Axions from Strings

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Based on:
Type IIb axions: MC, Goodsell, Ringwald, arXiv:1206.0819 [hep-th]
Review: MC, arXiv: 1309.6988 [hep-th]

Axions and strong CP problem

- Strong CP problem solved by axion a
- U(1)$_{PQ}$: anomalous global symmetry spontaneously broken at f_a
- a is the Goldstone boson of U(1)$_{PQ}$ $\quad a \to a + \mathrm{const}$
- Explicit breaking by QCD instantons

$$L_{axion} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\partial_\mu a}{f_a}\left(c_\psi \bar{\psi}\gamma^\mu \psi + c_\varphi \varphi^* \partial^\mu \varphi + \ldots\right) + \frac{c_F}{16\pi^2}\frac{a}{f_a} F^i_{\mu\nu}\tilde{F}_i^{\mu\nu} - V\left(\frac{a}{f_a}\right)$$

- V fixes $\langle a \rangle = 0$ with $m_a \sim \frac{\Lambda^2_{QCD}}{f_a} \sim \mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$
- Allowed window: $10^9\ \mathrm{GeV} \le f_a \le 10^{12}\ \mathrm{GeV}$ $\longrightarrow$ $1\ \mu\mathrm{eV} \le m_a \le 1\ \mathrm{meV}$

Star cooling and direct searches

DM overproduction $\quad \Omega_a \sim 0.2\ \vartheta^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$

Relaxed by late entropy dilution or inflation and anthropics

Axions and phenomenology

- small f_a regime: $f_a < H$ — axion heavy during inflation — no isocurvature fluctuations
  $U(1)_{PQ}$ breaking after inflation — domain walls, axionic strings

- large f_a regime: $f_a > H$ — $U(1)_{PQ}$ broken during inflation — $m_a = 0$
  isocurvature fluctuations — bounds for large tensors $\left(H \leq 10^{14}\ \mathrm{GeV}\right)$

$$\left(\frac{\delta T}{T}\right)_{\mathrm{iso}} \sim \left(\frac{\Omega_a}{\Omega_{DM}}\right)^{1/2} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/12} \left(\frac{H}{\pi f_a}\right) < 10^{-5}$$

Applications beyond DM:

i) Inflaton axion because of shift symmetry: $m_a \sim 0.1 H \sim 10^{13}\ \mathrm{GeV}$ $\quad f_a > M_p$

ii) Dark radiation axion from heavy field decay $\Delta N_{eff} \sim 0.5$ relax tension between Planck and HST

iii) Quintessence axion avoids fifth force bounds: $m_a \sim H_0 \sim 10^{-33}\ \mathrm{eV}$ $\quad f_a > M_p$

iv) ALP explain astrophysical anomalies: transparency of universe for γ-rays $\quad m_a \leq 10^{-9}\ \mathrm{eV}$
white dwarf cooling $\quad f_a \sim 10^{9}\ \mathrm{GeV}$

soft X-ray excess in galaxy clusters $\quad m_a < 10^{-12}\ \mathrm{eV}$
3.5 keV line $\quad f_a \sim 10^{9}$ - $10^{12}\ \mathrm{GeV}$

Axions from UV physics

Q1: What is the origin of axions with shift symmetry?

$$a(x) \to a(x) + \text{const}$$

Q2: What dynamics breaks $U(1)_{PQ}$ spontaneously and sets f_a ?
Is f_a related to some physical scale M_p, M_s, M_{kk}, M_{GUT}, M_{soft}?

Q3: What dynamics breaks $U(1)_{PQ}$ explicitly and sets m_a ?
Is m_a generated by QCD instantons or by other effects?

Fluxes, stringy instantons, worldsheet instantons,…..

Q4: How many ALPs can arise?
What range of f_a and m_a can they have?

