Looking for the LARGE volume axiverse

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Based mostly on 1206.0819 with M. Cicoli and A. Ringwald.

Top-down motivation

Global string compactifications must have many fields with masses below the string scale:

- Moduli; after stabilisation, masses $\sim M_{3/2}$. Couple gravitationally.
- Typically many Axion-like particles

In addition there may be

- Type II: $U(1)$s from $R-R$ four-form $C_4 = U_\alpha \wedge \beta^\alpha$ counted by $h^{2,1}_+$
- Open-string moduli, masses $> TeV$
- Exotic matter, masses $> TeV$
- Hidden matter
- Hidden gauge groups (e.g. hidden $U(1)$s)

The LHC may tell us about the visible sector, i.e. local structure of our theory. Can we detect any of these extra states? Would learn about global structure. E.g. what is the string scale?

WISPs

$$\underbrace{\text{WEAKLY Interacting}}_{\text{eg } \sigma < 10^{-12}\sigma_{em}} \quad \underbrace{\text{Slim}}_{<\mathcal{O}(\text{eV})} \quad \text{Particles}$$

$$\downarrow$$

(for this talk)

The QCD axion, axion-like particles (ALPs) [and hidden U(1)s]

Bottom-up motivation for WISPs

Light masses offer possibility of detection at the intensity frontier!! Many different experiments, [see J. Redondo's talk]:

- Haloscopes
- Helioscopes
- Beam dumps
- Light shining through walls
- Molecular interferometry

and of course cosmic searches such as isocurvature and tensor modes, rotation of CMB polarisation, ...

- Opportunity to probe weak couplings or very high energy scales!

Bottom-up motivation for Axions/ALPs

$$\mathcal{L} \supset -\frac{g_3^2}{32\pi^2}\frac{a\,C_{a3}}{f_a}F^b_{3,\mu\nu}\tilde{F}_3^{b,\mu\nu} - \frac{e^2}{32\pi^2}\frac{C_{i\gamma}}{f_{a_i}}a_i\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_{ie}}{2f_{a_i}}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu a_i\,,$$

- Axion as solution to strong CP problem!
- Candidates for dark matter
- An ALP offers a solution to non-standard energy loss of white dwarfs

$$f_i/C_{ie} \simeq (0.2 \div 2.6)\times 10^9\ \text{GeV}$$

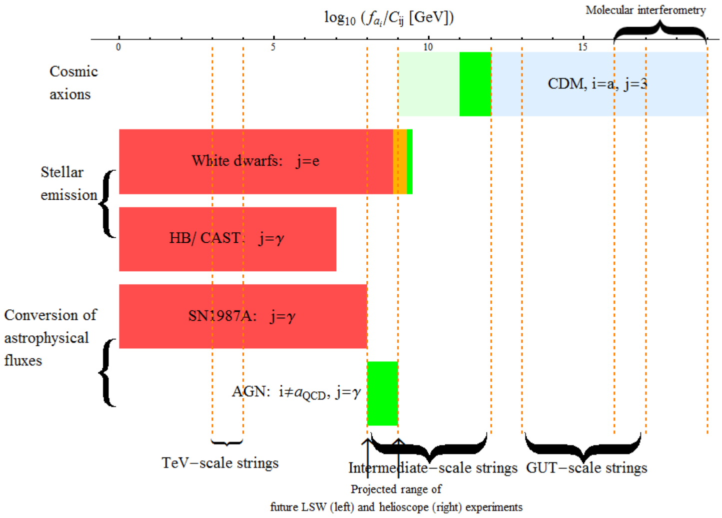
- ... and, for a light ALP($< 10^{-9}$ eV) anomalous transparency of the universe for VHE gamma rays

$$f_i/C_{i\gamma} \sim 10^8\ \text{GeV}$$

- ... and for same value of $f_i/C_{i\gamma}$, steps is power spectrum at critical energy of 100 GeV, hinting at $m_{ALP} \sim 10^{-9} \div 10^{-10}$ eV.
- These are compatible (need $C_{i\gamma}/C_{ie} \sim 10$) and could be searched for in future experiments!!

Future experiments

- Next generation of ALPS (light-shining-through-walls): $f_{a_i}/C_{i\gamma} \sim 10^8$ GeV
- Next generation of helioscopes (e.g. CAST): $f_{a_i}/C_{i\gamma} \sim 10^9$ GeV
- Haloscopes, $f_{a_i}/C_{i\gamma} \gtrsim 10^{10} \div 10^{12}$ GeV for $1 \div 10\mu$eV axion dark matter
- Molecular interferometry, searching via QCD coupling of axion, could probe decay constants $f \sim 10^{16} \div 10^{18}$ GeV!


log10 (fai/Cij [GeV])
Molecular interferometry
0
5
10
15
Cosmic axions
CDM, i=a, j=3
Stellar emission
White dwarfs: j=e
HB/ CAST: j=γ
Conversion of astrophysical fluxes
SN1987A: j=γ
AGN: i≠aQCD, j=γ
TeV−scale strings
Intermediate−scale strings
GUT−scale strings
Projected range of
future LSW (left) and helioscope (right) experiments

