Searching for axions and ALPs from string theory.

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Particles beyond the Standard Model?!

- Standard Model of Particle Physics: Fundamental description of known matter particles and gauge forces

Source: AAAS
Particles beyond the Standard Model?!

> Standard Model of Particle Physics: Fundamental description of known matter particles and gauge forces

> Standard Model of Cosmology: only about 5% of energy content of present universe consists of known particles
Particles beyond the Standard Model?!

- **Standard Model of Particle Physics**: Fundamental description of known matter particles and gauge forces

- **Standard Model of Cosmology**: only about 5% of energy content of present universe consists of known particles

- **Extensions of the Standard Model of Particle Physics**: several good motivated candidates for constituents of dark matter
  - SUSY: Neutralino, Gravitino
  - Peccei Quinn: Axion
Motivation: Explanation of unnatural smallness, $\theta < 10^{-10}$, of CP-violating topological term in QCD Lagrangian,

$$\mathcal{L}_{\text{CP-viol.}} = \frac{\alpha_s}{4\pi} \theta \text{ tr } G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Axion field $\theta \rightarrow a(x)/f_a$

- $\langle a \rangle = 0$
Peccei-Quinn extension of the Standard Model

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- Axion: ultralight particle, cf. Weinberg `78; Wilczek `78

$$m_a = \frac{m_\pi f_\pi \sqrt{m_u m_d}}{f_a (m_u + m_d)} \approx 6 \text{ meV} \times \left( \frac{10^9 \text{ GeV}}{f_a} \right)$$
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$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma} a \vec{E} \cdot \vec{B},$$

$$g_{a\gamma} \approx \frac{\alpha}{2\pi f_a} \sim 10^{-12} \text{ GeV}^{-1} \left( \frac{10^9 \text{ GeV}}{f_a} \right)$$
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> Welcome side effect:
- Axion: candidate for dark matter: created non-thermally via misalignment mechanism in form of coherent oscillations of axion field

$$\Omega_a h^2 \approx 0.7 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \left( \frac{\theta_i}{\pi} \right)^2$$
Particularly strongly motivated extensions of Standard Model based on string theory:

- Unification of all forces
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Spectrum of low-energy effective theory in (3+1)-dimensions is supersymmetric and possibly contains several kinds of very weakly interacting slim particles (WISPs): Axion, ALPs (Axion-Like Particles)

- if the compact space comprised of the 6 extra dimensions has certain geometrical and topological properties (Calabi-Yau; several cycles)
Axions in string theory

String compactifications generically contain pseudo-scalar fields with axionic coupling to gauge fields and anomalous global shift symmetry

\[ a_i \tilde{F} \tilde{F} \quad a_i \rightarrow a_i + \epsilon \]

These axion and axion-like particle (ALP) candidates arise in string compactifications as KK zero modes of antisymmetric tensor fields: cf. Witten `84

heterotic string : \( B_2 \)

IIB string : \( C_2, C_4 \)
Axions in IIB string theory

> Concentrate on IIB case (moduli stabilisation best understood):
Realisation of brane-world scenarios in string theory

> KK reduction (expansion in harmonic forms):
\[ C_2 = c^a(x)\omega_a, \ a = 1, \ldots, h^{1,1}_- \]
\[ C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \ldots, \ \alpha = 1, \ldots, h^{1,1}_+ \]

> Number of axionic fields determined by topology of CY orientifold: number of topologically non-equivalent 2-cycles or 4-cycles
Axions in IIB string theory

Number of cycles generically $O(100)$:

$$h^{1,1} + h^{2,1}$$

Figure 1: A plot of the Hodge numbers of the Kreuzer–Skarke list. $\chi = 2(h^{11} - h^{21})$ is plotted horizontally and $h^{11} + h^{21}$ is plotted vertically. The oblique axes bound the region $h^{11} \geq 0$, $h^{21} \geq 0$. 
Axions in IIB string theory

- Cycles can be wrapped by space-time filling D-branes

- Each of these branes gives rise to a gauge theory at low energy
  - Visible sector gauge theory realized by stacks of D7 branes wrapping small 4-cycles
  - Hidden sectors, in particular hidden photons, realized by branes wrapping cycles not intersecting visible sector branes
Axions in IIB string theory

- Each axionic field comes along with a real scalar field – saxion – which is real part of lowest component of chiral superfield,

\[ T_\alpha = \tau_\alpha + i c_\alpha \]

