# Axion-like Particles from String Compactifications

**MICHELE CICOLI**

Bologna University and ICTP Trieste

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Based on:

1. Axiverse and QCD axion: MC,Goodsell,Ringwald, arXiv:1206.0819 [hep-th]
2. Axions as dark radiation: MC,Conlon,Quevedo, arXiv:1208.3562 [hep-th]

# Introduction

Two longstanding problems of CY compactifications:

1. Moduli stabilisation
2. Derivation of GUT- or MSSM-like constructions

- Type II theories promising because of D-branes and O-planes
- Moduli stabilisation is a global issue $\leftrightarrow$ model building is a local issue
  $\Rightarrow$ physics decouples, separate study
- Focus on type IIB
  - Viable mechanisms to fix the moduli (KKLT, LVS and others)
  - Semi-realistic local models on the market:
    1. Magnetised intersecting D-branes wrapping cycles in the geometric regime
    2. Fractional D-branes at CY singularities
- Two solutions can be combined within a globally consistent compactification with a rigorous description of the CY background

# Chiral model building and axions

- Moduli stab compatible with chiral model building can be obtained within the LARGE Volume Scenario (LVS)
- 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: D5- & D7-tadpole, torsion charges and FW anomaly cancellation
  - Two possibilities for the visible sector:
    1. D7s in the geometric regime [MC,Mayrhofer,Valandro]
    2. D3s at del Pezzo singularities [MC,Krippendforf,Mayrhofer,Quevedo,Valandro]
  - Realisation of LVS axiverse with explicit QCD axion candidates [MC,Goodsell,Ringwald]
  - Dark radiation from light axions [MC,Conlon,Quevedo]
  - $\mathcal{O}(200\,\mathrm{eV})$ cosmic axion background and diffuse X-ray excess in galaxy clusters from axion-$\gamma$ conversion [Conlon,Marsh]
  - Axion dilution and non-thermal dark matter from moduli decays [Allahverdi,MC,Dutta,Sinha in preparation]

# Axions and strings

- QCD axion $a$ most plausible explanation of the strong CP problem
- Axion decay constant: $10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$
- Astrophysical hints point to light ALPs: $m_{a_i} \lesssim 10^{-(9\div 10)}\,\mathrm{eV}$ and $f_{a_i} \sim 10^{8\div 9}\,\mathrm{GeV}$

$\Rightarrow$ 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?

  Q3: Can ultra-light axions be detected?

# 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 $a$ comes with the corresponding 'saxion' $\tau$: $T = \tau + \mathrm{i}a \Rightarrow$ 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 $\tau$ is fixed perturbatively, $a$ is massless; if $\tau$ is fixed by non-perturbative effects, $a$ 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 $f_a \sim 10^{15}$ GeV [OK if axions are diluted]

# Moduli stabilisation

- Type IIB closed string moduli: axio-dilaton $S$, cx str moduli $U_\alpha$, $\alpha = 1, ..., h^{2,1}$,
  Kähler moduli $\quad T_i = \tau_i + \mathrm{i}\, a_i, \quad \tau_i = \mathrm{Vol}(D_i), \quad a_i = \int_{D_i} C_4, \quad i = 1, ..., h^{1,1}$
- $S$ and $U$ fixed at semi-classical level by background fluxes
- No-scale structure $\Rightarrow$ $T$-moduli flat at tree-level
- Sources for Kähler moduli stabilisation:

$$V = V_D + V_F^{\rm tree} + V_F^{\rm pert} + V_F^{\rm np}$$

  - $V_D \sim \mathcal{O}(1/\mathcal{V}^2)$: D-term potential
  - $V_F^{\rm tree} \sim \mathcal{O}(1/\mathcal{V}^2) = 0$: no-scale structure
  - $V_F^{\rm pert} \lesssim \mathcal{O}(1/\mathcal{V}^3)$: perturbative corrections (axions kept massless)
  - $V_F^{\rm np} \lesssim \mathcal{O}(1/\mathcal{V}^3)$: non-perturbative corrections (axions get massive)
- At leading order in $1/\mathcal{V}$: $V_D = 0$ fixes some moduli $\Rightarrow$ corresponding axions get eaten up by anomalous $U(1)$s
- At subleading order minimise $V_F$ $\Rightarrow$ Break SUSY

# Visible sector in the geometric regime

- Simplest LVS realisation
- Relevant moduli:
  - $\tau_b$: volume mode $\rightarrow$ light ALP
  - $\tau_{\rm np}$: diagonal dP divisor $\rightarrow$ heavy axion
  - $\tau_{\rm vs1}$ and $\tau_{\rm vs2}$: 2 intersecting rigid divisors $\rightarrow$ QCD axion + axion eaten by $U(1)$
- Overall volume: $\mathcal{V} = \tau_b^{3/2} - \tau_{\rm np}^{3/2} - (\tau_{\rm vs1} - x\,\tau_{\rm vs2})^{3/2} - \tau_{\rm vs2}^{3/2} \simeq \tau_b^{3/2}$
- Visible sector: 2 stacks of intersecting D7s wrapping $\tau_{\rm vs1}$ and $\tau_{\rm vs2}$
- Gauge fluxes induce chirality and just 1 moduli-dependent FI-term

$$\xi \propto \sqrt{\tau_{\rm vs2}} - x\sqrt{\tau_{\rm vs1} - x\,\tau_{\rm vs2}}$$

- D-term ($\xi = 0$) fixes a combination of $\tau_{\rm vs1}$ and $\tau_{\rm vs2}$
- Corresponding axion eaten up
- Modulus fixed gets an $\mathcal{O}(M_s)$ mass $\Rightarrow$ EFT in terms of $\tau_b$, $\tau_{\rm np}$ and $\tau_{\rm vs}$

# LVS moduli fixing

- Leading F-term potential from $\alpha'$ + non-pert. corrections:

$$V \sim \frac{\sqrt{\tau_{\rm np}}}{\mathcal{V}}\, e^{-\frac{4\pi\tau_{\rm np}}{N}} - W_0\, \frac{\tau_{\rm np}}{\mathcal{V}^2}\, e^{-\frac{2\pi\tau_{\rm np}}{N}} + \frac{W_0^2\xi}{g_s^{3/2}\mathcal{V}^3}$$

- Fix $\mathcal{V}$ and $\tau_{\rm np}$ at $\tau_{\rm np} \sim g_s^{-1}$ and $\mathcal{V} \sim W_0\, e^{\frac{2\pi}{N g_s}}$
- AdS minimum with spontaneous SUSY breaking
- Minkowski vacua via D-term uplifting or instantons at sing. [MC,Maharana,Quevedo,Burgess]
- Heavy axion $a_{\rm np}$ with a mass of order $m_{3/2}$ + massless volume axion $a_b$
- Subleading order: string loops fix $\tau_{\rm vs} = \alpha_{\rm vs}^{-1} \sim \mathcal{O}(10)$
- Massless local axion $a_{\rm vs} \Rightarrow n_{\rm ax} = 2$ light axions ($a_b + a_{\rm vs}$)
- For $h^{1,1} \sim \mathcal{O}(100)$ expect $n_{\rm ax}$ very large $\Rightarrow$ LVS axiverse with many light axions
- One axion is the QCD axion and the others get a tiny mass via higher order NP effects

# SUSY breaking and mass spectrum

- SUSY broken by moduli F-terms with $F^{\rm vs} \sim m_{3/2} M_P \neq 0 \Rightarrow$ local SUSY breaking
- Soft terms generated by gravity mediation: $M_{\rm soft} \sim m_{3/2}/\ln\mathcal{V} \sim W_0 M_P/(\mathcal{V}\ln\mathcal{V})$
- For $W_0 \sim 1$ and $\mathcal{V} \sim 10^{14} \Rightarrow M_{\rm soft} \sim \mathcal{O}(1)$ TeV and $M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{11}$ GeV
- Mass spectrum:
  - $m_{\tau_{\rm vs2}} \sim m_{a_{\rm vs2}} \sim M_s \sim 10^{11}$ GeV
  - $m_{\tau_{\rm np}} \sim m_{a_{\rm np}} \sim M_P \ln\mathcal{V}/\mathcal{V} \sim 100$ TeV
  - $m_{3/2} \sim 10$ TeV
  - $M_{\rm soft} \sim 1$ TeV
  - $m_{\tau_{\rm vs}} \sim M_P/(\mathcal{V}\ln\mathcal{V}) \sim 100$ GeV
  - $m_{\tau_b} \sim M_P/\mathcal{V}^{2/3} \sim 1$ MeV
  - $m_{a_{\rm vs}} \sim m_\pi f_\pi/f_{a_{\rm vs}} \sim 1$ meV
  - $m_{a_b} \sim M_P e^{-2\pi\mathcal{V}^{2/3}} \sim 0$
- $\tau_{\rm vs}$ and $\tau_b$ lighter than $10$ TeV $\Rightarrow$ might suffer from CMP
- $a_{\rm vs}$ good QCD axion candidate

# Light axions

- Axion decay constants:

$$f_{a_b} \simeq \frac{M_P}{4\pi\mathcal{V}^{2/3}} \simeq \frac{M_{\rm KK}}{4\pi} \simeq 10^9 \text{ GeV} \qquad f_{a_{\rm vs}} \simeq \frac{M_s}{\sqrt{4\pi}} \simeq 10^{10} \text{ GeV}$$

- $a_{\rm vs}$ is a perfect QCD axion candidate
- $a_b$ cannot be the QCD axion since its anomaly coefficient is too small: $k_b \sim \mathcal{V}^{-2/3}$
- Axion coupling to visible sector gauge bosons

$$\mathcal{L} = \left[\mathcal{O}\left(\frac{1}{M_P}\right) a_b + \mathcal{O}\left(\frac{1}{M_s}\right) a_{\rm vs}\right] F \wedge F = \left(\frac{k_b}{f_{a_b}}\, a_b + \frac{k_{\rm vs}}{f_{a_{\rm vs}}}\, a_{\rm vs}\right) F \wedge F$$

- $a_b$ is a light and almost decoupled ALP
- Notice that $k_{\rm vs} \sim 1$
- Can have also $n$ light ALPs with intermediate $f_a$: $n+2$ intersecting cycles and 1 D-term
  - Detect QCD axion in microwave cavities and ALPs in future LSW experiments
  - ALPs explain transparency of the Universe for TeV $\gamma$s and cooling of white dwarfs

# Light moduli

- Moduli couplings to visible sector gauge bosons:

$$\mathcal{L} \sim \left[ \mathcal{O}\left(\frac{1}{M_P}\right) \phi_b + \mathcal{O}\left(\frac{\mathcal{V}^{1/2}}{M_P}\right) \phi_{\rm vs} \right] F_{\mu\nu} F^{\mu\nu}$$

- $\phi_{\rm vs}$ does not suffer from CMP ($m_{\phi_{\rm vs}} \sim 100$ GeV) since it couples as $1/M_s$
- CMP for light modulus $\phi_b$ ($m_{\phi_b} \sim 1$ MeV)
- Possible solutions:
  - Dilution by the decay of heavy moduli [Kitano,Ratz,Murayama;Choi,Chun,Kim]
  - Dilution by thermal inflation [Lyth,Stewart]
    $\Rightarrow$ Axions do not form dark matter $\Rightarrow$ no constraints from isocurvature fluctuations
  - Damping of initial oscillations due to higher-dim. operators [Linde]
    $\Rightarrow$ Axions form dark matter $\Rightarrow$ constraints from isocurvature fluctuations

# Visible sector at singularities

- Overall volume: $\mathcal{V} = \tau_b^{3/2} - \tau_{\rm np}^{3/2} - \tau_{\rm vs}^{3/2} \simeq \tau_b^{3/2}$
- Visible sector cycle shrinks to zero size due to D-terms: $\xi \propto \tau_{\rm vs} \Rightarrow \tau_{\rm vs} \to 0$
- Corresponding axion gets eaten up
- $\tau_b$ and $\tau_{\rm np}$ fixed as in the geometric case
  $\Rightarrow a_b$ is a light axion whereas $a_{\rm np}$ is heavy
- Main difference with geometric case: no local SUSY breaking since $F^{\rm vs} \propto \xi = 0$
- Sequestered soft terms: $M_{\rm soft} \sim m_{3/2}/\mathcal{V} \ll m_{3/2}$
- Get TeV-scale SUSY for $\mathcal{V} \sim 10^7 \Rightarrow$ high string scale $M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
- Right GUT scale: $M_{\rm GUT} \sim M_s \mathcal{V}^{1/6} \sim 10^{16}$ GeV

# Mass spectrum

- Different mass spectrum:
  - $m_{\tau_{\rm vs}} \sim m_{a_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
  - $m_{\tau_{\rm np}} \sim m_{a_{\rm np}} \sim M_P \ln \mathcal{V}/\mathcal{V} \sim 10^{12}$ GeV
  - $m_{3/2} \sim M_P/\mathcal{V} \sim 10^{11}$ GeV
  - $m_{\tau_b} \sim M_P/\mathcal{V}^{2/3} \sim 10^6$ GeV
  - $M_{\rm soft} \sim m_{3/2}/\mathcal{V} \sim M_P/\mathcal{V}^2 \sim 1$ TeV
  - $m_{a_b} \sim M_P e^{-2\pi\mathcal{V}^{2/3}} \sim 0$
- No CMP since $m_{\tau_b} \sim 10^6\,\text{GeV} \gg 10\,\text{TeV}$
- Can get standard GUT theories
- High string scale allows for successful inflationary model building with $N_e \simeq 60$, $n_s \simeq 0.96$, $r \ll 1$, right amount of density perturbations and possibly power loss at large scales [Burgess,MC,Conlon,Pedro,Quevedo,Tasinato]

# Axions in sequestered models

- In dP singularities all local axions are eaten up
- Only the volume axion might remain light: $m_{a_b} \lesssim M_P \, e^{-2\pi\mathcal{V}^{2/3}} \sim 0$
- What is the QCD axion?
- Consider singularities more complicated than dP
  - A local axion is left over and can be the QCD axion with $f_{a_s} \simeq M_s/\sqrt{4\pi} \simeq 10^{14}$ GeV
  - The QCD axion abundance can be diluted by the decay of $\tau_b$
- The phase of an open string axion $\phi$ 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 $\xi = \tau_{\rm vs}/\mathcal{V}$
  - Check that D-terms do not resolve the sing. obtained by setting $\xi = 0$ for $\langle|\phi|\rangle = 0$
  - If $0 \neq \langle|\phi|\rangle = \sqrt{\xi} \simeq \langle\sqrt{\tau_{\rm vs}}\rangle \, M_s \Rightarrow$ tension between $\langle\tau_{\rm vs}\rangle = 0$ and $\langle|\phi|\rangle \neq 0$
  - $\tau_{\rm vs}$ is still below $\ell_s^4$ if $\langle\tau_{\rm vs}\rangle = \mathcal{V}^{-2\alpha}$ 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

# Bulk axions as dark radiation

- Relativistic axions produced from the decay of the light volume mode
  - When $H \sim m_{\tau_b}$ the volume mode starts to oscillate and stores energy
  - $\tau_b$ redshifts as matter ($\rho \sim a^{-3}$) $\Rightarrow$ it quickly dominates the energy density
  - $\tau_b$ reheats the Universe when it decays out of thermal equilibrium
- The volume axion $a_b$ is almost massless $\Rightarrow$ it behaves as dark radiation! [MC,Conlon,Quevedo][Higaki,Takahashi]
- Dark radiation expressed in terms of $N_{\rm eff}$ (effective number of neutrino-like species)

$$\rho_{\rm total} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- In the SM $N_{\rm eff,SM} = 3.04$: dark radiation leads to $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff,SM} > 0$
- Observational hints for $\Delta N_{\rm eff} \simeq 0.5 \div 1$ at $1 \to 2\sigma$:
  1. BBN: $N_{\rm eff} = 3.9 \pm 0.44$ at $1\sigma$ (D/H)
  2. CMB: $N_{\rm eff} = 3.84 \pm 0.40$ at $1\sigma$ (WMAP9+ACT+SPT+BAO+HST)
  3. New data: $N_{\rm eff} = 3.52^{+0.48}_{-0.45}$ at $2\sigma$ (PLANCK+WMAP9+ACT+SPT+BAO+HST)

# Volume decays to axions

1. **Decays to volume axions** (if not eaten by $U(1)$s)

$$\Gamma_{\Phi\to a_b a_b} \sim \frac{m_\Phi^3}{M_P^2}$$

Source for dark radiation!

2. **Decays to local axions** (if not eaten by $U(1)$s or lifted non-perturbatively)

$$\Gamma_{\Phi\to a_s a_s} \sim \frac{m_\Phi^3}{M_P^2}$$

3. **Decays to open string axions** $\theta$ ($C = \rho\, e^{i\,\theta}$ with $\langle\rho\rangle \neq 0$)

$$\mathcal{L} \supset -\sqrt{\frac{2}{3}}\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \Phi\theta\Box\theta + \frac{4}{3}\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \Phi\partial_\mu a_b\partial^\mu\theta$$

- $\Phi \to \theta\theta$ decays are mass suppressed
- $\Phi \to \theta a_b$ decays compete with $\Phi \to a_b a_b$ for $\langle\rho\rangle \sim M_P$ BUT $\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \sim \xi \sim \frac{1}{\mathcal{V}} \ll 1$

# Volume decays to Higgs bosons

- Giudice-Masiero coupling in the Kähler potential

$$K = -3\ln(T_b + \bar{T}_b) + \frac{H_u\bar{H}_u + H_d\bar{H}_d}{(T_b + \bar{T}_b)} + \left(\frac{Z H_u H_d}{(T_b + \bar{T}_b)} + \text{h.c.}\right)$$

- $Z = 1$ if Higgs sector has a shift symmetry [Hebecker,Knochel,Weigand]
- After canonical normalisation:

$$\mathcal{L} \supset \frac{1}{\sqrt{6}}\left[\Phi\left(\bar{H}_u \Box H_u + \bar{H}_d \Box H_d\right) + Z H_u H_d \Box \Phi + h.c.\right]$$

Last term gives the decay $\Phi \to H_u H_d$ with:

$$\Gamma_{\Phi \to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

# Volume decays to other particles

1. **Decays to gauge bosons**

   Tree-level: $f_a = S + h_a T_{\rm vs}$ (independent of $T_b$) – Loop level: $\left(\frac{\alpha_{\rm vs}}{4\pi}\right) \ln \mathcal{V}$

$$\mathcal{L} \supset \left(\frac{\alpha_{\rm vs}}{4\pi}\right) \Phi F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \qquad \Gamma_{\Phi\to\gamma\gamma} \sim \left(\frac{\alpha_{\rm vs}}{4\pi}\right)^2 \frac{m_\Phi^3}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

2. **Decays to matter scalars** $C$

$$\Gamma_{\Phi\to C\bar{C}} \sim \frac{m_0^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

3. **Decays to matter fermions, gauginos and Higgsinos**

$$\Gamma_{\Phi\to f f} \sim \frac{m_f^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

4. **Decays to hidden sector particles**

   Only unsuppressed decays to light gauge bosons on the large cycle and Higgses in sequestered hidden sectors

# Summary of leading decay channels

Leading decay channels for the volume mode:

- Model-independent decays:
  1. Visible sector Higgses
- Model-dependent decays:
  1. Volume axion: extra dark radiation
  2. Local closed string axions: extra dark radiation
  3. Light gauge bosons on the large cycle: extra dark radiation or dark matter if Higgsed
  4. Higgses in sequestered hidden sectors: extra dark matter

$\Rightarrow$ constraints on hidden sector model building from dark radiation and dark matter overproduction

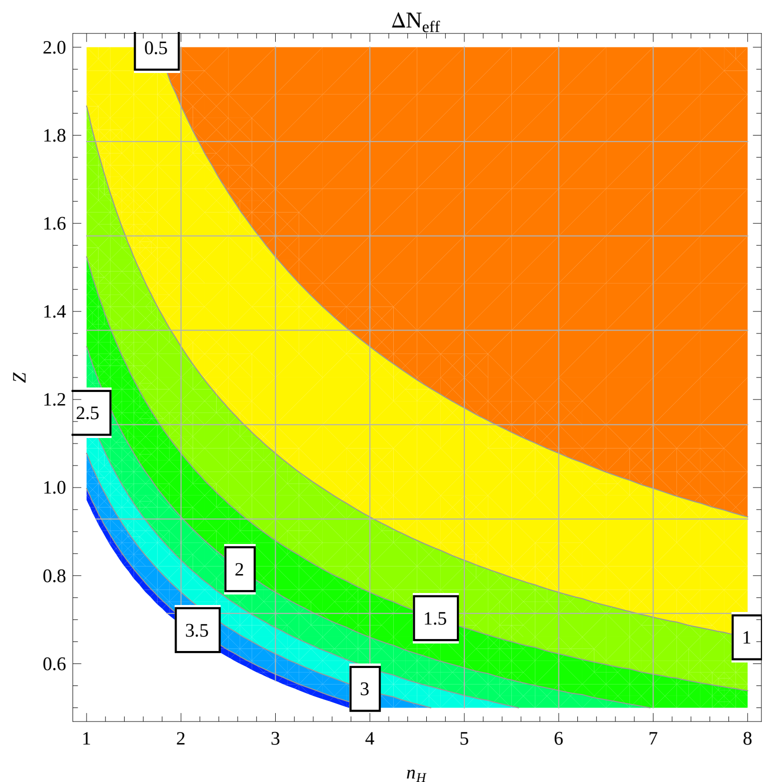
# Predictions for dark radiation

- Neutrinos thermalise whereas axions do not

$$\Rightarrow \quad \Delta N_{eff} = \frac{43}{7}\frac{\rho_{hidden}}{\rho_{SM}} = \frac{43\,\kappa}{7}\left(\frac{g(T_{dec})}{g(T_{rh})}\right)^{1/3} \simeq 3.48\,\kappa \quad \text{for} \quad T_{rh} \sim \mathcal{O}(1)\,\text{GeV}$$

where $\kappa = \frac{(1+9n_a/16)}{n_H Z^2}$ for $n_H$ Higgs doublets and $n_a$ local closed string axions

- If $n_a \sim \mathcal{O}(100)$ (axiverse) $\Delta N_{eff}$ is too big! $\Rightarrow n_a = 0$ (QCD axion is an open string)



# No $\Delta N_{\rm eff}$ and non-thermal dark matter

In globally consistent chiral brane models in explicit compact CY constructions, $a_b$ is generically eaten up due to consistency reasons [MC,Mayrhofer,Valandro in preparation]

$\Rightarrow$ no dark radiation overproduction!

$\Rightarrow$ Two scenarios for non-thermal dark matter [Allahverdi,MC,Dutta,Sinha in preparation]:

1. QCD axion is a closed string mode $a_s$ with $f_a \sim 10^{14}$ GeV:
   - $\Phi \to a_s a_s$ is a leading decay channel
     $\Rightarrow Z \neq 0$ to suppress $\Delta N_{\rm eff}$
   - $T_{\rm rh} \sim 1\,{\rm GeV} > \Lambda_{\rm QCD} \sim 200\,{\rm MeV}$
     $\Rightarrow$ No axion dilution $\Rightarrow$ tune initial misalignment
   - $\tau_b$ decay dilutes thermal DM since $T_{\rm rh} \sim 1\,{\rm GeV} < T_f \sim m_{\rm DM}/15 \sim 10\,{\rm GeV}$
   - Non-thermal DM as decay products: too much DM
     $\Rightarrow$ ‘Annihilation scenario’ $\Rightarrow$ Wino- or Higgsino-like DM (+ axions)

# No $\Delta N_{\rm eff}$ and non-thermal dark matter

2. QCD axion is an open string mode $\theta$ with intermediate $f_a$:
   - $\Phi \to \theta\theta$ is a subleading decay channel $\Rightarrow$ No $\Delta N_{\rm eff}$
     $\Rightarrow$ Two scenarios:
     - 'Annihilation scenario' if $Z \neq 0$
       $\Rightarrow T_{\rm rh} \sim 1\,{\rm GeV} \Rightarrow$ Wino- or Higgsino DM (+ axions)
     - 'Branching scenario' if $Z = 0$:
       - Leading decay channel is to gauge bosons (loop-suppressed)
       - Lower reheat temperature $T_{\rm rh} \sim \frac{\alpha_{\rm vs}}{4\pi} m_\Phi \sqrt{m_\Phi / M_P} \sim 10\,{\rm MeV} > T_{\rm BBN}$
       - Axions and thermal DM are diluted $\Rightarrow$ they are not DM
       - Non-thermal DM as decay products: too less DM if annihilation is too strong
         $\Rightarrow$ DM produced directly from the decay without any subsequent annihilation
         $\Rightarrow$ Bino-like DM

**NB:** Also any previous matter-antimatter asymmetry gets diluted!

- Welcomed effect for Affleck-Dine baryogenesis which can be too efficient
- If no asymmetry is left over after the decay of $\tau_b$
  $\Rightarrow$ co-genesis of DM and baryogenesis from the moduli decay in the presence of new $O({\rm TeV})$ coulored particles with $B$- and $CP$-violating couplings [Allahverdi,Dutta,Sinha]
  $\Rightarrow$ Can address baryon-DM coincidence!

# Conclusions

- Hard to build explicit string models with a successful QCD axion plus light ALPs
- LVS good framework for brane model building and moduli stabilisation
- General LVS strategy to fix the moduli might give an axiverse
- Axions in the geometric regime:
  - Chiral model with a local QCD axion with intermediate $f_a$ + 1 non-local light ALP
  - $n+2$ intersecting divisors + 1 D-term $\Rightarrow$ QCD axion plus $n$ ALPs with intermediate $f_a$
  - BUT need to solve the CMP!
- Axions for branes at singularities:
  - Closed string QCD axion with $f_a \sim 10^{14}$ GeV for sing. more complicated than dP
  - QCD axion can be the phase of an open string mode with intermediate $f_a$
  - Reheating driven by decays of the volume mode (axion cold DM can be diluted)
  - Dark radiation from light axions (but $a_b$ generically eaten by an anomalous $U(1)$s)
  - Bounds on $\Delta N_{\rm eff}$ strongly constrain model building and the axiverse
  - Cosmic axion background
  - Non-thermal DM from moduli decays: ‘annihilation’ or ‘branching’ scenario