Overview

- How the LVS gives an "axiverse"
- Masses, couplings to gluons, photons and matter
- When can we get a QCD axion?!
- Explicit models (a) with a QCD axion, (b) with ALPs!
- Cosmology

The LVS axiverse

following from M. Cicoli's talk

- For LARGE volume scenario (LVS) need

$$W = W_0 + Ae^{-a\tau_{dP}}, \qquad W_0 \sim 1$$

- τ_{dP} is a diagonal del Pezzo blow-up $\rightarrow$ removes issue of chirality.
- Do not need other NP effects: others can be fixed by D-terms, α' and g_s effects - open ($V \sim \frac{W_0^2}{\mathcal{V}^3}$) and closed ($V \sim \frac{W_0^2}{\mathcal{V}^4}$) string loops.
- Non-vanishing D-terms are dangerous ($V \sim \mathcal{V}^{-2}$) but are useful for stabilising cycles relative to each other

$$\xi_a = \frac{1}{4\pi\mathcal{V}} q_{aj} t^j = 0 \rightarrow \text{linear combination fixed}$$

- Each NP term in superpotential and each linearly independent D-term eats one axion
- In scenario where LARGE cycle unwrapped/no D-term, have at least $n_{ax} = h^{1,1} - 1 - d \geqslant 1$ light axions
- Generically this number may be large, particularly if many unwrapped cycles.
- Since further single instanton/gaugino condensate contributions may not be generic $\rightarrow$ very light axions $\rightarrow$ ALPs.

ALPs in IIB strings

$$S \supset -\left(dc_\alpha + \frac{M_P}{\pi} A_i q_{i\alpha}\right) \frac{\mathcal{K}_{\alpha\beta}}{8} \wedge \star \left(dc_\beta + \frac{M_P}{\pi} A_j q_{j\beta}\right)$$
$$+ \frac{M_P^2}{2(2\pi)^2} A_i A_j q_{i\alpha} \mathcal{K}_{\alpha\beta} q_{j\beta} + \frac{1}{4\pi M_P} r^{i\alpha} c_\alpha \mathrm{tr}(F \wedge F) - \frac{r^{i\alpha}\tau_\alpha}{4\pi M_P} \mathrm{tr}(F_i \wedge \star F_i).$$

- Axions periodic fields, $c_\alpha \to c_\alpha + M_P$, $T_\alpha = \tau_\alpha + ic_\alpha \sim T_\alpha + iM_P$
- Decay constants determined by diagonalising $(\mathcal{K}_0)_{\alpha\beta} \equiv \frac{\partial^2(-2\log \mathcal{V})}{\partial_{\tau_\alpha}\partial_{\tau_\beta}}$:

$$f_\alpha \equiv \frac{M_P}{4\pi}\sqrt{\lambda_\alpha},\, a_\alpha \sim a_\alpha + 2\pi f_\alpha$$

- Canonically normalise the axion fields

$$c_\alpha = 2\, a_\gamma \mathcal{C}_{\beta\alpha}, \quad \mathcal{C}_{\gamma'\alpha}\mathcal{K}_{\alpha\beta}\mathcal{C}^T_{\beta\delta'} = \delta_{\gamma'\delta'}, \quad \mathcal{C}_{\gamma'\alpha}\mathcal{C}^T_{\alpha\delta'} = \lambda^{-1}_{\gamma'}\delta_{\gamma'\delta'},$$

- Read off couplings to gauge groups:

$$\frac{f_{a_j}}{C_{ji}} = \frac{1}{8\pi}\frac{M_P}{r^{j\alpha}\mathcal{C}^T_{\alpha i}} \times \begin{cases} 1/2 & U(1) \\ 1 & SU(N) \end{cases}.$$

Decay constants

We expect

$$f_\alpha \sim \begin{cases} M_P/\tau_\alpha & \text{non} - \text{local axion} \\ M_s \sim M_P/\sqrt{\mathcal{V}} & \text{local axion} \end{cases}$$

e.g. for $\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right)$ we have $4\pi g_b^{-2} = \tau_b \sim \mathcal{V}^{2/3}$ and

$$\mathcal{K}_0 \sim \begin{pmatrix} \mathcal{V}^{-4/3} & \mathcal{V}^{-5/3} \\ \mathcal{V}^{-5/3} & \mathcal{V}^{-1} \end{pmatrix}$$

Have $f_{a_b} = \frac{\sqrt{3}}{4\pi}\frac{M_P}{\tau_b} \simeq \frac{M_P}{4\pi\mathcal{V}^{2/3}}$, $f_{a_s} = \frac{1}{\sqrt{6}(2\tau_s)^{1/4}}\frac{M_P}{4\pi\sqrt{\mathcal{V}}} \simeq \frac{M_s}{\sqrt{4\pi}\tau_s^{1/4}}$.

