Ultralight Axion-Like Particles from Strings.

Andreas Ringwald (DESY)

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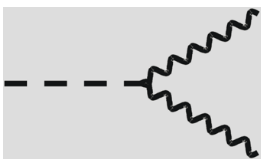
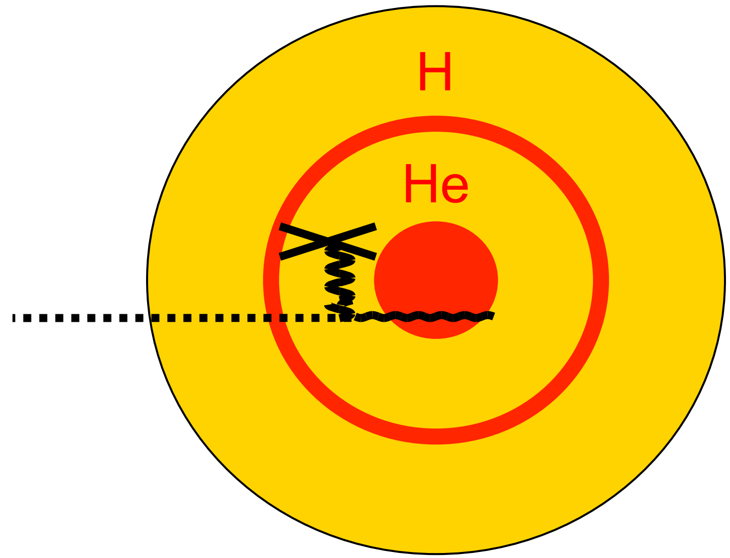
Hints for intermediate scale axion-like particles

- Number of astro hints pointing to existence of intermediate scale axion-like particles (ALPs) = ultralight pseudo-scalars (pseudo Nambu-Goldstone bosons) coupling to photons:



$$\mathcal{L} \supset -\frac{1}{4}\, g_{a\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



  - Energy losses of helium burning stars

$$g_{a\gamma} \equiv \frac{\alpha\, C_{a\gamma}}{2\pi\, f_a} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\ \mathrm{GeV}^{-1}$$

[Ayala et al. 14]

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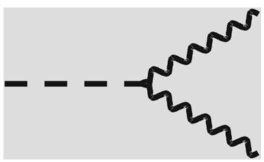

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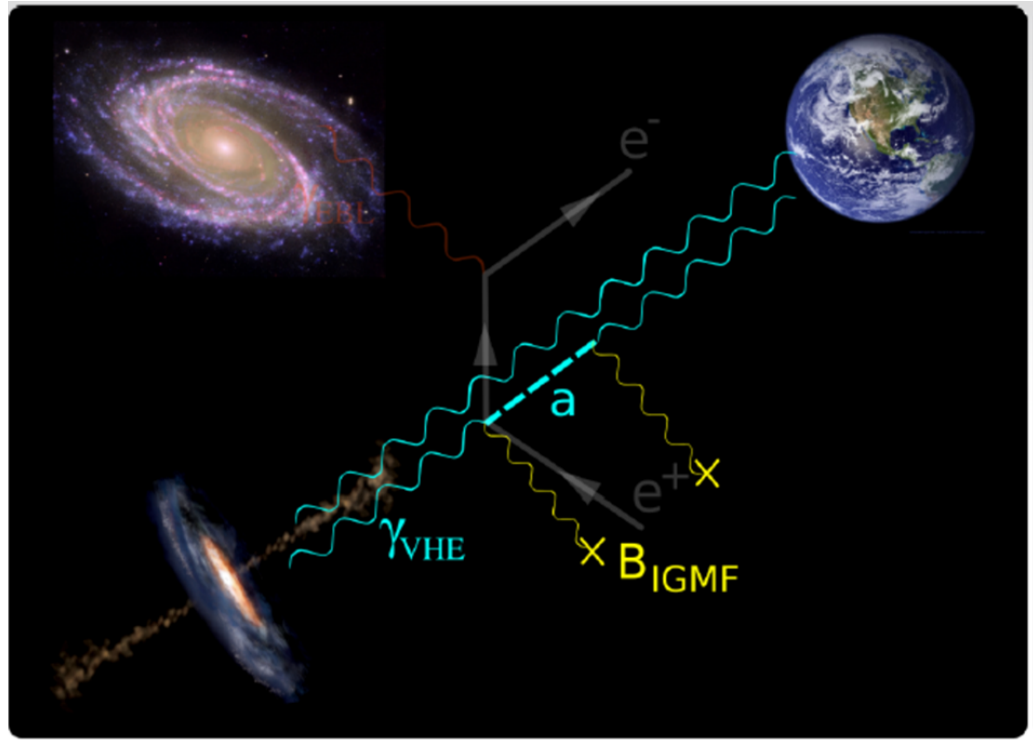

[Meyer]

  - Energy losses of helium burning stars
  - Cosmic transparency for VHE photons

  [Roncadelli et al.;...;Horns,Meyer ...]

