Axions in LARGE Volume Scenarios

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Based on:

1. Axiverse and QCD axion: MC,Goodsell,Ringwald, arXiv:1206.0819 [hep-th]
2. Moduli stabilisation and chirality: MC,Mayrhofer,Valandro, arXiv:1110.3333 [hep-th]
3. Global embedding of quivers: MC,Krippendorf,Mayrhofer,Quevedo,Valandro, arXiv:1206.5237 [hep-th]

Introduction

- QCD axion a most plausible explanation of the strong CP problem:

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{g_3^2}{32\pi^2}\,\frac{a}{f_a}\,F^b_{3,\mu\nu}\tilde{F}_3^{b,\mu\nu}, \qquad a \to a + 2\pi f_a$$

- Non-perturbative QCD effects fix $a=0$ with a small mass $m_a \sim m_\pi f_\pi / f_a \sim \mathcal{O}$(meV)
- Beam dump experiments and cooling of stars: $f_a \gtrsim 10^9$ GeV
- No overproduction of dark matter: $f_a \lesssim 10^{12}$ GeV
- Astrophysical hints point to light ALPs: $m_{a_i} \lesssim 10^{-(9\div 10)}$ eV and $f_{a_i} \sim 10^{8\div 9}$ GeV

$\Rightarrow$ QCD axion associated with a very high energy scale

$\Rightarrow$ search for it in UV completions of the SM such as string theory

- String compactifications have QCD axion candidates and even an 'axiverse' [Arvanitaki et al]
- Strong constraints on isocurvature fluctuations: if $H_{\rm inf} \sim M_{\rm GUT}$ (large tensor modes observed by PLANCK), the axiverse is ruled out!

  Q1: Is the axiverse a generic feature of string compactifications?

  Q2: Can find a concrete model with an explicit QCD axion?

Axions and strings

- Hard to build explicit string models with a successful QCD axion plus light ALPs
- Focus on type IIB flux compactifications since moduli stabilisation is more under control
- Low-energy spectrum contains many closed string axions (KK zero modes of antisymmetric forms) of order $h^{1,1} \sim \mathcal{O}(100)$ for a generic CY $\Rightarrow$ expect many ALPs [can have also open string axions (more model-dependent)] BUT:

1. Type IIB on a CY three-fold gives an $\mathcal{N} = 2$ 4D EFT $\Rightarrow$ get an $\mathcal{N} = 1$ EFT via an orientifold projection $\Rightarrow$ several axions removed from the spectrum
2. Each axion c comes with the corresponding 'saxion' τ: $T = \tau + \mathrm{i}c \Rightarrow$ need to fix the saxion with $m_\tau \gtrsim \mathcal{O}(10)$ TeV (CMP) $\Rightarrow$ the axions might become too heavy!
3. Axionic shift symmetry broken only by non-perturbative effects $\Rightarrow$ if τ is fixed perturbatively, c is massless; if τ is fixed by non-perturbative effects, c gets the same mass of the order $m_{3/2}$ - too heavy!
4. Axions can be eaten up by anomalous $U(1)$s (Green-Schwarz mechanism)
5. Hard to get $f_a \lesssim 10^{12}$ GeV since generically $f_a \sim 10^{16}$ GeV [OK if axions are diluted]

NB: Only ALPs with an intermediate f_a are relevant for experiments and astrophysics

IIB axiverse realisations

Two different realisations of the axiverse in type IIB compactifications:

1. A single non-perturbative correction to W fixes $h^{1,1}$ Kähler moduli plus one axion combination $\Rightarrow h^{1,1}-1$ axions get tiny masses by higher order instantons [Acharya et al]
   - Need to fine-tune $W_0 \ll 1$ to trust EFT
   - $W_{\rm np}$ generated by an ED3 or gaugino cond. on D7s wrapping an ‘ample divisor’
   - No microscopic realisation (hard to find a rigid ample div. and avoid chiral inters.)
2. LVS realisation of the axiverse for $W_0 \sim \mathcal{O}(1)$ [MC,Goodsell,Ringwald]
   - Explicit LVS compactifications with fluxes, D3/D7-branes and O3/O7-planes:
     - Description of the compact CY by toric geometry [MC,Kreuzer,Mayrhofer]
     - Global consistency: D7-tadpole, torsion charges and FW anomaly cancellation
     - Moduli fixing compatible with chirality. Two possibilities:
       (a) Visible sector D7s in the geometric regime [MC,Mayrhofer,Valandro]
       (b) Visible sector D3s at del Pezzo sing. [MC,Krippendforf,Mayrhofer,Quevedo,Valandro]
   - LVS solves tensions between brane fluxes and moduli stabilisation:
     - chirality *vs* non-vanishing non-perturbative effects
     - cancellation of FW anomalies *vs* generation of more than one non-pert. effect
     - D-term induced shrinking of the cycles supporting the visible sector

Non-perturbative effects and chirality

Tension between Kähler md stab by non-pert. effects and chirality [Blumenhagen,Moster,Plauschinn]

- Chirality induced by non-zero flux on intersections of branes $\Rightarrow$ visible sector with $\mathcal{F} \neq 0$
- Non-perturbative superpotential: $W_{\rm np} = \sum_i A_i \, e^{-a_i T_i}$
- If chiral modes on intersection between non-pert. cycle and visible sector, A_i depend on visible sector modes ϕ
- To preserve visible sector gauge group, $\langle \phi \rangle = 0$
  $\Rightarrow A_i = 0$ and no contribution from i-cycle

Constraint on the flux choice: no chirality at possible intersections between non-pert. cycle and visible sector

$\Rightarrow$ Place non-pert. effects on 'diagonal' del Pezzo divisors [MC,Kreuzer,Mayrhofer]

Can have an arbitrary number of them $n_{\rm np}$

$$\mathcal{V} = (\ldots)^{3/2} - \sum_{i=1}^{n_{\rm np}} \tau_i^{3/2}$$

NP effects and Freed-Witten anomaly

Tension between cancellation of FW anomaly and generation of more than one non-pert.effect [Blumenhagen,Braun,Grimm,Weigand][Collinucci,Kreuzer,Mayrhofer,Walliser]

Turn on half-integer flux on any *non-spin* 4-cycle D ($c_1(D)$ is odd) to cancel worldsheet anomalies [Minasian,Moore][Freed,Witten]:

$$F = f^i \eta_i + \frac{1}{2} c_1(D) \quad f^i \in \mathbb{Z} \quad \eta_i \in H^2(D, \mathbb{Z})$$

- $\mathcal{F} = F - B = 0$ on the ED3 or gaugino condensation stack, wrapping invariant cycle
- FW $\Rightarrow F \neq 0$

Need a proper choice of B to cancel F

BUT once B is fixed to cancel half-integral F on stack a, generically forces $\mathcal{F} \neq 0$ on a second non-spin stack b (unless they do not intersect)

$\Rightarrow$ FW anomaly generically prevents to have more than 1 non-pert. effect to fix Kähler moduli

$\Rightarrow$ Kähler moduli stabilisation by only 1 non-pert. effect!

This leads to the LARGE Volume Scenario ($\mathcal{V}$ fixed by interplay of α'-corr and NP effects on at least one diagonal dP div) [Balasubramanian,Berglund,Conlon,Quevedo] [MC,Conlon,Quevedo]

D-term shrinking

D-term induced shrinking of the cycles supporting the visible sector [Blumenhagen,Braun,Grimm,Weigand][Collinucci,Kreuzer,Mayrhofer,Walliser][MC,Kreuzer,Mayrhofer]

Flux generates FI-term $\xi_a = \frac{1}{\mathcal{V}} \int_{D_a} J \wedge \mathcal{F}_a \quad \Rightarrow \quad V_D = \sum_a \frac{g_a^2}{2} \left(\sum_b q_{ab} |\phi_b|^2 - \xi_a \right)^2$

- If VEV of charged fields $\langle \phi \rangle = 0$, D-term conditions imply $\xi_a = 0$
- $\xi_a = 0 \Rightarrow$ generically some 4-cycles shrink (away geometric approx)

$\xi_a \propto k_{ajk} \mathcal{F}_a^k t^j = 0$ homogeneous linear eqs in the $h^{1,1}$ Kähler md

- $n_{\rm np}$ non-pert. cycles do not enter in $\xi_a = 0$ eqs (diag dPs, no chiral inters)
- In general we have $n = h^{1,1} - n_{\rm np}$ unknowns in eqs $\xi_a = 0$
- The matrix of the system $\xi_a = 0$ will have rank d
- If $d = n$, then $t^j = 0 \Rightarrow d < n$, $(n-d)$ flat directions
- $n - d = 1 \Rightarrow$ all of the same size: $t_j \sim t_* \ \forall j$
  $\Rightarrow$ no LVS due to visible gauge coupling: $g^{-2} \sim t_*^2$
- $n - d \geq 2 \Rightarrow$ can get LVS in the geometric regime

If $d = 1$, the minimal n to allow for LVS is $n = 3 \Rightarrow h^{1,1} = 4$ for $n_{\rm np} = 1$

Axiverse and moduli stabilisation

LVS strategy to fix the moduli compatible with chirality [MC,Mayrhofer,Valandro] gives an axiverse:

- d combinations fixed by leading D-term potential $\Rightarrow$ d axions eaten by anomalous $U(1)$s
- $n_{\rm np}$ 'diagonal' dPs fixed by NP effects $W_{\rm np} = \sum_{i=1}^{n_{\rm np}} A_i\, e^{-a_i T_{\rm dP}^{(i)}}$
  $\Rightarrow$ Corresponding axions get the same mass of the order $m_{3/2}$
  - Rigidity of a dP div. guarantees the generation of $W_{\rm np}$
  - LVS needs non-pert. effects only for dPs $\Rightarrow$ no problem with FW anomalies
  - A 'diagonal' dP div. decouples from the visible sector $\Rightarrow$ no problem with chiral inters.
- Remaining $n_{\rm ax} = h^{1,1} - n_{\rm np} - d \geq 2$ moduli fixed perturbatively:
  - Volume mode fixed by α' corrections to K
  - Remaining moduli fixed by subleading g_s corrections to K

$\Rightarrow$ $n_{\rm ax} \geq 2$ light axions for visible sector in the geometric regime

- For $h^{1,1} \sim \mathcal{O}(100)$ expect $n_{\rm ax}$ very large
  $\Rightarrow$ LVS axiverse with many light axions [MC,Goodsell,Ringwald]
- One axion is the QCD axion and the others get a tiny mass via higher order NP effects

$$W_{\rm np} = \sum_{i=1}^{n_{\rm np}} A_i\, e^{-a_i T_{\rm dP}^{(i)}} + \sum_{j=1}^{n_{\rm ax}} B_j\, e^{-n_j a_j T_j}\,, \qquad n_j > 1 \quad \forall j$$

QCD axion

- Axion decay constant depends on the CY topology and the choice of brane set-up:
  - Visible sector wrapping a small rigid divisor, $f_a \sim M_s/\sqrt{4\pi}$ due to locality
  - Visible sector wrapping a non-local cycle, $f_a \sim M_{\rm GUT} \sim 10^{16}$ GeV
- $M_s = M_P/\sqrt{4\pi\mathcal{V}}$ can be very low for exponentially large $\mathcal{V}$
- TeV-scale soft-terms $M_{\rm soft} \sim m_{3/2} \sim W_0 M_P/\mathcal{V} \sim 1$ TeV obtained for $\mathcal{V} \sim 10^{14}$ if $W_0 \sim \mathcal{O}(1) \Rightarrow M_s \sim 5 \cdot 10^{10}$ GeV: perfect axion decay constant [Conlon]
- Explicit model with a local QCD axion plus $n_{\rm ALP}$ ALPs not eaten by anomalous $U(1)$s: $n_{\rm ALP}+2$ intersecting rigid cycles for the visible sector and 1 D-term [MC,Goodsell,Ringwald]
- Interesting phenomenology for QCD axion and ALPs with intermediate f_a:
  - QCD axion detectable in the next generation of LSW experiments
  - ALPs explain transparency of the universe for TeV γs and cooling of white dwarfs
- CMP for light moduli ($m_{\mathcal{V}} \sim m_{3/2}/\mathcal{V}^{1/2} \sim 1$ MeV) $\Rightarrow$ dilution by the decay of heavy moduli [Choi,Chun,Kim] or by thermal inflation [Lyth,Stewart]
- Axions do not form dark matter $\Rightarrow$ no constraints from isocurvature fluctuations

Explicit QCD axion example

Explicit type IIB model with a closed string QCD axion:

- not eaten up by any anomalous $U(1)$
- does not develop any potential by non-perturbative effects
- intermediate scale decay constant

NB: it gives also modulated reheating with large non-Gauss. [MC,Tasinato,Zavala,Burgess,Quevedo]

- Orientifold of a CY 3-fold with a K3 or a T^4 fibration over $\mathbb{P}^1$ and $h^{1,1} = 5$
- Hypersurface embedded in a toric variety [MC,Kreuzer,Mayrhofer]
- Relevant divisors:
  - D_1: K3 or T^4 fibre $\rightarrow$ light ALP
  - D_2: 4-cycle dual to the $\mathbb{P}^1$ base $\rightarrow$ light ALP
  - D_3: diagonal dP 4-cycle $\rightarrow$ heavy axion
  - D_4 and D_5: 2 intersecting rigid divisors $\rightarrow$ QCD axion + axion eaten by $U(1)$
- Kähler form: $J = t_1 \hat{D}_1 + t_2 \hat{D}_2 - t_3 \hat{D}_3 - t_4 \hat{D}_4 - t_5 \hat{D}_5$
- Overall volume: $\mathcal{V} = \alpha \left[\sqrt{\tau_1} \tau_2 - \gamma_3 \tau_3^{3/2} - \gamma_5 \tau_5^{3/2} - \gamma_4 \left(\tau_4 - x\, \tau_5 \right)^{3/2} \right]$

Fluxes and FI-terms

- Visible sector: 2 stacks N_a and N_b of inters. D7s wrapping $D_a = D_4$ and $D_b = D_5$
- Choice of gauge fluxes: chirality at the inters. between D_4 and D_5 but just 1 FI-term

$$F_a = \left(f_4 + \frac{1}{2}\right)\hat{D}_4 + f_5\hat{D}_5\,, \qquad F_b = g_4\hat{D}_4 + \left(g_5 + \frac{1}{2}\right)\hat{D}_5$$

- Induced $U(1)$ charges: $xq_{a\,5} = q_{a\,4} - \left(k_{444} - \frac{k_{445}^2}{k_{455}}\right)\left(f_4 + \frac{1}{2}\right)\,, \qquad x\,q_{b\,5} = q_{b\,4}$
- FI-terms:

$$\begin{aligned}\xi_a &= \frac{1}{4\pi\mathcal{V}}\int J\wedge F_a\wedge\hat{D}_a = \frac{1}{4\pi}\left(q_{a\,4}\frac{\partial K}{\partial\tau_4} + q_{a\,5}\frac{\partial K}{\partial\tau_5}\right)\\ \xi_b &= \frac{1}{4\pi\mathcal{V}}\int J\wedge F_b\wedge\hat{D}_b = \frac{1}{4\pi}\left(q_{b\,4}\frac{\partial K}{\partial\tau_4} + q_{b\,5}\frac{\partial K}{\partial\tau_5}\right)\end{aligned}$$

- Induced chiral intersections: $I_{ab} = \int (F_a - F_b)\wedge\hat{D}_a\wedge\hat{D}_b = q_{a\,5} - q_{b\,4}$
- Choose g_4 and g_5 s.t. $q_{b\,4} = q_{b\,5} = 0$
  $\Rightarrow \quad \xi_b = 0 \quad \Rightarrow \quad I_{ab} = q_{a\,5} \quad \Rightarrow \quad q_{a\,5} \neq 0$ (choose $q_{a\,4} = 0$ to simplify ξ_a)
- Non-pert. effects on D_3 (choose B s.t. $\mathcal{F}_3 = F_3 - B = 0$)

Leading moduli fixing

- D-term fixes a combination of τ_4 and τ_5 (define $\hat{\tau}_4 \equiv \tau_4 - x\,\tau_5$)

$$\xi_a = \frac{q_{a\,5}}{4\pi}\,\frac{\partial K}{\partial \tau_5} = \frac{q_{a\,5}}{4\pi}\,\frac{3\alpha\left(\gamma_5\sqrt{\tau_5} - \gamma_4\,x\sqrt{\hat{\tau}_4}\right)}{\mathcal{V}} = 0 \quad \Rightarrow \quad \tau_5 = \lambda\,\hat{\tau}_4, \quad \lambda \equiv \left(\frac{\gamma_4\,x}{\gamma_5}\right)^2$$

NB1: absence of intersection for $x = 0 \Rightarrow$ shrinking of D_5

NB2: combination of axions eaten up: $c_a = c_5 - \lambda\,\hat{c}_4$ with $\hat{c}_4 \equiv c_4 - x\,c_5$

NB3: modulus fixed by D-term gets an $\mathcal{O}(M_s)$ mass

$\Rightarrow$ study the EFT in terms of τ_1, τ_2, τ_3 and $\hat{\tau}_4$

- Leading F-term potential: standard LVS form (α' + non-pert. corrections):

$$V_{\mathcal{O}(\tau_3^{3/2}\mathcal{V}^{-3})} \sim \frac{\sqrt{\tau_3}}{\mathcal{V}}\,e^{-\frac{4\pi\tau_3}{N_3}} - W_0\,\frac{\tau_3}{\mathcal{V}^2}\,e^{-\frac{2\pi\tau_3}{N_3}} + \frac{W_0^2\hat{\xi}}{\mathcal{V}^3}$$

- Fix $\mathcal{V}$ and τ_3 at $\tau_3 \sim g_s^{-1}$ and $\mathcal{V} \sim W_0\sqrt{\tau_3}\,e^{\frac{2\pi\tau_3}{N_3}}$
- For $W_0 \simeq \mathcal{O}(1)$ and $\mathcal{V} \simeq \mathcal{O}(10^{14}) \Rightarrow M_{\rm soft} \sim m_{3/2} \sim \mathcal{O}(1)$ TeV and $M_s \simeq 5\cdot 10^{10}$ GeV
- Heavy axion c_3 with a mass of order $m_{3/2}$ + massless volume axion
- Subleading order: string loops fix τ_1 and τ_4
  $\Rightarrow$ massless c_1 (non-local axion) and c_4 (local QCD axion)

Subleading moduli fixing

- τ_4-dependent potential generated by g_s effects:

$$V_{\mathcal{O}(\tau_4^{-1/2}\mathcal{V}^{-3})} = \left(\frac{\mu_1}{\sqrt{\hat{\tau}_4}} - \frac{\mu_2}{\sqrt{\hat{\tau}_4} - \mu_3}\right)\frac{W_0^2}{\mathcal{V}^3}$$

- Minimum for $\hat{\tau}_4$ at $\hat{\tau}_4 = \frac{\mu_1\,\mu_3^2}{(\sqrt{\mu_1}+\sqrt{\mu_2})^2} \sim \mathcal{O}(10)$
- Minimum located at small $\hat{\tau}_4 \Rightarrow$ right visible sector gauge coupling: $\alpha_{\rm vs}^{-1} \simeq \hat{\tau}_4 \sim \mathcal{O}(10)$
- τ_1-dependent potential generated by g_s effects:

$$\delta V_{\mathcal{O}(\tau_1^{-1/2}\mathcal{V}^{-3})} = \left(\frac{\lambda_1}{\sqrt{\tau_1}} - \frac{\lambda_2}{\sqrt{\tau_1} - \lambda_3}\right)\frac{W_0^2}{\mathcal{V}^3}$$

- Minimum for τ_1 at $\tau_1 = \frac{\lambda_1\,\lambda_3^2}{(\sqrt{\lambda_1}+\sqrt{\lambda_2})^2} \sim \mathcal{O}(10)$
- Anisotropic CY with $\tau_2 \gg \tau_1 \sim \hat{\tau}_4 \sim \tau_3$
- 2 large and 4 small EDs $\Rightarrow$ 6D EFT

Axionic couplings

- Couplings of a_1, a_2 and a_4 to gauge bosons living on D_1, D_2, D_4 and D_5:

$$\begin{aligned}\mathcal{L} \quad &\simeq \quad \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_1 + \mathcal{O}\left(\frac{\hat{\tau}_4^{3/2}}{\mathcal{V} M_P}\right) a_2 + \mathcal{O}\left(\frac{\hat{\tau}_4^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_4\right] \mathrm{tr}(F_1 \wedge F_1) \\ &+ \quad \left[\mathcal{O}\left(\frac{\hat{\tau}_4^{3/2}}{\mathcal{V} M_P}\right) a_1 + \mathcal{O}\left(\frac{1}{M_P}\right) a_2 + \mathcal{O}\left(\frac{\hat{\tau}_4^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_4\right] \mathrm{tr}(F_2 \wedge F_2) \\ &+ \quad \sum_{i=4}^{5}\left[\mathcal{O}\left(\frac{1}{M_P}\right) a_1 + \mathcal{O}\left(\frac{1}{M_P}\right) a_2 + \mathcal{O}\left(\frac{\mathcal{V}^{1/2}}{\hat{\tau}_4^{3/4} M_P}\right) a_4\right] \mathrm{tr}(F_i \wedge F_i)\,.\end{aligned}$$

NB1: a_4 couples to visible sector on D_4 and D_5 as $1/M_s$

NB2: gauge theories on D_1 and D_2 are hidden sectors (hyperweak interaction on D_2)

- Axion decay constants:

$$f_{a_1} \simeq \frac{M_P}{4\pi\hat{\tau}_4} \simeq 10^{16}\,\mathrm{GeV}\,, \quad f_{a_2} \simeq \frac{M_P}{4\pi\tau_2} \simeq \frac{M_{\mathrm{KK}}^{6\mathrm{D}}}{4\pi} \simeq 5\,\mathrm{TeV}\,, \quad f_{a_4} \simeq \frac{M_s}{\sqrt{4\pi}} \simeq 10^{10}\,\mathrm{GeV}$$

NB1: a_4 is a perfect QCD axion candidate since its decay constant is intermediate

NB2: a_1 and a_2: light and almost decoupled ALPs

$\Rightarrow$ no problem with dark matter overproduction

Moduli mass spectrum

- Mass spectrum ($\mathcal{V} \sim 10^{14}$):
  - $m_{\tau_5} \sim m_{a_5} \sim M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{11}$ GeV
  - $m_{\tau_3} \sim m_{a_3} \sim M_P \ln \mathcal{V}/\mathcal{V} \sim 100$ TeV
  - $M_{soft} \sim m_{3/2} \sim M_P/\mathcal{V} \sim 1$ TeV
  - $m_{\tau_4} \sim M_P/(\mathcal{V} \ln \mathcal{V}) \sim 100$ GeV
  - $m_{\mathcal{V}} \sim m_{\tau_1} \sim M_P/\mathcal{V}^{2/3} \sim 1$ MeV
  - $m_{a_4} \sim m_\pi f_\pi / f_{a_4} \sim 1$ meV $\rightarrow$ QCD axion
  - $m_{a_1} \sim M_P e^{-2\pi n \tau_1} \lesssim 10^{-36}$ GeV (for $n \geq 2$)
  - $m_{a_2} \sim M_P e^{-2\pi \mathcal{V}^{2/3}} \sim 0$
- τ_4 does not suffer from CMP since it couples as $1/M_s$
- $\mathcal{V}$ and τ_1 suffer from CMP
- Possible solutions: thermal inflation or decay of τ_4 at $T_{rh} \sim \sqrt{\Gamma_{\tau_4} M_P} \sim \sqrt{m_{\tau_4}^3 M_P/(48\pi M_s^2)} \sim M_P/(\sqrt{48\pi}\mathcal{V}(\ln \mathcal{V})^{3/2}) \sim 1$ GeV
- a_4 gets diluted $\Rightarrow$ no dark matter $\Rightarrow$ no constraints from isocurvature fluctuations

Global embedding of D-branes at sing

'Diagonal' dPs crucial to embed quiver theories [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]:

- Consider them to support the visible sector and turn on a non-zero flux: $\xi_{\rm dP} \propto \int_{D_{\rm dP}} J \wedge \mathcal{F}_{\rm dP} = k_{{\rm dP}jk}\mathcal{F}^k_{\rm dP} t^j \propto t_{\rm dP} = 0 \Rightarrow t_{\rm dP} \to 0$
- Need 2 dP$_n$ divisors exchanged by the orientifold involution $\Rightarrow h^{1,1}_- \geq 1$
- 2 dPs do not intersect each other $\Rightarrow$ they do not touch the O7 $\Rightarrow U(N)$ groups
- Need still at least one 'diagonal' dP with non-pert. effects ($n_{\rm np} \geq 1$)
- The stabilisation of the bulk moduli is the same as before $\Rightarrow$ minimal set-up involves again $h^{1,1} = 4$ with $h^{1,1}_- = 1$ G-modulus (reduction of B_2 and C_2) and $h^{1,1}_+ = 3$ T-moduli (1 local blow-up + 1 NP cycle + volume mode)
- A dP$_n$ divisor has $n+1$ 2-cycles (1 is the canonical class whose dual 4-cycle is dP$_n$ itself, the other n 2-cycles, if non-trivial, are dual to non-local cycles)
- A dP$_n$ divisor has 2 anomalous $U(1)$s $\Rightarrow d = 2$ moduli fixed by D-terms (G-modulus and local blow-up, local axions eaten up)
- Other 'diagonal' dP and volume mode fixed by NP + α' effects
- If $h^{1,1} > 4$ need in general also perturbative effects

Axions in sequestered models

Models with D3s at sing. can give sequestering: $M_{\rm soft} \sim m_{3/2}/\mathcal{V}$ [Blumenhagen et al]

- Get TeV-scale SUSY for $\mathcal{V} \sim 10^{6\div 7} \Rightarrow$ high string scale $M_s \sim M_{\rm GUT} \sim 10^{16}$ GeV
- No CMP since $m_{\mathcal{V}} \sim m_{3/2}/\sqrt{\mathcal{V}} \sim 10^6$ GeV

Simplest LVS quiver with $h^{1,1} = 4$: local axions are eaten up

Volume axion: $m_{a_{\mathcal{V}}} \lesssim M_P \, e^{-2\pi \mathcal{V}^{2/3}} \sim 0 \Rightarrow$ dark radiation! [MC,Conlon,Quevedo][Higaki,Takahashi]

Q: what is the QCD axion?

- Consider more complicated singularities with more than 2 local cycles
  - 1 local axion is left over and can be the QCD axion with $f_{a_s} \simeq M_s/\sqrt{4\pi} \simeq 10^{15}$ GeV
  - QCD axion abundance can be diluted by the decay of non-local moduli
- Phase of an open string axion ϕ can be the QCD axion
  - D-terms give a VEV to $|\phi| = f_a$: $V_D \simeq g^2 \left(|\phi|^2 - \xi\right)^2$ with $\xi = \tau_{\rm blow}/\mathcal{V}$
  - Check that D-terms do not resolve the sing. obtained by setting $\xi = 0$ for $\langle|\phi|\rangle = 0$
  - If $0 \neq \langle|\phi|\rangle = \sqrt{\xi} \simeq \langle\sqrt{\tau_{\rm blow}}\rangle \, M_s \Rightarrow$ tension between $\langle\tau_{\rm blow}\rangle = 0$ and $\langle|\phi|\rangle \neq 0$
  - $\tau_{\rm blow}$ is still below ℓ_s^4 if $\langle\tau_{\rm blow}\rangle = \mathcal{V}^{-2\alpha}$ with $\alpha > 0 \Rightarrow f_a = \langle|\phi|\rangle \simeq M_s/\mathcal{V}^{\alpha}$
  - Volume suppression can bring f_a at the intermediate scale

Conclusions

- Hard to build explicit string models with a successful QCD axion plus light ALPs
- LVS good framework to solve tensions between brane fluxes and moduli stabilisation
- General LVS strategy to fix the moduli gives an axiverse
- Axions in the geometric regime:
  - Explicit chiral model with a local QCD axion not eaten by anomalous $U(1)$ and with intermediate f_a: testable!
    + 2 non-local light ALPs with $f_{a_1} \sim M_{\rm GUT}$ and $f_{a_2} \sim 1$ TeV
  - Models with a local QCD axion plus $n_{\rm ALP}$ ALPs, all with intermediate f_a:
    $n_{\rm ALP} + 2$ local intersecting rigid divisors + 1 D-term $\rightarrow$ good for phenomenology
- QCD axion for models with branes at singularities:
  - Local blow-up for singularities more complicated than dP$_n$
  - Phase of an open string mode