$$\begin{aligned} \mathcal{L} \supset & \frac{c_b}{M_P} g_b^2 \, \mathrm{tr}(F_b \wedge F_b) + \frac{c_s}{M_P} g_s^2 \, \mathrm{tr}(F_s \wedge F_s) \\ \simeq & \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{\tau_s^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_s \right] \mathrm{tr}(F_b \wedge F_b) \\ + & \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{1}{\tau_s^{3/4} M_s}\right) a_s \right] \mathrm{tr}(F_s \wedge F_s). \end{aligned}$$

- Non-local ALPs can have small decay constants, e.g. $\frac{M_P}{\mathcal{V}^{2/3}}$, but the couplings to matter are always $\gtrsim M_P$ suppressed
- If we want ALPs in the classic axion window, they need to be "local," and have an intermediate string scale: $f_i \sim M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$, $\mathcal{V} \sim 10^{15}$.
- To have an axion and ALP, need several intersecting local cycles

K3 fibrations

For K3 fibrations, can have anisotropic compactifications with $t_b \sim \mathcal{V}$, $\tau_f = t_f^2 \sim 1$:

$$\mathcal{V} = t_b t_f^2 + t_s^3 = t_b \tau_f + t_s^3$$

$$\begin{aligned}
\mathcal{L} \supset & \frac{c_f}{M_P} g_f^2 \,\mathrm{tr}(F_f \wedge F_f) + \frac{c_b}{M_P} g_b^2 \,\mathrm{tr}(F_b \wedge F_b) + \frac{c_s}{M_P} g_s^2 \,\mathrm{tr}(F_s \wedge F_s) \\
\simeq & \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_f + \mathcal{O}\left(\frac{\tau_s^{3/2}}{\mathcal{V} M_P}\right) a_b + \mathcal{O}\left(\frac{\tau_s^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_s \right] \mathrm{tr}(F_f \wedge F_f) \\
+ & \left[\mathcal{O}\left(\frac{\tau_s^{3/2}}{\mathcal{V} M_P}\right) a_f + \mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{\tau_s^{3/4}}{\mathcal{V}^{1/2} M_P}\right) a_s \right] \mathrm{tr}(F_b \wedge F_b) \\
+ & \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_f + \mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{1}{\tau_s^{3/4} M_s}\right) a_s \right] \mathrm{tr}(F_s \wedge F_s).
\end{aligned}$$

Important when we wrap a SM brane on the fibre,

$$f_{a_f} \simeq \frac{M_P}{4\pi\tau_s}, \qquad f_{a_b} \simeq \frac{M_P}{4\pi\tau_b} \sim \frac{M_P}{\mathcal{V}}, \qquad f_{a_s} \simeq \frac{M_s}{\sqrt{4\pi}\tau_s^{1/4}}$$

Can show that for a <u>general</u> anisotropic K3 fibration, exactly <u>one</u> axion with $f \sim M_{GUT} = M_P/\tau_f$, all others are of order M_s or smaller!

Matter couplings

In global SUSY, derive matter couplings from

$$\int d^4\theta\, \Phi\overline{\Phi}\left(T_\alpha + \overline{T}_\alpha\right) \supset (\psi\sigma^\mu\overline{\psi})\partial_\mu c_\alpha \,.$$

In SUGRA find

$$\mathcal{L} \supset \partial_{T_\alpha}\left(\log[e^{-\frac{K_0}{2}}\hat{K}_i]\right)(\psi^i\sigma^\mu\overline{\psi}^{\bar{i}})\partial_\mu c_\alpha .$$

nb this is different to moduli couplings!
We then translate these into ALP-matter couplings (to axions ρ_i''):

$$\frac{\hat{X}^i_\psi}{f_i} = \frac{1}{3M_P} C_{\beta\alpha} \begin{cases} \frac{t_\alpha}{2\mathcal{V}} + \frac{1}{t_{ab}} r^{ai} r^{bj} k_{ijk} K^{k\alpha} & \text{Matter on curve } t_{ab} \\ \frac{t_\alpha}{2\mathcal{V}} + \frac{r^{a\alpha}}{\tau_a} & \text{Matter on cycle } a \\ \frac{t_\alpha}{2\mathcal{V}} & \text{Matter at a singularity} \end{cases}$$

- Dependent on conjectures for Kähler metrics
- Loop corrections should be important for quiver locus, $\frac{t_\alpha}{2\mathcal{V}} = 0$ or $\sim \mathcal{V}^{-2/3}$.