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma\gamma}}{f_a} \gtrsim 10^{-12}\ \mathrm{GeV}^{-1}$$

$$f_a \lesssim 10^9\,\mathrm{GeV} \times C_{a\gamma\gamma}$$

$$m_a \lesssim 10^{-7}\ \mathrm{eV}$$

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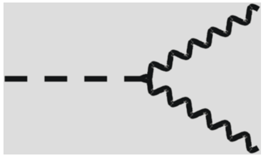

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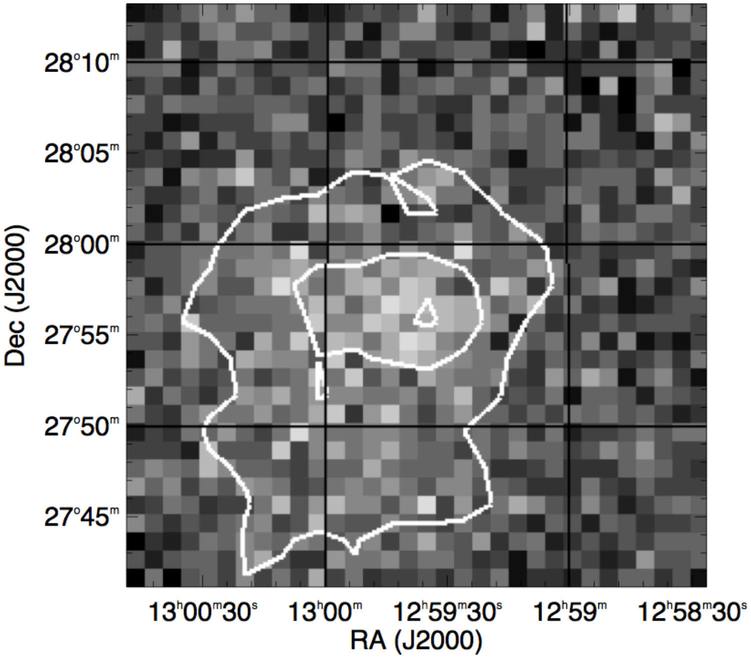

[Boyer et al., Soft excess in Coma as observed by EUVE `04]

  - Energy losses of helium burning stars
  - Cosmic transparency for VHE photons
  - Dark radiation and soft X-ray excesses from clusters
    [Conlon et al. ...]

$$g_{a\gamma\gamma} \gtrsim \sqrt{0.5/\triangle N_{\rm eff}} \times 1.4 \times 10^{-13}\,{\rm GeV}^{-1}$$

$$\text{for} \quad m_a \lesssim 10^{-12}\,{\rm eV}$$

Hints for intermediate scale axion-like particles

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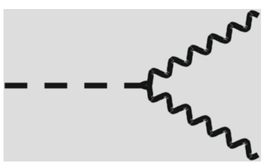

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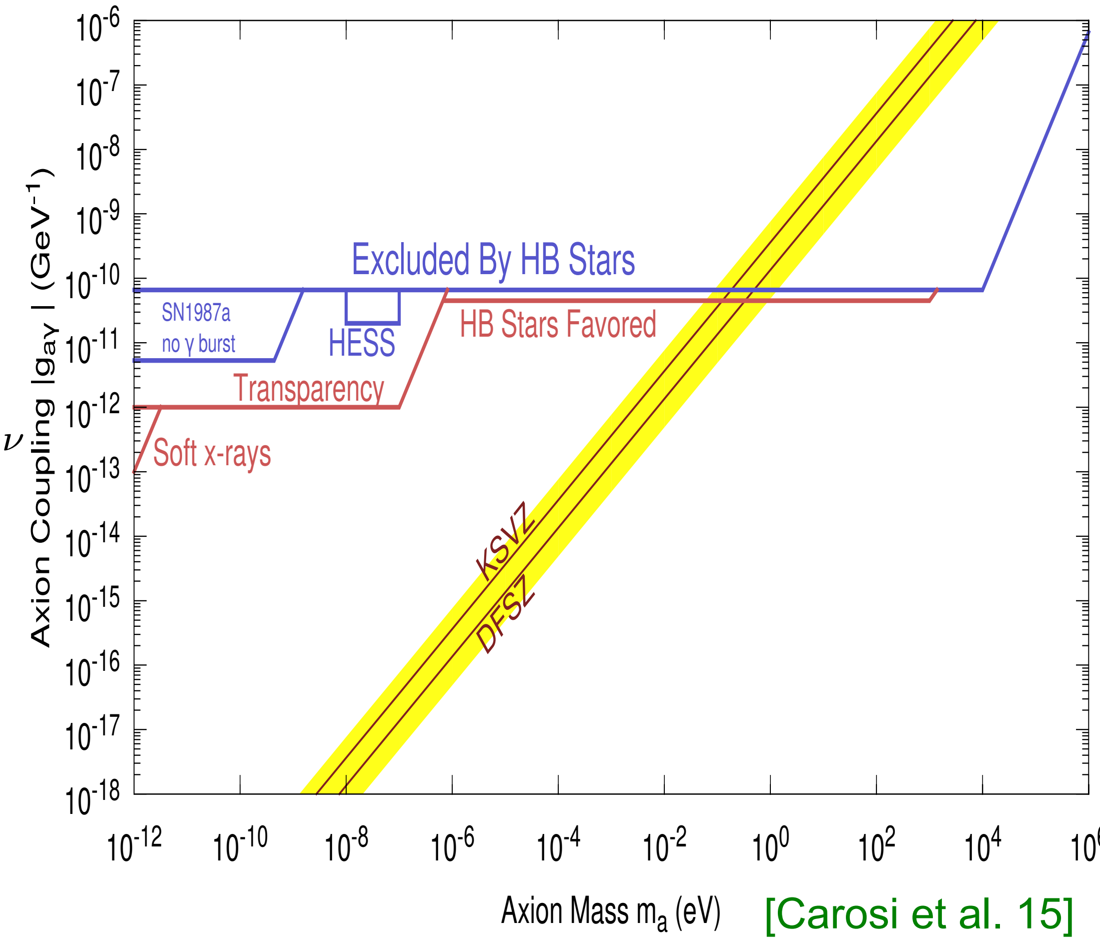
  - Energy losses of helium burning stars
  - Cosmic transparency for VHE photons
  - Dark radiation and soft X-ray excesses from clusters

- Suggest existence of 1-2 ALPs:



[Carosi et al. 15]

UV completions yielding intermediate scale axion/ALPs

- Ad-hoc UV completions: [Peccei,Quinn `77; Kim `79; Shifman et al. `80; Dine et al. `81; ...]

  Add one/more hidden complex scalar fields to the SM, whose vevs v_i break global anomalous chiral $U(1)_{\mathrm{PQ}_i}$ Peccei-Quinn symmetries,

$$\sigma_i(x) = \frac{1}{\sqrt{2}}\left[v_i + \rho_i(x)\right] e^{i a_i'(x)/f_{a_i'}}$$

  At energies much below the symmetry breaking scales v_i, the low-energy effective field is that of Nambu-Goldstone bosons,

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a_i'\,\partial^\mu a_i' - \frac{\alpha_s}{8\pi}\left(\sum_{i=1}^{n_{\mathrm{ax}}} C_{ig}\frac{a_i'}{f_{a_i'}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\left(\sum_{i=1}^{n_{\mathrm{ax}}} C_{i\gamma}\frac{a_i'}{f_{a_i'}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\sum_{i=1}^{n_{\mathrm{ax}}} C_{ie}\frac{\partial_\mu a_i'}{f_{a_i'}}\right)\bar{e}\gamma^\mu\gamma_5 e$$

  with decay constants $f_{a_i'} = v_i$, which can be chosen ad hoc at intermediate scales. The axionic couplings C_{ij} to SM gauge bosons arise due fermionic SM-SM-$U(1)_{\mathrm{PQ}_i}$ chiral triangle anomalies and depend on the particular PQ charge assignments of the fermions in the model, e.g.

  KSVZ: all SM fermions have no PQ charge; one vector-like extra color triplet with chiral PQ assignment:

$$C_{a'g} = 1\,, \qquad C_{a'\gamma} = 6\left(C_{\mathrm{em}}^{(Q)}\right)^2\,, \qquad C_{a'e} = 0$$

  DFSZ: two Higgs doublets H_u, H_d; SM fermions have PQ charge; no extra fermion:

$$C_{a'g} = 6, \qquad C_{a'\gamma} = 16, \qquad C_{a'e} = 2\sin^2\beta$$

UV completions yielding intermediate scale axion/ALPs

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a_i'\,\partial^\mu a_i' - \frac{\alpha_s}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{ig}\frac{a_i'}{f_{a_i'}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{i\gamma}\frac{a_i'}{f_{a_i'}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\sum_{i=1}^{n_{\rm ax}} C_{ie}\frac{\partial_\mu a_i'}{f_{a_i'}}\right)\bar{e}\gamma^\mu\gamma_5 e$$

The proper QCD axion solving the strong CP problem is the linear combination

$$\frac{A}{f_A} \equiv \sum_{i=1}^{n_{\rm ax}} C_{ig}\frac{a_i'}{f_{a_i'}}$$

The ALPs are living in the space perpendicular to the axion. They are still Nambu-Goldstone bosons and do not couple to gluons. E.g. in case with two axion-like fields,

$$\frac{A}{f_A} = C_{1g}\frac{a_1'}{f_{a_1'}} + C_{2g}\frac{a_2'}{f_{a_2'}}, \qquad \frac{a}{f_a} = -C_{2g}\frac{a_1'}{f_{a_2'}} + C_{1g}\frac{a_2'}{f_{a_1'}},$$

with normalization

$$\frac{1}{f_A^2} = \frac{1}{f_a^2} = \left(\frac{C_{1g}}{f_{a_1'}}\right)^2 + \left(\frac{C_{2g}}{f_{a_2'}}\right)^2$$

UV completions yielding intermediate scale axion/ALPs

> Drawbacks of these ad hoc models:

1. Hidden complex scalars introduced by hand
2. PQ symmetries introduced by hand
3. PQ symmetry breaking scales introduced by hand
4. Axion/ALPs not protected from explicit symmetry breaking effects due to higher dimensional operators

$$\mathcal{L} \supset \frac{1}{M_{\rm Pl}^{D-4}} \mathcal{O}_D \sim \sigma_1^n \sigma_2^k , \qquad D = n + k > 4$$

modifying their potential, potentially shifting their minima away from zero

- Can be disastrous for the axionic solution of the strong CP problem: need to require

$$D \gtrsim \frac{9}{[1 - 0.1 \cdot \log(f_A / 10^9\,{\rm GeV})]}$$

- Can make axion/ALPs too massive,

$$m_{12}^{(n,k)} \sim v_1^{(n-1)/2} v_2^{(k-1)/2} / M_{\rm Pl}^{(D-4)/2}$$

> ALPs from strings automatically avoid these drawbacks

- Accidental axion and ALPs in heterotic orbifold
- Closed string axion and ALPs in IIB string theory

Accidental ALPs in heterotic orbifold compactifications

1. Plenitude of hidden complex scalar fields in orbifold compactifications
2. Multitude of discrete symmetries which are exact at perturbative level
   - R-symmetries from the broken SO(6) symmetry of compact space
   - Stringy discrete symmetries from joining and splitting of strings
3. PQ symmetries can occur in the low-energy EFT as accidental remnants of these discrete symmetries, that is the discrete symmetries forbid explicit PQ symmetry violating operators up to a certain mass dimension in low-energy effective Lagrangian
   [Choi,Kim,Kim 07; Choi,Nilles,Ramos-Sanchez,Vaudrevange 09]
4. Axion/ALP mass protected if discrete symmetries large

Accidental ALPs in heterotic orbifold compactifications

> Ad-hoc example: (DFSZ x KVSZ)-like model featuring $Z_{13} \otimes Z_5 \otimes Z_5'$ sym.

ψ_i	q_L	u_R	d_R	L	N_R	l_R	H_u	H_d	H_l	H_N	σ_2	T	Q_L	Q_R	σ_1
$\mathbb{Z}_{13}$	ω_{13}^5	ω_{13}^3	ω_{13}^8	ω_{13}^9	ω_{13}^3	ω_{13}^7	ω_{13}^{11}	ω_{13}^{10}	ω_{13}^2	ω_{13}^7	ω_{13}^{12}	ω_{13}^9	1	ω_{13}^6	ω_{13}^7
$\mathbb{Z}_5$	1	ω_5	ω_5^4	1	ω_5	ω_5^4	ω_5	ω_5	ω_5	ω_5	1	ω_5^2	ω_5	ω_5^3	ω_5^3
$\mathbb{Z}_5'$	1	ω_5^4	1	1	ω_5^2	ω_5^4	ω_5^4	1	ω_5	ω_5^2	ω_5	ω_5^3	1	ω_5^4	ω_5

- Only allowed Yukawa couplings: [Dias,Machado,Nishi,AR,Vaudrevange `14]

$$
\begin{aligned}
\mathcal{L}_Y &= Y_{ij}\overline{q}_{iL}\widetilde{H}_u u_{jR} + \Gamma_{ij}\overline{q}_{iL}H_d d_{jR} + G_{ij}\overline{L}_i H_l l_{jR} \\
&+ F_{ij}\overline{L}_i \widetilde{H}_N N_{jR} + y_{ij}\overline{(N_{iR})^c}\sigma_1 N_{jR} + y_Q \overline{Q}_L \sigma_1 Q_R
\end{aligned}
$$

  - Neutrino see-saw relations
  - No flavour-changing neutral currents, since there is only one Higgs doublet for each type of fermion

- At mass dimension four, model has four accidental global U(1)s:
  - $U(1)_{\mathrm{B}}$, ensuring baryon number conservation of ordinary quarks
  - $U(1)_{\mathrm{Q}}$, ensuring conservation of the number of the exotic color triplet
  - $U(1)_{\mathrm{PQ}_i}$, two Peccei-Quinn symmetries, whose charge assignments can be chosen as

ψ	q_L	u_R	d_R	L	N_R	l_R	H_u	H_d	H_l	H_N	σ_2	T	Q_L	Q_R	σ_1
K_ψ	0	0	0	$-1/2$	$-1/2$	$-1/2$	0	0	0	0	0	0	$1/2$	$-1/2$	1
X_ψ	0	$-X_u$	$-X_d$	$\frac{1}{3}(4X_u+X_d)$	0	$2X_u$	$-X_u$	X_d	$-\frac{1}{3}(2X_u-X_d)$	$-\frac{1}{3}(4X_u+X_d)$	1	$-2X_u$	0	0	0

Accidental ALPs in heterotic orbifold compactifications

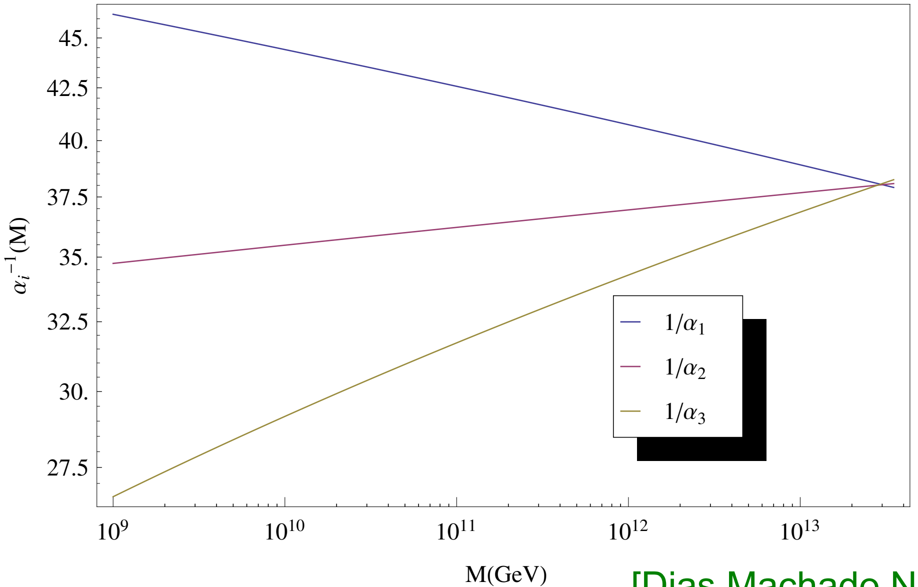
- Lowest dimensional operators respecting discrete symmetry, but breaking PQ symmetries, have mass dimension 14 or higher,

$$\frac{1}{M_{\rm Pl}^{10}} H_N^\dagger H_d \sigma_1^{*5} \sigma_2^7 \,, \quad \frac{1}{M_{\rm Pl}^{11}} H_l^\dagger H_u \sigma_1^5 \sigma_2^{*8} \,, \quad \frac{1}{M_{\rm Pl}^{11}} H_N^\dagger H_u \sigma_1^{*5} \sigma_2^8$$

inducing masses

$$\delta m_A \sim m_a \sim \frac{v\ v_1^{5/2} v_2^{7/2}}{2^6 M_{\rm Pl}^5 f_A} \sim 10^{-21}\ {\rm eV}\,, \qquad {\rm for}\quad v_1 \sim v_2 \sim f_A \sim 10^{13}\ {\rm GeV}$$

- Model has gauge coupling unification close to intermediate scale, $M_{\rm U} \sim 10^{13}\,{\rm GeV}$



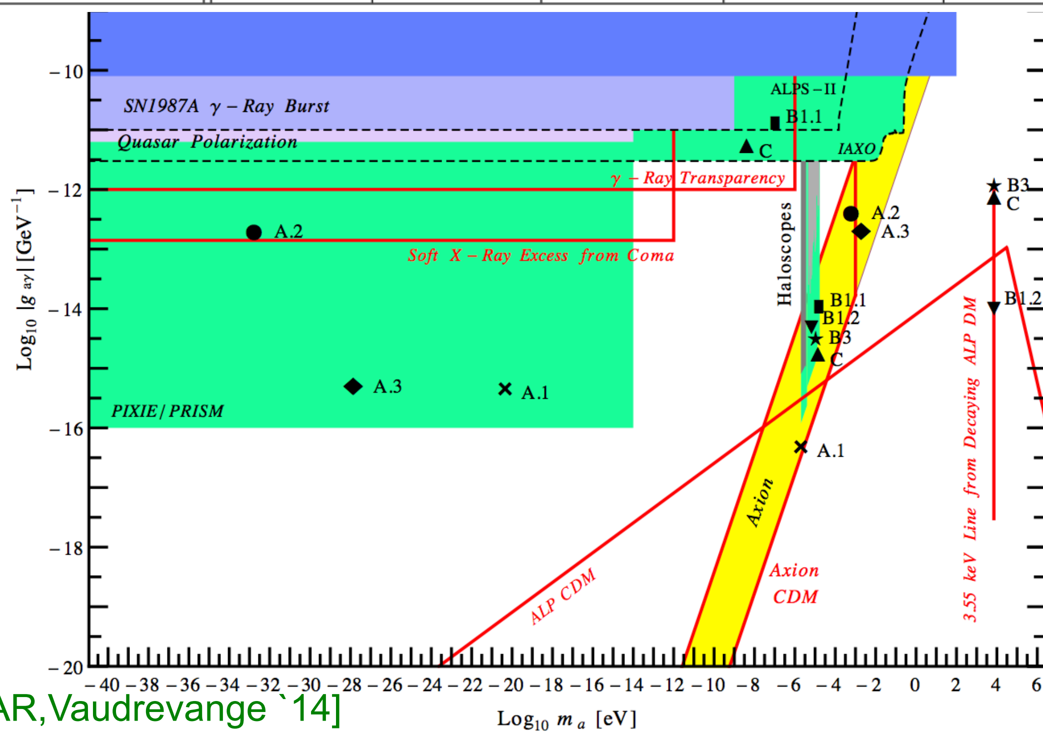
[Dias,Machado,Nishi,AR,Vaudrevange `14]

- Can be embedded in non-minimal SU(5) GUT [Dias,Franco,Pleitez 07]
- Proton stabilized since SU(5) multiplets involve beyond SM exotics and due to discrete symmetry

Accidental ALPs in heterotic orbifold compactifications

> For intermediate scales, models have axion plus ALP in astro range:

Model	Input values		Resulting low-energy parameters						
	$v_1 = f_{a'_1}$ [GeV]	$v_2 = f_{a'_2}$ [GeV]	f_A [GeV]	m_A [eV]	m_a [eV]	$\lvert g_{A\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{a\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{Ae}\rvert$	$\lvert g_{ae}\rvert$
A.1	1×10^{13}	2.5×10^{12}	8.3×10^{11}	7.2×10^{-6}	1.3×10^{-22}	8.2×10^{-16}	5.4×10^{-16}	2×10^{-16}	1.7×10^{-17}
A.2	1×10^{10}	7.5×10^{10}	9.3×10^{9}	6×10^{-4}	1.8×10^{-33}	4×10^{-13}	2×10^{-13}	2.5×10^{-15}	6.3×10^{-15}
A.3	1×10^{13}	1×10^{10}	3×10^{9}	2×10^{-3}	1×10^{-28}	2×10^{-13}	5×10^{-16}	5×10^{-14}	2×10^{-17}
B1.1	3×10^{11}	1×10^{9}	3×10^{11}	2×10^{-5}	1×10^{-7}	1.6×10^{-14}	1.4×10^{-11}	0	1×10^{-12}
B1.2	9×10^{11}	1.26×10^{12}	9×10^{11}	6.7×10^{-6}	7.1×10^{3}	5.2×10^{-15}	1.1×10^{-14}	0	8×10^{-16}
B3	1.1×10^{12}	1.84×10^{9}	5.5×10^{11}	1.1×10^{-5}	7.1×10^{3}	3.4×10^{-15}	1.3×10^{-12}	0	0

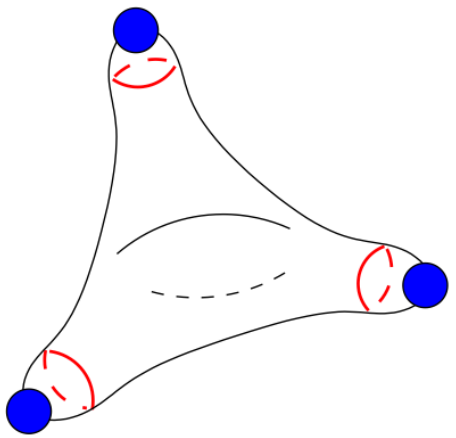


[Dias,Machado,Nishi,AR,Vaudrevange `14]

Accidental ALPs in heterotic orbifold compactifications

> Mini-landscape of 348 MSSM-like models in Z6-II orbifold compactifications [Nilles,Vaudrevange1403.1597]

- SM gauge group
- 3 generations of quarks and leptons
- 1 (or more) Higgs pairs
- Further exotics: vector-like under SM gauge group
- O(100) hidden (SM singlet) complex scalars



> Ongoing search for accidental ALPs [Kim,Nilles,AR,Vaudrevange in prep.]

- Created all terms in superpotential up to order 6 in fields respecting discrete sym.:
  - $\mathbb{Z}_6 \times \mathbb{Z}_3 \times \mathbb{Z}_2 \times \mathbb{Z}_2$ from strings splitting and joining
  - $\mathbb{Z}_{36}^R \times \mathbb{Z}_{18}^R \times \mathbb{Z}_4^R$ from broken SO(6) Lorentz symmetry of compact space [Nilles et al. 1308.3435; Cabo Bizet et al. 1308.5669]

Accidental ALPs in heterotic orbifold compactifications

- Determined the accidental $U(1)_{\rm global}$ symmetries: found models with many of them, up to O(100)

Order in $\mathcal{W}$	# accidental $\mathrm{U}(1)_{\rm global}$ per model
Order(3)	54
Order(4)	4
Order(5)	1
Order(6)	1

- Determine the SM-SM-$U(1)_{\rm global}$ triangle anomalies to find the accidental PQ symmetries and the couplings of the ALPs to SM gauge bosons
- Break $U(1)_{\rm global}$ at intermediate scales and analyze couplings
- Which terms in superpotential break $U(1)_{\rm global}$ explicitly? ALP masses?

Closed string ALPs in string theory

1. Massless bosonic spectrum of closed string sector of string theories in 10D contains form fields satisfying gauge symmetries

MASSLESS SPECTRUM OF STRING THEORIES				
THEORY	DIMENSION	SUPERCHARGES	BOSONIC SPECTRUM	
Heterotic $E_8 \times E_8$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ $A_\mu^{i\bar{j}}$ in adjoint representation	
Heterotic $SO(32)$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ $A_\mu^{i\bar{j}}$ in adjoint representation	
Type I $SO(32)$	10	16	NS-NS	$g_{\mu\nu}, \phi$
			$A_\mu^{i\bar{j}}$ in adjoint representation	
			R-R	$C_{(2)}$
Type IIB	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(0)}, C_{(2)}, C_{(4)}$
Type IIA	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(1)}, C_{(3)}$

[Quevedo `02]

2. Symmetries broken by compactification

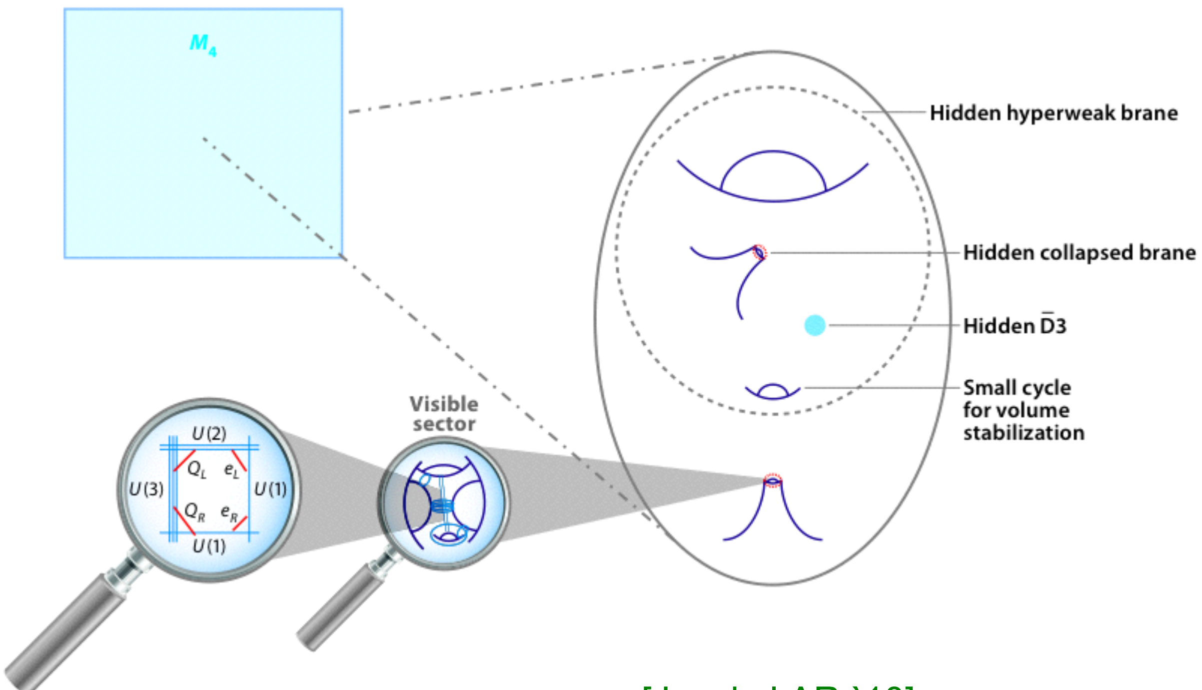
3. Kaluza-Klein decomposition contains ALPs, with decay constants determined by string or compactification scale
[Witten 84; Conlon 06; Svrcek,Witten 06]

4. Shift symmetries only violated through non-perturbative effects

Closed string ALPs in IIB string theory

> Concentrate on IIB case: Realisation of brane-world scenarios

- Visible sector gauge theory realized by stacks of D7 branes wrapping small 4-cycles
- Gravity propagates in the bulk, leading to a string scale $M_s \sim M_P/\sqrt{\mathcal{V}}$ and a KK scale $M_{\rm KK} \sim M_P/\mathcal{V}^{2/3}$ possibly much much smaller than the Planck scale M_P, at the expense of a large compactification volume $\mathcal{V} \gg 1$



[Jaeckel,AR `10]

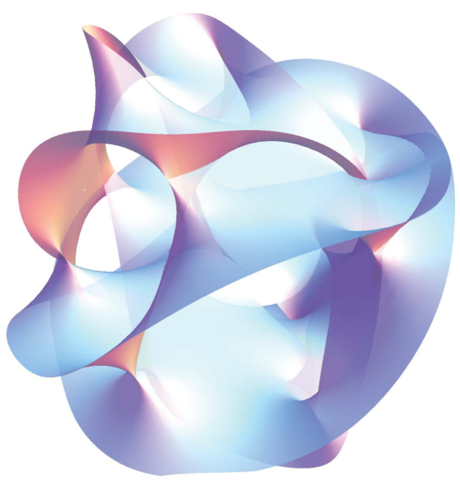
Closed string ALPs in IIB string theory

> KK reduction (expansion in harmonic forms):

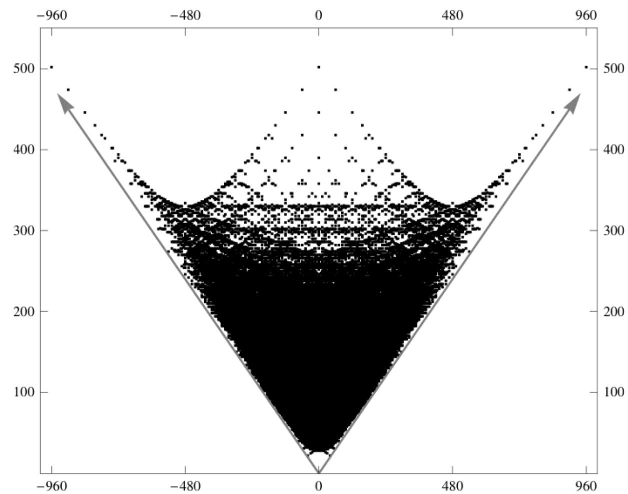
$$C_2 = c^a(x)\omega_a, \quad a = 1, \dots, h_-^{1,1}$$

$$C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \dots, \quad \alpha = 1, \dots, h_+^{1,1}$$

> Number of ALPs determined by topology of CY orientifold: number of topologically non-equivalent 2-cycles or 4-cycles



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



[Kreuzer,Skarke]

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 $h^{11} \geq 0$, $h^{21} \geq 0$.

$$2(h^{1,1} - h^{2,1})$$

> An axiverse may naturally arise from strings [Arvanitaki et al. `09]

Closed string ALPs in IIB string theory

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

$$T_\alpha = \tau_\alpha + i\, c_\alpha$$

- τ_α … Kähler modulus measuring the volume of 4-cycle

> 4D EFT [Jockers, Louis `05]

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

from KK reduction of D-brane action,

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

- volume measures gauge coupling, $\tau_\alpha \sim g^{-2}$
- c_α has axionic coupling, $\sim c_\alpha F \wedge F$

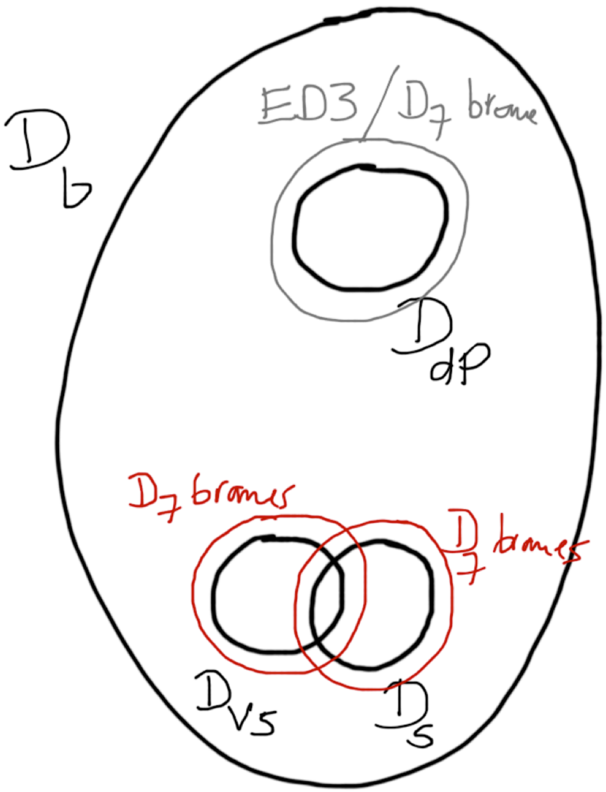
Closed string ALPs in LARGE volume IIB string theory

> LVS requires at least four 4-cyles: [Cicoli et al. `11]

- bulk (large volume) cycle, size fixed perturbatively
- dP cycle, size fixed non-perturbatively
- cycle supporting the stack of branes describing the visible sector, size fixed perturbatively
- cycle supporting a stack of branes providing D-terms to stabilise the volume of the visible cycle

> LVS has at least two light ALPs:
[Cicoli, Goodsell, AR, 1206.0819]

- large volume ALP a'_b with $f_{a'_b} \sim M_{\rm KK} \sim M_P/\mathcal{V}^{2/3}$
small coupling, $C_{b{\rm vs}} \simeq \mathcal{O}\left(\mathcal{V}^{-2/3}\right)$ $\quad m_{a'_b} \sim m_{3/2}\, {\rm e}^{-c\,n\,\tau_b}$
- visible sector ALP $a'_{\rm vs}$ with $f_{a'_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}}$,
$C_{\rm vs\,vs} = \mathcal{O}(1)$ $\quad m_{a'_{\rm vs}} \sim m_{3/2}\, {\rm e}^{-c\,n\,\tau_{\rm vs}}$