Axion origin

- In QFT a gauge field has 2 self couplings:

$$g^{-2}\ F_{\mu\nu}F^{\mu\nu} + i\vartheta\ \varepsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

a priori g and ϑ are unrelated

- In SUSY:

$$\mathrm{Re}(f(\Phi))\ F_{\mu\nu}F^{\mu\nu} + i\,\mathrm{Im}(f(\Phi))\ \varepsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

g and ϑ determined via a single holomorphic function $f(\Phi)$

- $f(\Phi)$ can be either constant or field-dependent

- If $f(\Phi) = \dfrac{\Phi}{\Lambda}$ with $\Phi = \varphi_1 + i\ \varphi_2$ $\longrightarrow$ $\dfrac{1}{g^2} = \dfrac{\varphi_1}{\Lambda}$ and $\vartheta = \dfrac{\varphi_2}{\Lambda} \equiv \dfrac{a}{f_a}$

$\longrightarrow$ Any theory with SUSY and field-dependent couplings has axions!

Main example: string theory SUSY for consistency and no free parameter

In every string compactifications every gauge field has an associated axion $\rightarrow$ closed string / open string

String moduli

- String theory lives in 10D and needs SUSY for consistency
- Compactification: $X_{10D} = M_{4D} \times Y_{6D}$
- 4D EFT for $E \ll M_{\mathrm{KK}} \approx 1/\mathrm{Vol}\left(Y_{6D}\right)^{1/6}$
- Geometrical and topological properties of Y_{6D} determine 4D physics
- N=1 SUSY in 4D if Y_{6D} is a Calabi-Yau manifold $\longrightarrow$ chiral theory $\longrightarrow$ realistic!
- Y_{6D} can de deformed in size and shape

i) Maths: deformations parameterised by moduli

ii) 4D Physics: moduli are new scalar particles with gravitational couplings

- Moduli ϕ massless at classical level $\longrightarrow$ flat potential $V(\phi)=0$ $\longrightarrow$ $\langle 0|\phi|0\rangle$ unfixed!
- 2 problems:

i) Unobserved long-range forces (for $m < 1$ meV)

ii) Unpredictability since $g_{YM} = g_{YM}(\phi)$, $Y_{ijk} = Y_{ijk}(\phi)$ and mass spectrum depends on ϕ

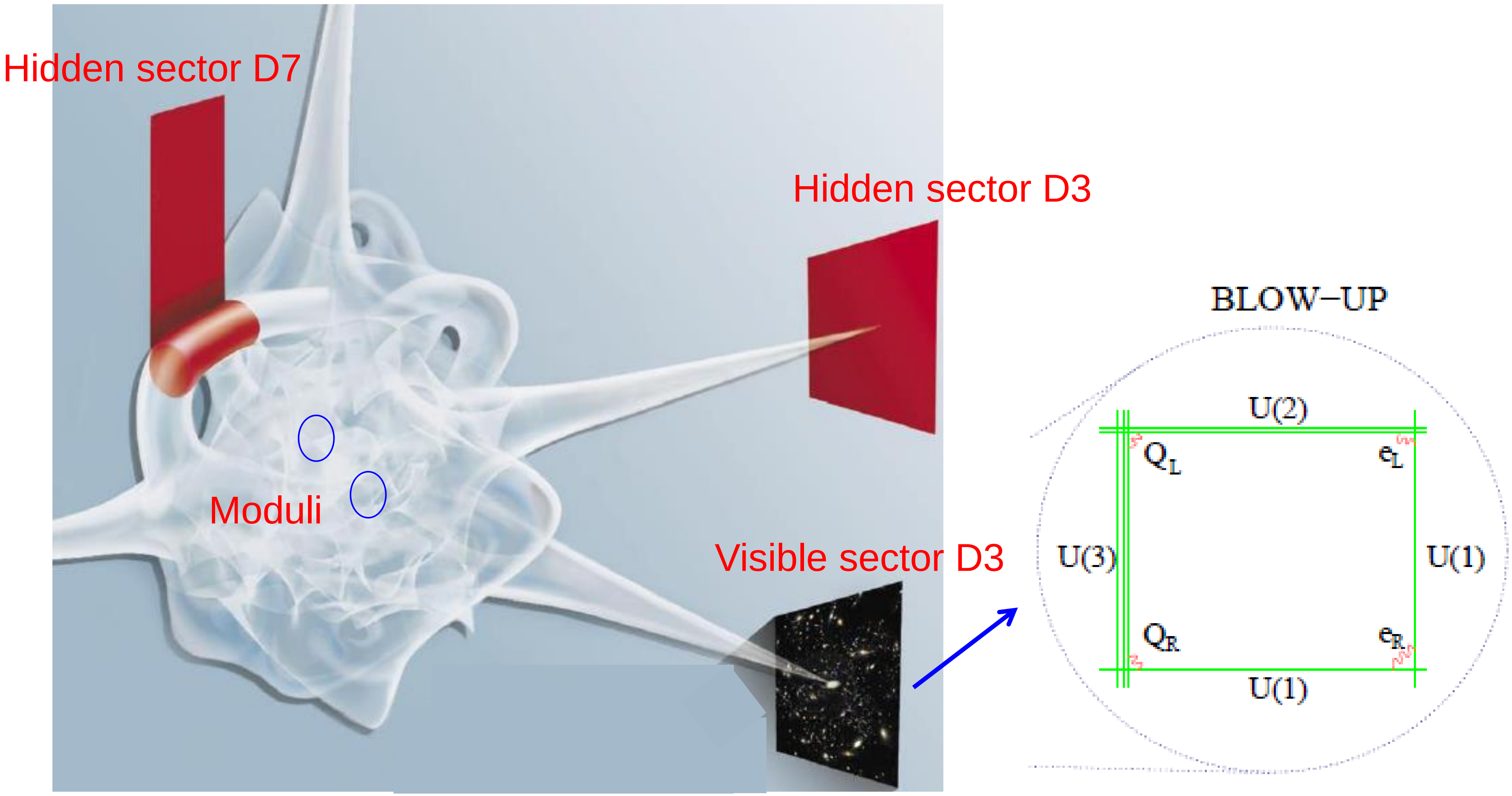
$\longrightarrow$ need to develop $V(\phi) \neq 0$ via quantum corrections $\longrightarrow$ fix $\langle 0|\phi|0\rangle$

$\longrightarrow$ get $m > 50$ TeV via moduli stabilisation to avoid cosmological problems

String models

- Ubiquitous presence of geometric moduli (closed strings)
- Branes provide non-Abelian gauge symmetries and chiral matter (open strings)
- Standard Model (or MSSM/GUT theories) localised on branes (D3/D7 in type IIB)

→ model-building is a local issue while moduli stabilisation/SUSY breaking is a global issue



Axions from closed strings

- Type II strings: U(N) gauge group realised on N Dp-branes wrapping internal (p-3) cycles Σ_{p-3}
- Closed string spectrum contains p-forms C_p with gauge symmetry

$$C_p \to C_p + d\Lambda_{p-1}$$

- Dp-brane action

$$S_{Dp} = \underbrace{\int_{M^4\times\Sigma_{p-3}} \sqrt{g+F}}_{\text{DBI}} + i \underbrace{\int_{M^4\times\Sigma_{p-3}} \sum_q C_q \wedge e^F}_{\text{Chern-Simons}}$$

- From DBI:

$$S_{\text{DBI}} = \ldots + \int_{M^4} \sqrt{g} F_{\mu\nu} F^{\mu\nu} \quad \underbrace{\int_{\Sigma_{p-3}} \sqrt{g}}_{g^{-2} = \text{Vol}(\Sigma_{p-3}) \equiv \tau}$$

- From Chern-Simons:

$$S_{\text{CS}} = \ldots + \int_{M^4} F \wedge F \quad \underbrace{\int_{\Sigma_{p-3}} C_{p-3}}_{\vartheta}$$

→ Gauge kinetic function: $f = T \quad \text{with} \quad T = \tau + i\vartheta$ String modulus

→ Axion shift symmetry: $C_p(x,y) = \vartheta(x)\omega_p(y) \xrightarrow[\vartheta(x)\to\vartheta(x)+c]{} C_p + c\omega_p = C_p + d\Omega_{p-1}$

locally in the extra dimensions

Axions from closed strings

- Shift symmetry breaking:

  i) Perturbative level: complete breaking by background fluxes which break SUSY

  $$m_{\vartheta,\mathrm{flux}} \sim m_{3/2} \sim M_p / \mathcal{V}$$ e.g. type IIB dilaton and complex structure moduli

  ii) Non-perturbative level: breaking to discrete shift symmetry by stringy instantons

  $$m_{\vartheta,\mathrm{inst}} \sim m_\tau \sim m_{3/2} > 50\ \mathrm{TeV}$$ If τ fixed non-perturbatively as in KKLT models

  $$m_{\vartheta,\mathrm{inst}} \ll m_\tau \sim m_{3/2}$$ If τ fixed perturbatively as in LVS models → Axiverse!

- Too get viable QCD axion need to check $m_{\vartheta,\mathrm{inst}} \ll m_{\vartheta,\mathrm{QCD}} \sim \Lambda_{QCD}^2 / f_a$

- f_a from kinetic terms determined by Kahler potential K

$$L_{kin} = \frac{\partial^2 K(T+\bar{T})}{\partial T_i \partial \bar{T}_{\bar{j}}} \partial_\mu T_i \partial^\mu \bar{T}_{\bar{j}} = \frac{1}{4} \frac{\partial^2 K}{\partial \tau_i \partial \tau_j} \left(\partial_\mu \tau_i \partial^\mu \tau_j + \partial_\mu \vartheta_i \partial^\mu \vartheta_j \right)$$

i) bulk cycles: $K = -3 \ln \tau_{bulk}$ → $f_a^2 \sim \frac{\partial^2 K}{\partial \tau_{bulk}^2} M_p^2 \sim \frac{M_p^2}{\tau_{bulk}^2} \sim M_{KK}^2$

ii) local cycles (blow-ups): $K = \frac{\tau_{loc}^2}{\mathcal{V}}$ → $f_a^2 \sim \frac{\partial^2 K}{\partial \tau_{loc}^2} M_p^2 \sim \frac{M_p^2}{\mathcal{V}} \sim M_s^2$

→ $U(1)_{PQ}$ always broken in EFT → $f_a > H$

→ large f_a unless $M_s \sim 10^{11}$ GeV with $m_{3/2} \sim 1$ TeV for $\mathcal{V} \sim 10^{15}$ but cosmological problems

Axions from open strings

- Non-zero world-volume gauge flux F on N Dp-branes

$$U(N) \to SU(N) \times U(1) \qquad \text{Anomalous}$$

- Flux-dependent U(1) charge of T-modulus
- Axion ϑ eaten up by anomalous U(1) while τ gives rise to a field-dependent FI-term
- $M_{U(1)} \sim M_s$ $\longrightarrow$ global $U(1)_{PQ}$ in EFT
- D-term potential for charged open string $\Phi = \rho\, e^{i\vartheta}$

$$V_D \simeq g^2 \left(\rho^2 - \xi\right)^2$$

- D = 0 gives

$$\langle \rho \rangle = \sqrt{\xi} = f_a^{open} \qquad \text{Spontaneous breaking of } U(1)_{PQ}$$

- From Chern-Simons (e.g. for D7 wrapping Σ_4): $C_4(x,y) = Q_2(x) \wedge D_2(y) + \vartheta(x)\tilde{D}_4(y)$

$$S_{CS} = \ldots + \underbrace{\int_{\Sigma_4} D_2 \wedge F}_{q} \int_{M^4} Q_2 \wedge F$$

- By dualising to the axion and adding kinetic terms get:

$$\frac{M_{U(1)}^2}{2}\left(A_\mu + \partial_\mu a\right)\left(A^\mu + \partial^\mu a\right) \qquad M_{U(1)}^2 = q^2 g^2 \left(f_a^{closed}\right)^2$$

- From DBI:

$$\xi = \frac{1}{\mathcal{V}} \int_{\Sigma_4} J \wedge F = q \frac{\partial K}{\partial \tau}$$

Closed vs open string axions

- Combination of closed and open string axions eaten by anomalous U(1)

$$M_{U(1)}^2 = g^2\left[\left(f_a^{open}\right)^2 + \left(f_a^{closed}\right)^2\right]$$

$$\left(f_a^{open}\right)^2 = \rho^2 = \xi \simeq \frac{\partial K}{\partial \tau} M_p^2 \qquad\qquad \left(f_a^{closed}\right)^2 \simeq \frac{\partial^2 K}{\partial \tau^2} M_p^2$$

i) bulk cycles: $K = -3\ln \tau_{bulk}$ $\qquad \tau_{bulk} \gg 1$

$$\left(f_a^{open}\right)^2 \simeq \frac{\partial K}{\partial \tau_{bulk}} M_p^2 \simeq \frac{M_p^2}{\tau_{bulk}} \gg \left(f_a^{closed}\right)^2 \simeq \frac{\partial^2 K}{\partial \tau_{bulk}^2} M_p^2 \simeq \frac{M_p^2}{\tau_{bulk}^2}$$

open string axion eaten up

ii) local cycles (blow-ups): $K = \frac{\tau_{loc}^2}{\mathcal{V}}$ $\qquad \tau_{loc} \ll 1$

$$\left(f_a^{open}\right)^2 \simeq \frac{\partial K}{\partial \tau_{loc}} M_p^2 \simeq \frac{\tau_{loc}}{\mathcal{V}} M_p^2 \simeq \tau_{loc} M_s^2 \ll \left(f_a^{closed}\right)^2 \simeq \frac{\partial^2 K}{\partial \tau_{loc}^2} M_p^2 \simeq \frac{M_p^2}{\mathcal{V}} \sim M_s^2$$

closed string axion eaten up

→ $U(1)_{PQ}$ spontaneously broken at low energy → $f_a < H$

→ $f_a \sim 10^{11}$ GeV << $M_s \sim 10^{16}$ GeV with $M_{soft} \sim 1$ TeV and no cosmological problems

due to sequestering

Conclusions

- 4D string models:
  i) closed string axions a (KK zero modes of antisymmetric forms $\Phi = \phi + i\, a$)
  $f_a \simeq 10^{16\text{-}17}$ GeV $\longrightarrow$ Fuzzy DM, inflation, quintessence
  ii) open string axions ϑ (phase of a matter field $\phi = |\phi|\, e^{i\vartheta}$)
  $f_\vartheta \simeq 10^{10\text{-}11}$ GeV $\longrightarrow$ QCD axion, astrophysical hints,….

- But axions can be:
  i) removed from the spectrum by orientifold projection
  ii) eaten up by anomalous U(1)s
  a) open string axions eaten up for branes wrapping bulk cycles
  b) closed string axions eaten up for branes at singularities
  iii) too heavy if fixed supersymmetrically
  (saxion ϕ has to get a mass larger than 50 TeV)

- Axions enjoy a shift symmetry $\longrightarrow$ moduli stabilisation:
  i) axions are heavy ($m_a \simeq m_\phi$ > 50 TeV) if saxions are fixed non-perturbatively
  ii) axions are light ($m_a << m_\phi$) if saxions are fixed perturbatively $\longrightarrow$ Axiverse!

Generic prediction: light axions are unavoidable in models with perturbative moduli stabilisation!

$\longrightarrow$ Generic production of axionic dark radiation $\Delta N_{eff} \neq 0$

- Several applications: QCD axion, DR, astrophysics, inflation, quintessence……Fuzzy DM?