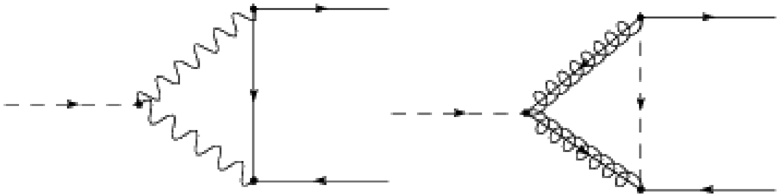
Loop couplings to matter fields

Couplings to electrons is most important:

$$\mathcal{L} \supset \frac{C^A_{ie}}{2f_i}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu\phi_i + \frac{C^V_{ie}}{2f_i}\bar{e}\gamma^\mu e\partial_\mu\phi_i,$$
$$C^{A,V}_{ie} = \hat{X}^{A,Vj}_e + \Delta_{i\gamma\gamma}[C^{A,V}_{ie}] + \delta_{ai}\Delta_{QCD}[C^A_{ae}], \quad (1)$$

where $\hat{X}^{A,Vj}_e \equiv \frac{1}{2}(\tilde{X}^j_{e_R} \pm \tilde{X}^j_{e_L})$ and $\Delta_{QCD}[C^A_{ae}] = \frac{3\alpha^2}{4\pi}\Delta C_{a\gamma\gamma}\log(\Lambda_{QCD}/m_a)$
In SUSY theories, loops involve gauginos as well as photons:

$$\mathcal{L} \supset -\int d^2\theta\ (i\phi_i)\frac{g_{a\gamma}}{4}W^\alpha W_\alpha \supset \frac{1}{4}g_{i\gamma}\phi_i F_{em,\mu\nu}\tilde{F}^{\mu\nu}_{em} + \frac{1}{2}g_{i\gamma}\partial_\mu\phi_i\lambda^\alpha\sigma^\mu\bar{\lambda}, \quad (2)$$



Loop couplings cont'd

To a rough approximation we can take

$$\Delta_{i\gamma\gamma}[C^A_{ie}] \approx \frac{3\alpha^2}{4\pi^2} C_{i\gamma} \log(M_{SUSY}/m_e) + \frac{2\alpha^2}{4\pi^2} C_{i\gamma} \log(\Lambda/M_{SUSY}),$$
$$\Delta_{i\gamma\gamma}[C^V_{ie}] \approx \frac{2\alpha^2}{4\pi^2} C_{i\gamma} \log(\Lambda/M_{SUSY}), \quad (3)$$

where M_{SUSY} is the scale of superpartner masses, and Λ the cutoff of the theory, of the order of the string scale.

(Full expression in paper ...)

Couplings summary

Bottom line:

- For quiver locus, matter couplings to most axions dominated by loops:

$$C_{i\gamma}/C_{ie} \sim \frac{4\pi^2}{2\alpha^2 \log \Lambda/M_{SUSY}} \sim 10^4 \div 10^5$$

- For geometric regime,

$$C_{i\gamma}/C_{ie} \sim \frac{8\pi}{3}\tau_i \sim 10 \div 100 \qquad \text{local cycle}$$

i.e. <u>this geometric regime ratio is exactly what we want to explain the astrophysical anomalies</u>!

Masses

May have higher superpotential corrections to masses, and also Kähler potential corrections [Conlon, '06]

$$\begin{aligned} V_{\delta W} &= \frac{-2\pi n \tau_i W_0}{\mathcal{V}^2} e^{-2\pi n \tau_i} \cos 2\pi n c_i \\ V_{\delta K} &\sim \frac{W_0^2}{\mathcal{V}^3} e^{-2\pi n \tau_i} \cos 2\pi n c_i \end{aligned} \tag{4}$$

T_s axion has a mass $\sim M_P/\mathcal{V}$, but "local" axions with masses from Kähler corrections have

$$m_{\text{local}} \sim e^{-n\pi\tau_{\text{local}}} \times \begin{cases} M_P & \text{Superpotential terms or QCD-like masses} \\ m_{3/2} & \text{Kähler potential terms} \end{cases}$$

Can be $\sim 10^{-11}$ eV for SM cycle sizes, or less.
Non-local axions get negligible masses: $e^{-\pi\tau_b} < 10^{600}$ for $\mathcal{V} = 10^4$, $\tau_b \simeq V^{2/3}$.

The QCD axion

$$\mathcal{L} \supset \frac{g_3^2}{32\pi^2}\left(\theta - \frac{a\, C_{a3}}{f_a}\right) \mathrm{tr}\,(F_3 \wedge F_3)$$

- Might imagine that, since there is always one light axion corresponding to τ_b, it could be the QCD axion for SM on a local cycle when the local axion is eaten.
- This is not true. Consider

$$\mathcal{L} \simeq \frac{1}{8\mathcal{V}}\left(\partial_\mu c_s + \frac{M_P}{\pi} q A_\mu\right)^2 + \left(\partial_\mu c_s + \frac{M_P}{\pi} q A_\mu\right)\frac{\partial^\mu c_b}{4\mathcal{V}^{5/3}} + \frac{(\partial_\mu c_b)^2}{8\mathcal{V}^{4/3}}$$
$$+ \frac{g^2}{4\pi M_P} c_s \mathrm{tr}\,(F \wedge F)\,,$$
$$\rightarrow \frac{1}{2}\left(\partial_\mu a_s + \frac{M_P}{2\sqrt{\mathcal{V}}\pi} q A_\mu\right)^2 + \frac{1}{2}(\partial_\mu a_b)^2 + \frac{g^2}{4\pi M_P}\left(2\sqrt{\mathcal{V}} a_s - a_b\right) \mathrm{tr}(F \wedge F).$$

- But $f_b \sim M_P/\mathcal{V}^{2/3}$ so $C_{a3} \sim \mathcal{V}^{-2/3} \rightarrow$ effective tiny anomaly!