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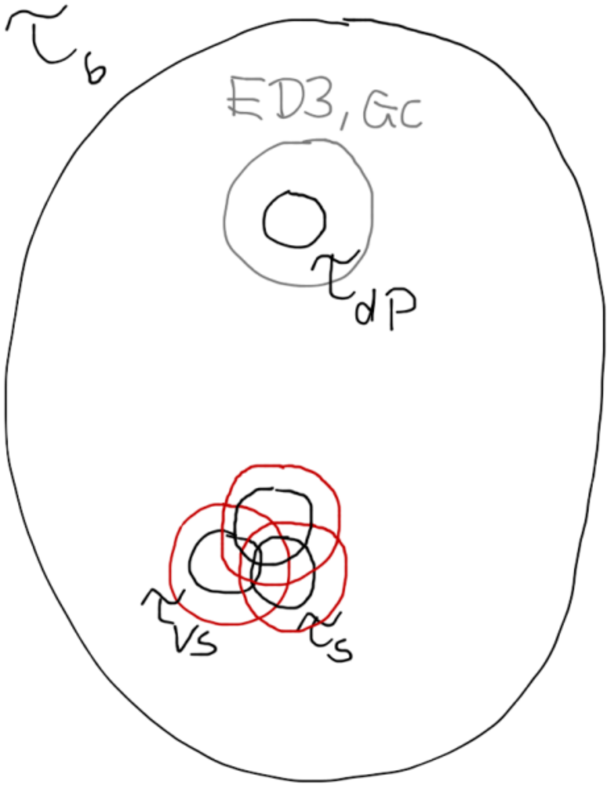
- LVS has at least two light ALPs: [Cicoli, Goodsell, AR, 1206.0819]
  - large volume ALP a'_b with $f_{a'_b} \sim M_{\rm KK} \sim M_P/\mathcal{V}^{2/3}$ small coupling, $C_{b\rm vs} \simeq \mathcal{O}\left(\mathcal{V}^{-2/3}\right)$ $\quad m_{a'_b} \sim m_{3/2}\, \mathrm{e}^{-c\, n\, \tau_b}$
  - visible sector ALP $a'_{\rm vs}$ with $f_{a'_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}}$, $C_{\rm vs\, vs} = \mathcal{O}(1)$ $\qquad m_{a'_{\rm vs}} \sim m_{3/2}\, \mathrm{e}^{-c\, n\, \tau_{\rm vs}}$
- More light ALPs if there are more small cycles intersecting visible sector branes



Closed string ALPs in LARGE volume IIB string theory

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

$$M_s \sim \frac{M_P}{\sqrt{4\pi\mathcal{V}}} \sim 10^{10}\,\mathrm{GeV}$$

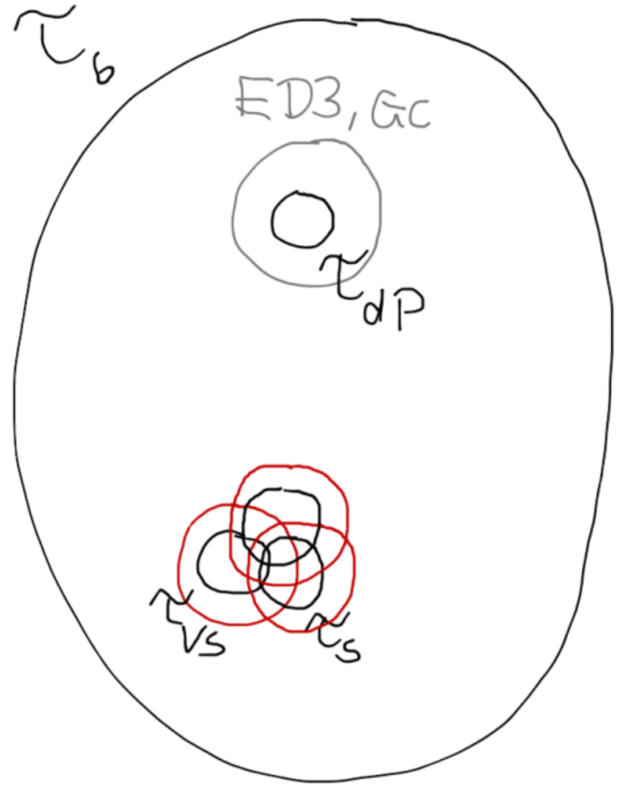
$$m_{\tau_s} \sim \frac{M_P}{\mathcal{V}^{1/2}} \sim 10^{10}\,\mathrm{GeV}$$

$$m_{\tau_{\rm dP}} \sim \frac{M_P}{\mathcal{V}} \ln\mathcal{V} \sim 30\,\mathrm{TeV}$$

$$m_{3/2} \sim \sqrt{g_s/(4\pi)}\, W_0 \frac{M_P}{\mathcal{V}} \sim 1\,\mathrm{TeV}$$

$$m_{\tau_{\rm vs}} \sim \alpha_{\rm vs} m_{3/2} \sim 40\,\mathrm{GeV}$$

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 0.1\,\mathrm{MeV}$$



- 4D EFT of LVS with intermediate string scale may offer ALP explanation of astrophysical hints, since in this scenario naturally more than one ALP with $f_{a'_{\rm vs_i}} \sim M_s \sim 10^{10}\,\mathrm{GeV}$

Summary and conclusions

- 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
- 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 inverse Hubble scale
- Promise fulfilled in orbifold compactifications of the heterotic string and in LARGE Volume Scenario of IIB string compactifications