- \( \tau_\alpha \) … Kähler modulus measuring the volume of 4-cycle \( \mathcal{A} \)

- 4D EFT from KK reduction of D-brane action

\[
S_p = \frac{-2\pi}{(2\pi \sqrt{\alpha'})^{p+1}} \left( \int_\Sigma d^{p+1} x e^{-\phi} \sqrt{\det(g + B + 2\pi \alpha' F)} + i \int_\Sigma e^{B + 2\pi \alpha' F} \wedge \sum_q C_q \right)
\]

- \( T_\alpha \) is gauge kinetic function for theory on D7-brane:
  - volume measures gauge coupling, \( \tau_\alpha \sim g^{-2} \)
  - \( c_\alpha \) has axionic coupling, \( \sim c_\alpha F \wedge F \)
Axions in IIB string theory

- 4D effective field theory, cf. Jockers, Louis `05

\[ S \supset -d c_\alpha \frac{K_{\alpha \beta}}{8} \wedge *d c_\beta - \frac{r^{i \alpha} \tau_\alpha}{4\pi M_P} (F_i \wedge *F_i) + \frac{r^{i \alpha} c_\alpha}{4\pi M_P} (F \wedge F), \]

with \( K_{\alpha \beta} \equiv \frac{\partial^2 K}{\partial \tau_\alpha \partial \tau_\beta} \), \( K = -2 \ln \mathcal{V} \), \( r^{i \alpha} \equiv \ell_s^{-4} \int_{D_i} \tilde{\omega}^\alpha \)

- Decay constants and coupling to gauge bosons via canonical normalization of axion and gauge kinetic terms and matching to:

\[ L \supset \frac{1}{2} \partial_\mu a_i \partial^\mu a_i - \frac{g_3^2}{32\pi^2} \left( \theta_0 + C_{i33} \frac{a_i}{f_{a_i}} \right) F_{3,\mu \nu} \tilde{F}_{3}^{\mu \nu} \]

\[ - \frac{g_2^2}{32\pi^2} C_{iWW} \frac{a_i}{f_{a_i}} F_{W,\mu \nu} \tilde{F}_{W}^{\mu \nu} - \frac{g_Y^2}{32\pi^2} C_{iYY} \frac{a_i}{f_{a_i}} F_{Y,\mu \nu} \tilde{F}_{Y}^{\mu \nu} \]
An axiverse - QCD axion plus possibly many ultra-light ALPs whose mass spectrum is logarithmically hierarchical – may naturally arise from strings, cf. Arvanitaki et al. `09

Challenges to obtain an axiverse:

- Only axions which are not projected out by orientifold projection appear in LE EFT
- Only axions which do not get too heavy by Kähler moduli stabilisation can be candidates for QCD axion and other light ALPs, cf. Conlon `06
- Only axions which are not eaten by Stückelberg mechanism to give masses to brane-localized anomalous U(1) gauge bosons will appear in LE EFT

Acharya, Bobkov, Kumar `11: Moduli stabilisation via single non-perturbative correction to superpotential (cf. Bobkov,Braun, Kumar, Raby `10) fixes all Kähler moduli plus one axion combination: axiverse with $W_0 \ll 1$ and $f_a \sim 10^{16}$ GeV

Cicoli, Goodsell, AR, 1206.0819: Moduli stabilisation of the so-called LARGE Volume Scenario (LVS) which exploits both perturbative and non-perturbative effects to fix Kähler moduli gives rise to an axiverse with $W_0 \sim 1$ and $f_a \sim 10^{10}$ GeV
Strategy to fix moduli in LVS:
(cf. Cicoli, Mayrhofer, Valandro ‘11)

- Exploit del Pezzo four-cycle supporting single non-perturbative effect; dP modulus fixed at small size, dP saxion and axion heavy; interplay with leading order alpha’ correction yields exponentially large CY volume

- Visible sector with chirality built by wrapping magnetised D7-branes around rigid but not del Pezzo four cycles; D-term conditions stabilise d combinations of Kähler moduli, leaving

  \[ n_{\text{ax}} \equiv h^{1,1} - 1 - d \geq 1 \]

  flat directions; latter fixed by pert. corrections

- LVS requires \( n_{\text{ax}} \geq 2 \): one of the remaining cycles should be small to obtain correct value of 

  \[ g_{\text{vs}}^2 \sim \frac{1}{\tau_{\text{vs}}} \],

  while there should be at least one further which can be large; latter fixed at

  \[ V \sim \tau_b^{3/2} \sim W_0 e^{2\pi \tau_{dP}} \]