Constraints

- Have shown constraints on axions with sizeable couplings, but the extra axions (non-local, or hidden sector) will have tiny couplings to SM

Remaining constraints are cosmological:

- Black hole superradiance $m_a > 3 \times 10^{-11}$eV (or $\lesssim 10^{-21}$eV)
- Isocurvature modes $H_{\mathrm{inf}} < 4.3 \times 10^{-5} \left(\frac{\Omega_m}{\Omega_{a_i}}\right) \Theta_i f_{a_i}$.
- DM overproduction $\frac{\Omega_{a_i} h^2}{0.112} \approx 1.4\gamma \times \left(\frac{m_i}{\mathrm{eV}}\right)^{1/2} \left(\frac{f_{a_i}}{10^{11}\ \mathrm{GeV}}\right)^2 \left(\frac{\Theta_i}{\pi}\right)^2$

Cosmology

Some preliminary discussion of cosmology of the scenario:

- Classic CMP says for gravitationally-coupled fields need to decay before BBN (or have small initial misalignments and be stable) so, with $\frac{T_{BBN}^2}{M_P}\Gamma \sim g^2 m^3$ with $g \sim 1/M_P$ need $m \gtrsim 10^4$ GeV.
- Moduli satisfying this could then dominate energy density of universe and inject entropy, reheating and maybe giving "non-thermal WIMP miracle" (c.f. [Acharya, Kane, Kumar, Watson, 09])
- So, in LVS, thermal or non-thermal history? Need to know moduli masses & couplings, inflationary Hubble scale - we have powers of $\mathcal{V}$ appearing in couplings and masses that can affect this
- [Conlon, Quevedo, 07] showed CS moduli cannot play a role, and Kähler moduli stabilised by NP effects (so $m \sim m_{3/2} \log \mathcal{V}$) coupling locally decay at $T \sim 10^7$ GeV for $m_{3/2} \sim 20$ TeV, $g \sim \sqrt{\mathcal{V}}/M_P$ - too early to dilute DM etc.
- In new scenario, local moduli stabilised by loops have masses $\sim \alpha_{SM} m_{3/2}$ - so much lower decay temperature, and they may accomplish this.

Now have three possibilities:

- GUT scale strings ($\mathcal{V} \sim 10^4 \div 10^6$), high $m_{3/2} > H_{\text{inf}}$ - so branes at singularities with sequestering
- GUT scale strings ($\mathcal{V} \sim 10^4 \div 10^6$), low $m_{3/2} < H_{\text{inf}}$ - SM on non-local cycles (will have explicit examples)
- Intermediate scale strings, ($\mathcal{V} \sim 10^{15}$), $m_{3/2} < H_{\text{inf}}$ - SM on local cycles

Cosmology: $H_{\text{inf}} < m_{3/2}$

Here we need to consider the sequestered scenario, with $M_s \simeq 10^{14}$ GeV, $\mathcal{V} \sim 10^7$, $m_{3/2} \sim 10^{10}$GeV

- No CMP: volume and fibre modulus have masses $m_{\tau_b} = m_{3/2}/\sqrt{\mathcal{V}} \simeq 5 \cdot 10^6$ GeV and $m_{\tau_f} = m_{3/2}/\mathcal{V}^{2/3} \simeq 500$ TeV, couple to SM with Planck strength
- Successful (fibre) inflation [Burgess, Cicoli, Quevedo, 08] and reheating [Cicoli, Mazumdar, 10], non-thermal history for DM
- Does sequestering work, and how heavy are the sparticles? Moduli redefinitions? Big open problem!
- Difficult to build models with a closed-string QCD axion, since at e.g. del Pezzo singularities all local axions are eaten

Cosmology: $H_{\rm inf} > m_{3/2}$ part I

First consider the standard model on non-local cycles, with $\mathcal{V} \sim 10^4$, $W_0 \sim 10^{-10}$, $m_{3/2} \sim M_{\rm soft} \sim 3$TeV:

- The large cycle modulus τ_b is light, $m_{\tau_b} = m_{3/2}/\sqrt{\mathcal{V}} \simeq 30$ GeV, so suffers from CMP
- Del Pezzo modulus τ_{dP} and the corresponding axion a_{dP} get mass $m_{\tau_{dP}} \sim m_{a_{dP}} = m_{3/2} \ln \mathcal{V} \simeq 30$ TeV.
- Has Planck-strength coupling to the SM, so can provide entropy injection, decays at a temperature:

$$T_{\tau_{dP}} \sim T_{a_{dP}} \simeq \sqrt{\Gamma_{\tau_{dP}} M_P} \simeq \left(\frac{m_{\tau_{dP}}}{M_P}\right)^{1/2} m_{\tau_{dP}} \simeq 5\,\text{MeV!}$$

- Can have a QCD axion with a large decay constant

Cosmology: $H_{inf} > m_{3/2}$ part II

Now consider the standard model on local cycles, with $\mathcal{V} \sim 10^{14}$, $W_0 \sim 1$, $m_{3/2} \sim M_{soft} \sim$TeV:

- Non-local moduli are light, volume mode is of the order $m_{\tau_b} = m_{3/2}/\sqrt{\mathcal{V}} \simeq 0.1$ MeV, while that of the fibre modulus is $m_{\tau_f} = m_{3/2}/\mathcal{V}^{2/3} \simeq 0.5$ keV
- However, the SM modulus has mass $m \sim m_{3/2} \log \mathcal{V}$ so decays at ~GeV, which may provide entropy injection!
- In any case, non-local axions are not problematic for DM: $f \sim 10^8$ GeV! Hidden axions will be too light to overproduce DM.
- We may have axions which couple substantially to the SM.

Axions vs GUTs

- Imagine that we have built a GUT model such that $SU(5)$ lies on a diagonal del Pezzo cycle, i.e. $\mathcal{V} \supset -\tau_{dP}^{3/2}$
- $SU(5) \subset U(5)$, we must make the $U(1) \subset U(5)$ massive via a diagonal flux upon the stack, which must be globally non-trivial.
- This then gauges the axion corresponding to the cycle τ_{dP}
- ... and thus only closed-string axion candidate remaining is the volume mode $\rightarrow$ cannot be QCD axion, need open-string axion.
- More generally, need D-terms/NP effects to not eat all local axions, can be difficult
- $\rightarrow$ need explicit examples

Explicit examples

Two examples from [Cicoli, Mayrhofer, Valandro 11] on a K3 fibration realised as a hypersurface in a toric variety, having volume form

$$\mathcal{V} = \frac{1}{6}\sum_{i,j,k} k_{ijk} t_i t_j t_k = (t_1 - t_5)(2t_4 - t_5)t_5 + t_4 t_5^2 - \frac{1}{3}t_5^3 - \frac{1}{3}(t_4 - t_7)^3$$

$$= \frac{1}{2} t_{\text{base}} \tau_1 + t_4 t_5^2 - \frac{1}{3} t_5^3 - \frac{1}{3}\tau_7^{3/2}$$

where

$$\tau_1 = (2t_4 - t_5)t_5, \qquad \tau_4 = 2t_1 t_5 - t_5^2 - (t_4 - t_7)^2,$$
$$\tau_5 = 2(t_1 - t_5)(t_4 - t_5), \qquad \tau_7 = (t_4 - t_7)^2.$$

So volume not easily written in terms of four-cycle volumes. However, by choosing branes and fluxes, can use D-terms to simplify.

GUT-like model

- GUT model with 5 D7 branes on D_4, 2 D7 branes on D_5, a Whitney brane to cancel tadpoles and a set of flux choices leads to D-terms fixing

$$\tau_4 = \frac{3}{19}\,\tau_1 - \tau_7\,, \qquad \tau_5 = \frac{18}{19}\,\tau_1$$

- Integrate out heavy moduli, effectively have volume

$$\mathcal{V} = \alpha\left(\tau_1^{3/2} - \gamma\tau_7^{3/2}\right)\,,$$

- Gaugino condensate wrapping τ_7 stabilises the volume at $\mathcal{V} \sim 10^4$.
- Because the FI term equation is linear in τ, can effectively integrate out axions too - two corresponding combinations are eaten:

$$c_a = \frac{3}{19}\,c_1 - c_4 - c_7, \qquad c_b = \frac{18}{19}\,c_1 - c_5\,.$$

- Can derive axion couplings from effective volume form; get

$$\mathcal{L} \supset \frac{\left(\frac{3}{19}\,c_1 - c_7\right)}{M_P}\,g^2_{SU(5)}\mathrm{tr}(F_{SU(5)} \wedge F_{SU(5)}) + \frac{18}{19}\,\frac{c_1}{M_P}\,g^2_{U(1)}\mathrm{tr}(F_{U(1)} \wedge F_{U(1)})$$
$$\simeq \mathcal{O}\left(\frac{1}{M_P}\right)\,a_1\mathrm{tr}(F_{SU(5)} \wedge F_{SU(5)}) + \mathcal{O}\left(\frac{1}{M_P}\right)\,a_1\mathrm{tr}(F_{U(1)} \wedge F_{U(1)}).$$

- $c_7 \sim a_7 + \ldots$ is made heavy by gaugino condensate, leaving QCD axion a_1!

$SU(3) \times SU(2)$ model

- Now choose 3 branes on D_4 and 1 on the K3 fibre $D_1 \to SU(3) \times SU(2)$. With appropriate flux choices, have chiral model with only one, linear, D-term condition

$$\tau_4 = 3\,(\tau_1 - \tau_5) - \tau_7\,, \to 0 = 3c_1 - c_4 - 3c_5 - c_7\,.$$

- Effective volume now

$$\mathcal{V} = \frac{1}{3}\left(\sqrt{\tau_s}\,\tau_b - \tau_7^{3/2}\right)\,, \tau_s \equiv \tau_1 - \tau_5, \qquad \tau_b \equiv \frac{10\tau_1 - \tau_5}{2}\,.$$

- Now can stabilise volume at $\mathcal{V} \sim 10^{14}$ and get

$$\mathcal{L} \supset \frac{(3\,c_s - c_7)}{M_P}\, g^2_{SU(3)} \mathrm{tr}(F_{SU(3)} \wedge F_{SU(3)}) + \frac{1}{9}\,\frac{(2c_b - c_s)}{M_P}\, g^2_{SU(2)} \mathrm{tr}(F_{SU(2)} \wedge F_{SU(2)}$$

$$\simeq \mathcal{O}\left(\frac{1}{M_P}\right) a_s\, \mathrm{tr}(F_{SU(3)} \wedge F_{SU(3)}) + \mathcal{O}\left(\frac{1}{M_P}\right) a_b\, \mathrm{tr}(F_{SU(3)} \wedge F_{SU(3)})$$

$$+\mathcal{O}\left(\frac{\tau_7^{3/2}}{\mathcal{V} M_P}\right) a_s\, \mathrm{tr}(F_{SU(2)} \wedge F_{SU(2)}) + \mathcal{O}\left(\frac{1}{M_P}\right) a_b\, \mathrm{tr}(F_{SU(2)} \wedge F_{SU(2)}).$$

- QCD axion a_s, $f_{a_s} \simeq \frac{M_P}{4\pi\tau_s} \simeq 10^{16}$GeV, and an ALP with decay constant $f_{a_b} \simeq \frac{M_P}{4\pi\tau_b} \simeq 5$ TeV.

Intermediate QCD axion and ALPs

- Clear that to get intermediate-scale couplings must have local axions, so SM on local cycles.
- To stabilise in the geometric regime compatibly with chirality, we can use D-terms; loop effects between branes and the orientifold plane, and with a Whitney brane. E.g. for

$$\mathcal{V} = \alpha\left(\sqrt{\tau_1}\tau_2 - \gamma_3\tau_3^{3/2} - \lambda_4\hat{\tau}_4^{3/2}\right), \quad \text{where} \quad \lambda_4 \equiv \gamma_5\lambda^{3/2} + \gamma_4\,,$$

have $V_{(g_s)} = \left(\frac{\mu_1}{\sqrt{\hat{\tau}_4}} - \frac{\mu_2}{\sqrt{\hat{\tau}_4} - \mu_3}\right)\frac{W_0^2}{\mathcal{V}^3} + \mathcal{O}\left(\frac{1}{\mathcal{V}^4}\right)$.

- Clearly to have an ALP as well as the QCD axion, need at least three local, intersecting moduli

A model of ALPs

- Simplest example of three local moduli is blow-up of Z_7 singularity; can study locally because exceptional divisors are compact

$$\mathcal{V} = \mathcal{V}_0 + \frac{1}{6}\left[8\left(t_1^3 + t_2^3 + t_3^3\right) - 6\left(t_1^2 t_3 + t_1 t_2^2 + t_2 t_3^2\right) + 6 t_1 t_2 t_3\right],$$

- With a judicious choice of fluxes, have one D-term condition which stabilises

$$\tau_3 = \frac{\tau_2}{\tau_1}\left(2\tau_2 - \tau_1\right),$$

- This is not linear, so although can integrate out for moduli stabilisation, for axions must look again at the metric, get

$$\mathcal{K}_{ij} = \frac{(6\tau_2^2 + 2\tau_1\tau_2 - \tau_1^2)^{-1}}{14\sqrt{2}\,\mathcal{V}\sqrt{\tau_1}} \begin{pmatrix} 28\tau_2^2 + 12\tau_1\tau_2 - 5\tau_1^2 & \tau_1(10\tau_2 - 3\tau_1) & \tau_1(\tau_1 + 6\tau_2) \\ \tau_1(10\tau_2 - 3\tau_1) & \tau_1(48\tau_2 - 13\tau_1) & \tau_1(12\tau_2 - 5\tau_1) \\ \tau_1(\tau_1 + 6\tau_2) & \tau_1(12\tau_2 - 5\tau_1) & \tau_1(11\tau_1 + 24\tau_2) \end{pmatrix}$$

$$\xrightarrow{\tau_i = \tau_*} \frac{1}{14\sqrt{2}\,\mathcal{V}\sqrt{\tau_*}} \begin{pmatrix} 5 & 1 & 1 \\ 1 & 5 & 1 \\ 1 & 1 & 5 \end{pmatrix}$$

Get axionic couplings

$$\mathcal{L} \supset \frac{g^2\sqrt{\mathcal{V}}}{2\pi M_P}\left[3.6\, a_{QCD}\, \mathrm{tr}(F_a \wedge F_a) - (3.6\, a_{ALP} + 0.6\, a_{QCD})\, \mathrm{tr}(F_b \wedge F_b)\right].$$

Explaining astrophysical anomalies

This can be applied generally to build models explaining the astrophysical anomalies: recall we need

$$C_{i\gamma}/C_{ie} \simeq 10, \qquad f_{a_i}/C_{i\gamma} \simeq 10^8 \text{ GeV}, \qquad m_{\text{ALP}} \lesssim 10^{-9} \div 10^{-10} \text{ eV}.$$

For this class of models get

$$\frac{C_{i\gamma}}{C_{ie}} \sim \frac{8\pi\tau_*}{3}, \qquad \frac{f_{a_i}}{C_{i\gamma}} = \frac{1}{8\pi N_{i\gamma}\tau_*^{1/4}} \frac{M_P}{\sqrt{\mathcal{V}}} = \frac{1}{8\pi N_{i\gamma}\tau_*^{1/4}} \sqrt{\frac{g_s M_P m_{3/2}}{W_0}}.$$

For $m_{3/2} = 10$ TeV, $g_s \simeq 0.1$ and $W_0 \sim 10$ we can easily arrive at the desired figures for $N_{i\gamma} \sim 10$.
If we want a mass $\sim 10^{-10}$eV, a single Kähler instanton will do with $\tau_* \sim \frac{1}{\pi} \ln\left(\frac{g_s m_{3/2}}{m_{\text{ALP}}}\right) \sim 16$; otherwise it would be much lighter.

Conclusions

- In the LVS expect an axiverse of potentially many light axions, most of which will couple very weakly
- Building models with detectable ALPs or even just a QCD axion can be challenging, when moduli stabilisation etc is taken into account $\rightarrow$ have explicit examples, but more are needed!
- If the astrophysical hints are correct, need intermediate scale strings and SM on local branes in geometric regime!

Kinetic Mixing and LARGE Volumes

- Holomorphic kinetic mixing parameter depends only on complex structure and open moduli:

$$\chi^h_{ab} = \chi^{1-\text{loop}}_{ab}(z_i, y_i) + \chi^{\text{non-perturbative}}_{ab}(z_i, e^{-T_j}, y_i)$$

- For separated branes, no light states $\rightarrow$ no volume dependence from Kähler potential
- Fluxes do not break supersymmetry
- Complex structure moduli typically $\mathcal{O}(1)$, or small in warped throats
- Expect typical $\chi^h_{ab} \sim \mathcal{O}(1/16\pi^2)$
- Find $\chi_{ab} \sim g_a g_b/16\pi^2$
- Hyperweak brane leads to mixing $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/3}$ (swiss cheese) or $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/2}$ (K3 fibre)

Anisotropic masses

- If we instead have two dimensions very large, then $t \sim \mathcal{V}$, can get small masses without small gauge couplings, since the two-forms can propagate orthogonally to the brane
- K3 fibrations are ideal:

$$\mathcal{V} = t_1 t_2^2 + \frac{2}{3} t_2^3 = \frac{1}{2}\sqrt{\tau_1}\left(\tau_2 - \frac{2}{3}\tau_1\right)$$

- $\tau_1 = t_1^2, \tau_2 = 2 t_1 t_2$ with t_2 large
- Metric and inverse:

$$\mathcal{K}_0 = \begin{pmatrix} \tau_1^{-2} & 0 \\ 0 & 2\tau_2^{-2} \end{pmatrix}, \quad \text{and} \quad \mathcal{K}_0^{-1} = \begin{pmatrix} \tau_1^2 & 0 \\ 0 & \tau_2^2/2 \end{pmatrix}$$

- Now wrap a brane on τ_1 and put a gauge flux on t_1 and stabilise moduli via loops; have

$$\chi \sim \frac{10^{-2}}{\sqrt{\tau_1}}, \qquad m_{\gamma'} \sim \frac{M_P}{\mathcal{V}}$$

- Can realise $\chi \sim 10^{-6}$ and $m_{\gamma'} \sim$ meV
- In this case also have “Dark Force” KK modes!!
- Can obtain this scenario with stabilised moduli by adding extra blow-up mode

$$\mathcal{V} = t_1 t_2 (t_2 + t_3) = \sqrt{\tau_1 \tau_3 (\tau_2 - \tau_3)}$$

Anisotropic hidden $U(1)$ predictions