑ For configurations of fluxes with vacua near the conifold $|z| \ll 1$, no regions with $\epsilon\,,\eta \ll 1$
- ☑ Inflationary regions exist for configurations of fluxes with no Minkowski vacua.
  One was found with a dS vacum

F_1, H_1	F_2, H_2	F_3, H_3	F_4, H_4
1,1	0,-10	0,1	-10,1
2,4	2,4	1,2	3,1
1,3	0,0	10,2	0,1
2,4	0,0	6,2	0,2
43,10	193,64	198,-10	-10,-10
90,3	193,165	-10,0	-10,0

- Possible to stabilise to dS when NP terms for Kähler moduli are included

[Saltman, Silverstein,'04]



Example of flux configuration with small slow-roll parameters:

$$F_1 = H_1 = H_3 = H_4 = 1,$$
$$F_4 = H_2 = -10$$

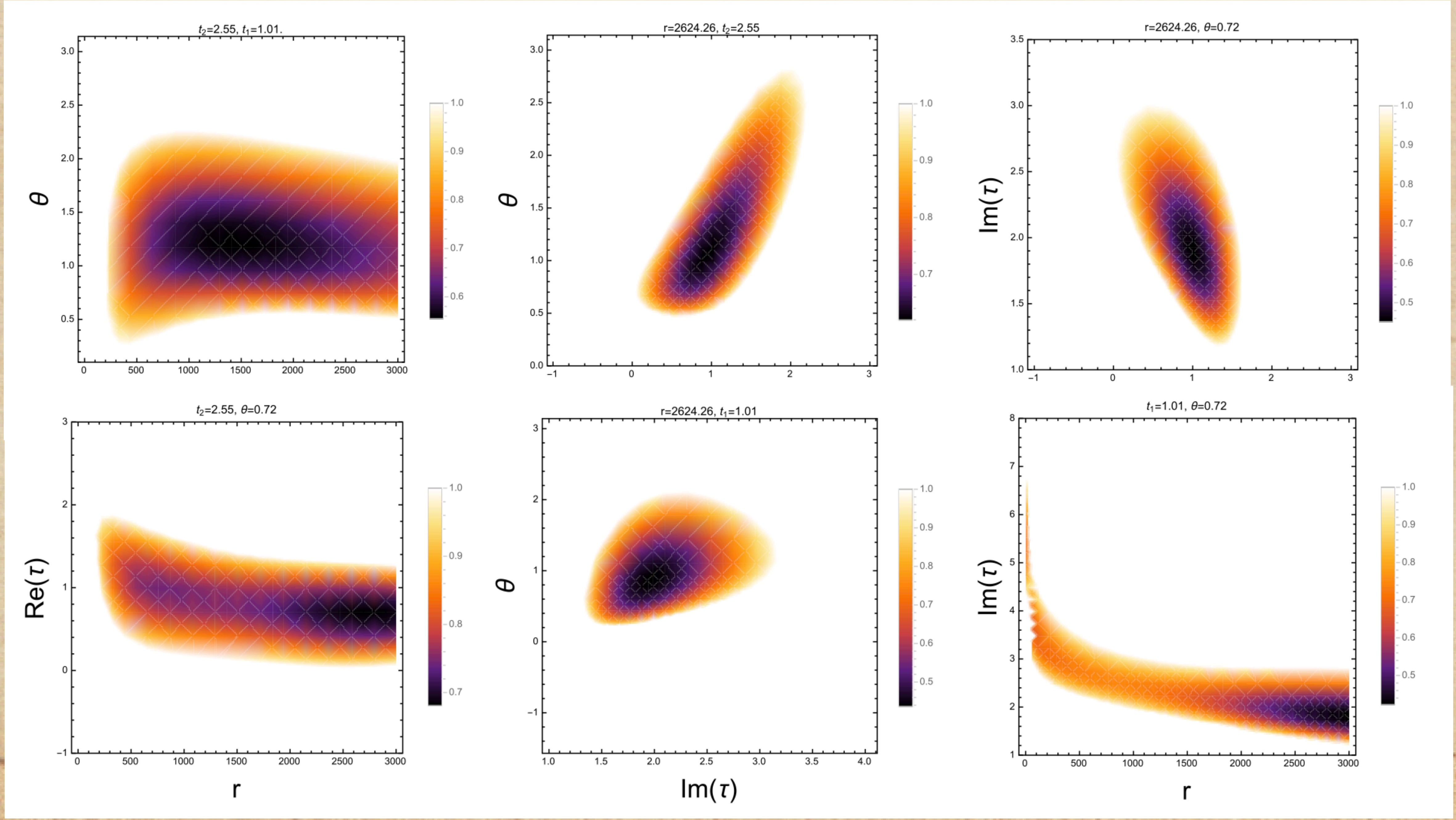
Eigenvector along η dominated by r direction

$$v_\eta \sim (0.12, 0.004, 0.99, 0.09)$$
$$= (t_1, t_2, r, \theta)$$

Inflation in the mirror quintic

- Motivated by these results we explore slow-roll in the orbifold convergence region $r > r_C$

$F_1 = 2,\ H_1 = 4,\ F_3 = 6,\ H_3 = 2,\ H_4 = 2,$ (again no minima)



Summary

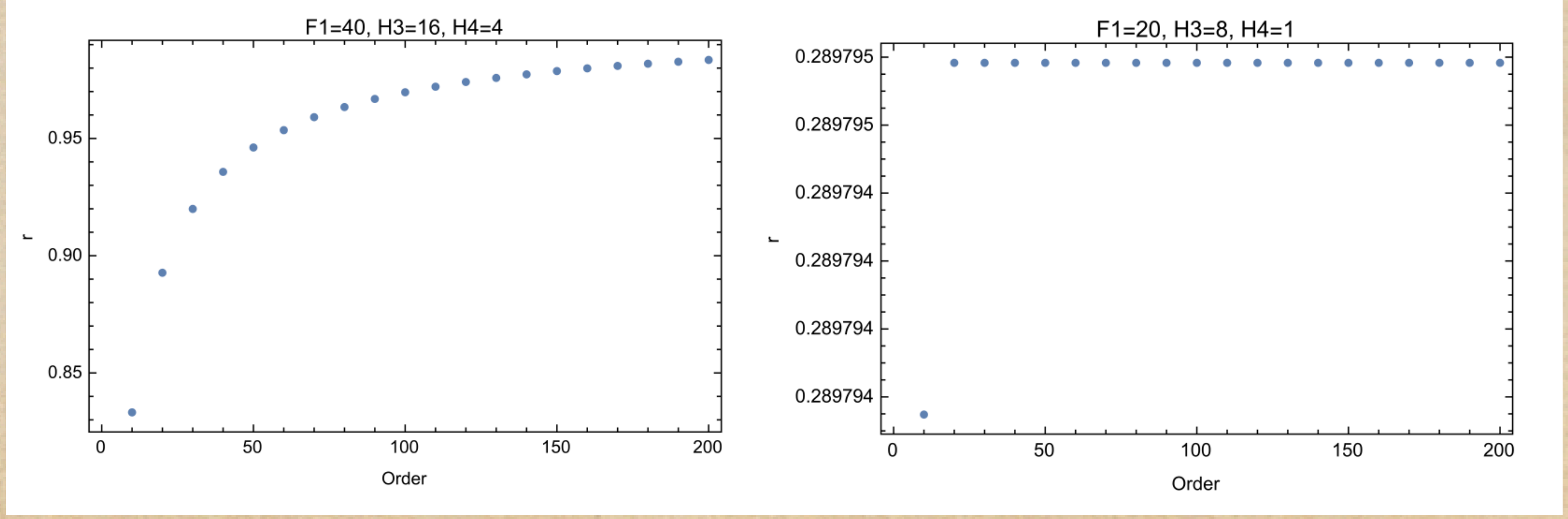
- We studied vacua of explicit type IIB orientifold flux compactifications on the mirror quintic

- We mapped the whole moduli space of the complex structure: near and away from the singular points $\psi = 0, 1, \infty$

- We did this by solving the PF equations to higher order in the series expansion (till convergence is achieved) around the singular and regular points and the transition matrices

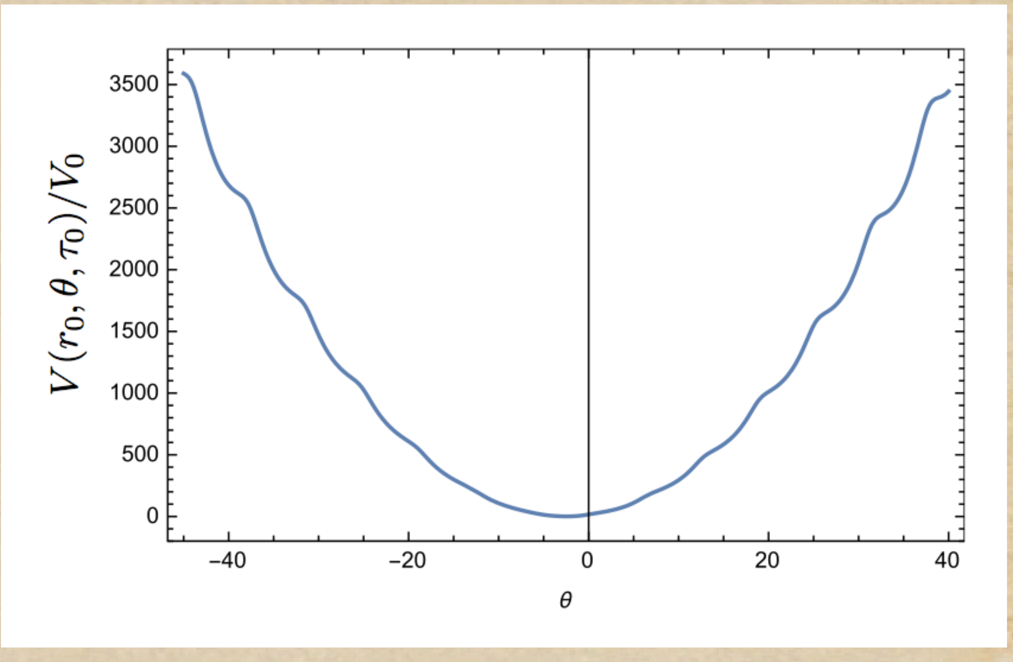
Summary: hierarchies

- Found an order one correction to GKP vacua with hierarchies near the conifold point *with* and *without* higher order terms
- Vacua generically for non-trivial monodromies
- *Apparent* vacua at leading order vanish as higher order terms are included.



Summary: inflation

- No inflationary regions along shift symmetric directions. Inflation occurs along a linear combination of all moduli.



- Oscillatory terms not small enough to realise monomial slow-roll inflation. But more general inflation could be possible: *bumpy inflation*

[Parameswaran, Tasinato, IZ, '16]

- Inflationary regions found for flux configurations with no Minkowski minima.

- One example found with dS vacuum!

Outlook

- Kähler moduli stabilisation. LV not possible.

  [a la Denef et al. '04]

- Multi-field natural inflation (large effective decay constant increases with $h^{1,1}$. They have $h^{1,1} = 50$, we have $h^{1,1} = 101!$)

  [a la McAllister et al. '14-'15]

- Beyond slow-roll inflation with sharp cliffs and gentle plateaus in the potential: reduced field ranges, r and V_{inf}. Distinctive features: α_s

  [Parameswaran, Tasinato, IZ, '16]