More on this: talk by Michele Cicoli
LVS axiverse

Mass scales for \( g_s \sim 0.1, W_0 \sim 1, \mathcal{V} \sim 10^{14} \): 

\[
M_s \sim \frac{M_P}{\sqrt{4\pi \mathcal{V}}} \sim 10^{10} \text{ GeV}
\]

\[
m_{\tau s} \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{10} \text{ GeV}
\]

\[
m_{\tau dP} \sim \frac{M_P}{\mathcal{V}} \ln \mathcal{V} \sim 30 \text{ TeV}
\]

\[
m_{3/2} \sim \sqrt{g_s/(4\pi)W_0} \frac{M_P}{\mathcal{V}} \sim 1 \text{ TeV}
\]

\[
m_{\tau vs} \sim \alpha_{vs} m_{3/2} \sim 40 \text{ GeV}
\]

\[
m_{\tau b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 0.1 \text{ MeV}
\]

- No cosmological moduli problem since \( \tau_b \) diluted by entropy production due to decay of \( \tau_{vs} \) reheating universe to \( O(\text{GeV}) \)
Scaling of axion decay constants and couplings:

\[ f_{ab} = \frac{\sqrt{3}}{4\pi} \frac{M_P}{\tau_b} \sim \frac{M_P}{4\pi \mathcal{V}^{2/3}} \sim \frac{M_{10D}}{4\pi}, \quad f_{as} = \frac{1}{\sqrt{6}} \frac{(2\tau_s)^{1/4}}{4\pi \sqrt{\mathcal{V}}} \sim \frac{M_s}{\sqrt{4\pi \tau_s^{1/4}}}, \]

\[ C_{bbb} \sim g_{b}^{-2} \frac{f_{ab}}{M_P} \sim \mathcal{O}(1), \quad C_{sbb} \sim g_{b}^{-2} \frac{f_{as} \tau_s^{3/4}}{\mathcal{V}^{1/2} M_P} \sim \mathcal{O}(\epsilon) \sim \mathcal{O}\left(\mathcal{V}^{-1/3}\right), \]

\[ C_{bss} \sim g_{s}^{-2} \frac{f_{ab}}{M_P} \sim \mathcal{O}(\epsilon^2) \sim \mathcal{O}\left(\mathcal{V}^{-2/3}\right), \quad C_{sss} \sim g_{s}^{-2} \frac{f_{as}}{\tau_s^{3/4} M_s} \sim \mathcal{O}(1). \]

- **a_{VS}**: QCD axion with \( f_{a_{VS}} \sim f_{a_s} \sim 10^{10} \text{ GeV} \)
- **a_{b}**: essentially massless ALP with \( f_{ab} \sim 10^{8} \text{ GeV} \), but nearly decoupled, \( C_{bss} \sim 10^{-10} \)
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\]

- \(a_{VS}\): QCD axion with \(f_{avs} \sim f_{as} \sim 10^{10} \text{ GeV}\)
- \(a_{b}\): essentially massless ALP with \(f_{ab} \sim 10^8 \text{ GeV}\), but nearly decoupled, \(C_{bss} \sim 10^{-10}\)
- Possibly more ultralight, \(m_{ab} \ll m_a\), ALPs with \(f_{as} \sim 10^{10} \text{ GeV}\), \(C_{sss} \sim 1\)
Axion and ALPs with intermediate scale decay constant?

- Current limits and possible hints from astrophysics and cosmology:
Hints for axion or ALP effects in propagation of TeV photons through universe?

- TeV photons of distant Active Galactic Nuclei (AGN) should feature absorption breaks due to electron-positron pairproduction on the Extragalactic Background Light (EBL)
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  - 50 spectra (HESS, MAGIC, Veritas), assumption: minimal EBL; absorption ruled out by more than 4 sigma.
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> Possible explanation: Photon <-> ALP conversion in astrophysical magnetic fields (Roncadelli et al., Sanchez-Conde et al.)

$$P(a \leftrightarrow \gamma) = 4 \frac{(g_a \gamma \omega B)^2}{m_a^4} \sin^2 \left( \frac{m_a^2}{4\omega} L_B \right)$$
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➢ Has to be an ALP: too light for a QCD axion with such a decay constant.

\[ g_{i\gamma} \equiv \frac{\alpha C_{i\gamma}}{2\pi f_{a_i}} = 10^{-12} \div 10^{-11} \text{GeV}^{-1} \]

\[ \Rightarrow \frac{f_{a_i}}{C_{i\gamma}} \simeq 10^8 \div 10^9 \text{GeV} \]

for \( m_{a_i} \lesssim \text{neV} \)
Hint for axion/ALP-production in white dwarfs?

- Non-standard energy-loss mechanism in white dwarfs, cf. Isern et al.

- Compatible with axion or ALP production in electron-bremsstrahlung

\[ g_{ie} \equiv \frac{C_{ie} m_e}{f_{ai}} = (2.0 \div 7.0) \times 10^{-13} \]

\[ \rightarrow \frac{f_{ai}}{C_{i,e}} \simeq (0.7 \div 2.6) \times 10^9 \text{ GeV} \]

for \( m_{ai} \lesssim \text{keV} \)
Can we explain these hints within IIB axiverse?

- Anomalous transparency of universe and anomalous energy loss of white dwarfs could be explained by

\[ \frac{C_{i\gamma}}{C_{ie}} \sim 10, \quad \frac{f_{a_i}}{C_{i\gamma}} \sim 10^8 \text{ GeV}, \quad m_{\text{ALP}} \lesssim 10^{-9} \div 10^{-10} \text{ eV.} \]

- Model where visible sector build from intersecting branes in geometric regime

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

- Yields required values for \( m_{3/2} = 10 \text{ TeV}, \ g_s \simeq 0.1 \) and \( W_0 \sim 10 \).

- ALP mass could be generated by single Kähler potential instanton, e.g.

\( m_{\text{ALP}} \sim m_{3/2} e^{-\pi \tau_*} \sim 10^{-10} \text{ eV} \) requires

\[ \tau_* \sim \frac{1}{\pi} \ln \left( \frac{g_s m_{3/2}}{m_{\text{ALP}}} \right) \sim 16. \]

- Astrophysical hints compatible with intermediate string-scale scenario.
Laboratory probes of axion and ALPs with intermediate scale decay constant?
Search for solar axions and ALPs

- Sun strong source of axions and ALPs
- Helioscope searches for axions/ALPs and HPs

\[ P(a \leftrightarrow \gamma) = 4 \frac{(g_a \gamma \omega B)^2}{m_a^4} \sin^2 \left( \frac{m_a^2}{4 \omega L_B} \right) \]
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- CAST ... CERN Axion Solar Telescope
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- CAST … CERN Axion Solar Telescope
- IAXO … International Axion Observatory (under investigation)
Search for solar axions and ALPs

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Search for ALPs via light-shining-through-walls

- ALPs can pass walls
- Light-shining-through-walls experiments: (here ALPS (@DESY)):
Search for ALPs via light-shining-through-walls

ALPS:

- HERA dipole (8.4 m, 5 T)
- Primary laser: enhanced LIGO laser (1064 nm, 35 W)
- Frequency doubled: 523 nm
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**ALPS-II plans (2016+):**
- 12 + 12 HERA dipoles
- Increased power build-up (~5000)
- Cavity also on regeneration part
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> Similar plans also at Fermilab (REAPR)
Summary and conclusions

- String phenomenology holds the promise of an axiverse – the QCD axion plus a (possibly large) number of further ultralight axion-like particles, possibly populating each decade of mass down to the Hubble scale.

- Promise fulfilled in LARGE Volume Scenario of IIB string compactifications.

- Models that exhibit a QCD axion with an intermediate-scale decay constant and additional even lighter axion-like particles having the same decay constant and coupling to the photon can explain astrophysical anomalies and be tested in the next generation of helioscopes and light-shining-through-walls experiments.

- Cosmology of LVS axiverse still to be investigated in detail.
Backup: Hidden photons

Graph showing different regions:
- Non-zero FI-term
- Dark Forces
- Stückelberg anisotropic
- KK anisotropic
- Hidden CMB

Axes:
- $\log_{10} \lambda$ vs $\log_{10} m_\gamma$ [eV]
Backup: Hidden photons
Backup: More probes of ultralight axions and ALPs

cf. Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell `09