Intermediate Scale Accidental Axion and ALPs

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Contents

Intermediate Scale for Axions and Axion-Like Particles

Based on:

AD, Machado, Nishi, Ringwald, Vaudrevange, arXiv:1403.5760

Intermediate Scale for Axions and Axion-Like Particles

There are good motivations from particle physics, astrophysics, and cosmology for considering models that lead to effective Lagrangians having light pseudoscalars fields, a_s,

$$\mathcal{L}_a = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a\, F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{g_{ae}}{2}\partial_\mu a\, \bar{e}\gamma^\mu\gamma_5 e$$

- This is a common outcome of theories which have a global $U(1)$ symmetry, broken at the energy scale f_a, by a SM singlet field VEV

  $$\sigma(x) = \frac{1}{\sqrt{2}}\left[v_a + \rho(x)\right] e^{ia(x)/f_a}, \qquad v_a \sim f_a \equiv \text{decay constant}$$

  For a chiral anomalous $U(1)$ the couplings are suppressed by f_a as

  $$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}, \quad g_{ae} = \frac{C_{ae}}{f_a}, \qquad C_{a\gamma}, C_{ae} \sim \mathcal{O}(1) \;\; \text{(from model)}$$

- $U(1)$ exact: $\mathcal{L}_a$ has the shift sym. $a(x) \to a(x) + cte$, and $m_a = 0$, with $a(x)$ being a Nambu-Goldstone Boson (NGB)

- $U(1)$ explicitly broken: $m_a \neq 0$ and $a(x)$ is a pseudo-NGB.

- **Axion-Like Particles (ALPs)** denote particles interacting as in $\mathcal{L}_a$.

Intermediate Scale for Axions and Axion-Like Particles

Axion, $a = A$, is a prominent example of a pseudo NGB in Standard Model UV completions *designed* with a global $U(1)_{PQ}$ *anomalous* chiral sym. spontaneously broken at the scale f_A , for solving the strong CP problem. → $\overline{\theta}$ as a dynamical parameter [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\overline{\theta}\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \rightarrow -\frac{\alpha_s}{8\pi}\frac{A}{f_A} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

with a nonperturbative potential whose minimum leads to CP conservation

$$V(A) \quad \Rightarrow \quad \langle \tfrac{A}{f_A} \rangle = \overline{\theta} = 0, \quad \text{(PQ mechanism)}$$

Limits from neutron e.d.m imply $|\overline{\theta}| \lesssim 10^{-10}$ [Baker et al. 06].

- Viable UV completions with axions are the ones having a singlet $\sigma(x)$ with a large VEV [Kim 79; Shifman et al. 78; Dine et al. 80; Zhitnitski 80]
- Nonperturbative QCD effects explicitly break $U(1)_{PQ}$ leading to a mass that is related to the axion-photon coupling

$$m_A \approx \frac{m_\pi f_\pi}{f_A} \approx 6\times 10^{-6}\text{eV} \times \left(\frac{10^9\text{GeV}}{f_A}\right); \;\; g_{A\gamma} = \frac{\alpha}{2\pi}\frac{C_{A\gamma}}{f_A} \sim 10^{-12}\text{GeV}^{-1}\left(\frac{10^9\text{GeV}}{f_A}\right)$$

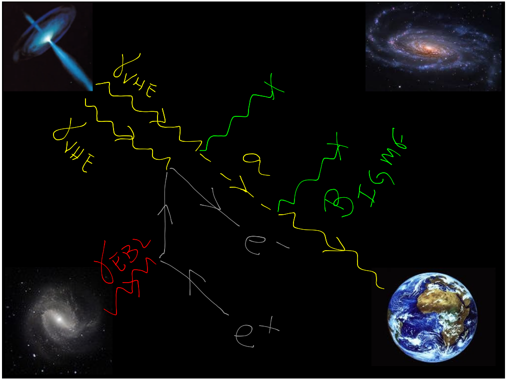
- Interesting **intermediate energy scale** range axions/ALPs is

$$10^9 \text{ GeV} \lesssim f_A, f_a \lesssim 10^{13}\text{GeV} \Rightarrow 10^{-7}\text{eV} \lesssim m_A \lesssim 1\,\text{meV} \quad (\text{SN 1987A}, f_A > 4\times 10^8 \text{ GeV})$$

Motivations for Axion plus ALPs: γ-ray transparency of the Universe

Anomalous transparency of the Universe for very energetic γ-ray [Mirizzi et al; De Angelis et al 07], indicated by AGN spectra.

- AGNs should show an energy and redshift-dependent exponential atenuation $e^{-\tau(E,z)}$, due e^+e^- pair production off the EBL [Fermi-LAT 12; H.E.S.S. 12]. Transparency for large optical depth, $\tau > 2$, [Aharonian et al 07; Aliu et al 08; Essey, Kusenko; Horns, Meyer 12].
- Explanation: γ-rays ↔ a oscillations in the magnetic fields around AGNs, and in the intergalactic medium [De Angelis et al; Simet at al 08; Sanches-Conde et al 09].



- ALP with: $|g_{a\gamma}| \gtrsim 10^{-12}\,\text{GeV}^{-1}$; $m_a \lesssim 10^{-7}\text{eV}$ [Horns, Meyer, Raue 13].

Motivations for ALPs: X-ray line signal at 3.55 keV and Soft X-ray excess from Coma cluster

Observation of a X-ray line signal at **3.55 keV** in the stacked spectrum of a number of galaxy clusters [Bulbul et al 14], and in Andromeda galaxy and Perseus cluster [Boyarsky et al 14].

- A possible interpretation for the new line is an ALPs decaying into photons $a \to \gamma + \gamma$ [Higaki et al. 14; Jaeckel et al 14].

$$m_a \backsimeq 7.1\,\mathrm{keV}$$

$$10^{-18}\mathrm{GeV}^{-1}\sqrt{\frac{1}{x_a}} \lesssim |g_{a\gamma}| \lesssim 10^{-12}\mathrm{GeV}^{-1}\sqrt{\frac{10^{-10}}{x_a}}, \quad x_a \equiv \frac{\rho_a}{\rho_{DM}}$$

Soft X-ray excess from Coma cluster observed [Lieu et al 96].

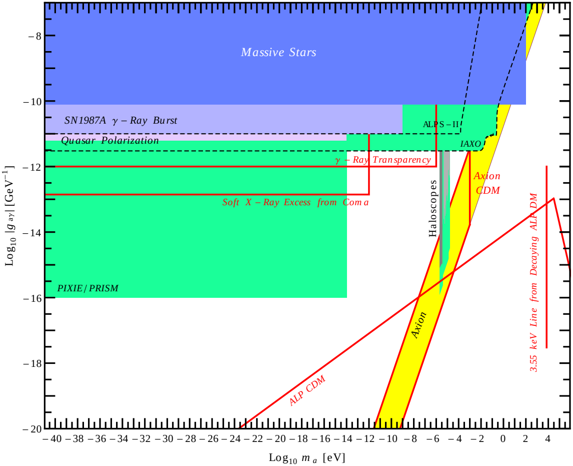
- May be explained by the conversion of a cosmic ALP background radiation into photons in the cluster magnetic field explained if [Conlon, Marsh 13; Angus et al 13]

$$|g_{a\gamma}| \gtrsim 10^{-13}\mathrm{GeV}^{-1}\sqrt{0.5/\Delta N_{eff}}\,; \quad m_a \lesssim 10^{-12}\mathrm{eV}$$

$\Delta N_{eff} \sim 0.5$ is the extra neutrinos species.

Summary of motivations for developing models with axion plus ALPs

Limits/projected explorations, and favorable regions on $g_{a\gamma} \times m_a$ suggesting that more than one ALP with intermediate scales may exist.



[AD, Machado, Nishi, Ringwald, Vaudrevange, 1403.5760]

Projected sensitivities of: ALPS-II; helioscope IAXO; haloscope ADMX and ADMX-HF; and PIXIE/PRISM cosmic background observatories.

UV completions leading to intermediate scale axion/ALPs

Based on the previous phenomena we consider SM extensions with anomalous chiral $U(1)_{PQ_i}$ PQ symmetries broken by $\langle \sigma_i(x) \rangle$

$$SM \otimes U(1)_{PQ_1} \otimes U(1)_{PQ_2} \otimes ..., \quad \sigma_i(x) = \frac{1}{\sqrt{2}} [v_i + \rho_i(x)] e^{ia'_i(x)/f_{a'_i}}$$

At low energies ($\ll v_i \sim f_{a'_i}$) the effective field theory have pseudo-NGBs interacting with gluons, photons, and matter fields,

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a'_i \partial^\mu a'_i - \sum_{ij}^{n_{ax}} m_{ij} a'_i a'_j - \frac{\alpha_s}{8\pi} \left(\sum_i^{n_{ax}} C_{ig} \frac{a'_i}{f_{a'_i}} \right) G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} \left(\sum_i^{n_{ax}} C_{i\gamma} \frac{a'_i}{f_{a'_i}} \right) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Taking into account field theory some questions have to be posed:

1- It is artificial to impose anomalous symmetries like $U(1)_{PQ_i}$. Global symmetries should be *accidental*, arising from an extra principle.

2- It is needed to guarantee that corrections do not lead to $\delta\overline{\theta} > 10^{-10}$.

3- Small masses m_{a_s} for the ALPs need to be generated and protected from destabilization due to operators breaking $U(1)_{PQ_i}$.

Stabilization of the intermediate scale axion/ALPs

No reason to believe gravitational interactions preserve global symmetries. Focusing on models with two singlets, for $U(1)_{PQ_i}$ higher dim. operators

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

modifies the potential, destabilizing the solution of the strong CP problem unless [Ghigna et al.; Holman et al.; Kamionkowski et al. 92; Kallosh et al. 95]

$$D \gtrsim \frac{9}{1 - 0.1 \log\left(\frac{f_A}{10^9 \mathrm{GeV}}\right)} \quad \Rightarrow \quad \overline{\theta} + \delta\theta_g = |\langle A \rangle / f_A| < 10^{-10}$$

Excessively large mass for the axion/ALP may be induced, spoiling their role in interesting phenomena

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

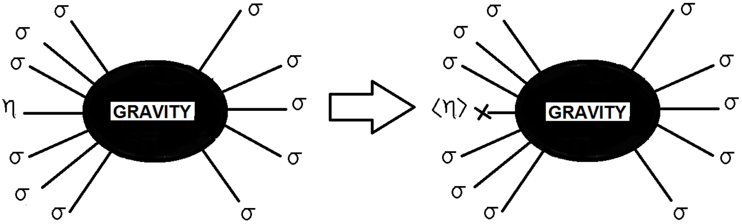
- If only sufficiently high order operators contribute, strong CP problem sol. maintained and interesting ALP masses induced.
- Discrete Z_N symmetries are useful for these purposes.

Stabilization of the Intermediate Scale Axion/ALPs: Z_N Symmetries

Discrete symmetries such as Z_N may be remnants of broken local sym.

$$\mathcal{U}(1) \to Z_N \equiv e^{i2\pi k/N}, \qquad k = 0, 1, \ldots, N-1$$

Such *"discrete gauge symmetries"* might be respected by gravitational interactions. Local symmetries can masquerade as Z_N to an observer having only low energy probes [Krauss, Wilczek 89; Coleman et al. 92].



$$O_{N+1} \equiv \frac{\eta(x)\,\sigma(x)^N}{M_{Pl}^{N-3}} \qquad \Longrightarrow \qquad O_N \equiv \frac{\langle\eta\rangle}{M_{Pl}^{N-3}}\sigma(x)^N$$

Being O_{N+1} invariant under $\mathcal{U}(1)$, O_N, and all other interactions below the scale $\langle\eta\rangle$, will be invariant by Z_N.

UV completions leading to intermediate scale axion/ALPs

We consider UV completions of the SM which are models having a set of discrete Z_N symmetries

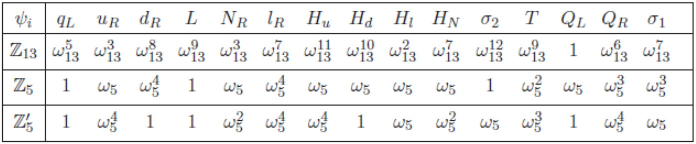
$$\mathrm{SM} \otimes Z_N \otimes Z_M \otimes Z_P$$

- The main characteristics are:
    1. $U(1)_{PQ_i}$ sym. are quasi exact and accidental at low energies.
    2. All dangerous nonrenormalizable operators which explicitly violate the $U(1)_{PQ_i}$ and destabilize the axion/ALP are forbidden by the Z_N factors.
    3. The allowed operators suppressed by M_{Pl} generate the appropriate masses for the ALPs.

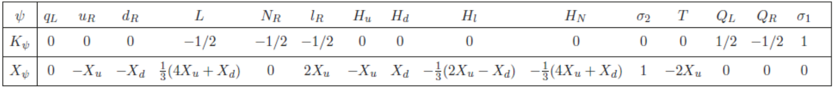
$Z_{13} \otimes Z_5 \otimes Z_5'$ model with two pseudo Nambu-Goldstone bosons.

A (DFSZ × KSVZ)-like model with accidental $U(1)_{PQ_1} \otimes U(1)_{PQ_2}$

- BSM: 4 Higgs doublets H_b, a scalar triplet T, 2 singlets σ_i, 3 right handed neutrinos N_{R_i}, a vectorial quark (Q_L, Q_R).



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



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

- Yukawa terms $Z_{13} \otimes Z_5 \otimes Z_5'$ and $U(1)_{PQ_1} \otimes U(1)_{PQ_2}$ invariants:

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

- Seesaw mechanism, and two more accidental global $U(1)$s in the renormalizable operators, besides the hypercharge $U(1)_Y$ factor
  - $U(1)_B$, baryon number conservation,
  - $U(1)_Q$, exotic quark number conservation

$Z_{13}\otimes Z_5\otimes Z'_5$ model with two pseudo Nambu-Goldstone bosons.

- Lowest dim. effective mass op.:

$$\mathcal{O}_{14}\equiv\frac{1}{M_{Pl}^{10}}H_N^{\dagger}H_d\sigma_1^{*5}\sigma_2^{7}$$

$$\Downarrow$$

$$m_a\sim\frac{v_W v_1^{5/2}v_2^{7/2}}{2^6 M_{Pl}^5 f_A}\sim 10^{-33}\ \text{eV},\quad m_A=0.6\ \text{meV}$$

  for $v_1\sim f_A\sim 10^{10}$ GeV, and $v_2\sim 7.5\times 10^{10}$ GeV
- In this model the axion and ALP decay constants are related

$$\frac{1}{f_A^2}=\frac{1}{f_a^2}=\left(\frac{C_{1g}}{f_{a'_1}}\right)^2+\left(\frac{C_{2g}}{f_{a'_2}}\right)^2$$

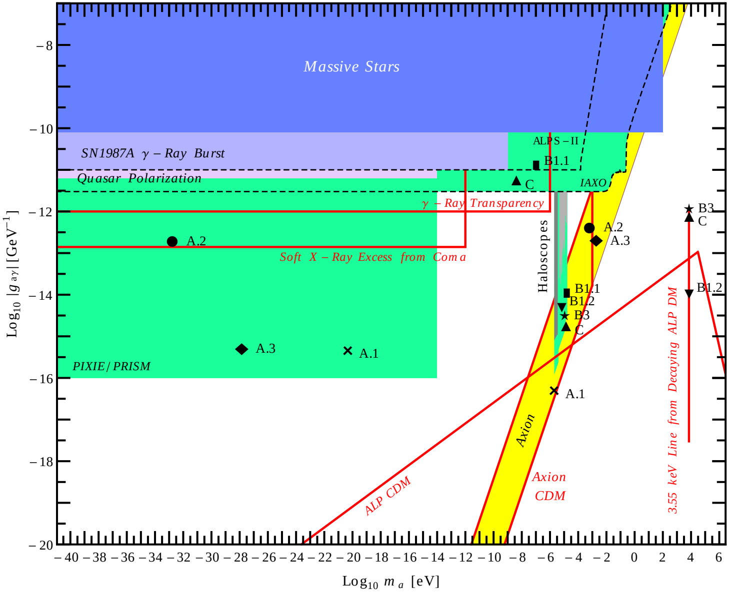
  This usually happens in models without photophilc ALP.
- It can be shown that

$$\left(g_{A\gamma}+\frac{\alpha}{2\pi f_A}\times 1.95\right)^2+g_{a\gamma}^2=\frac{\alpha}{2\pi}\left[\left(\frac{C_{1\gamma}}{f_{a'_1}}\right)^2+\left(\frac{C_{2\gamma}}{f_{a'_2}^2}\right)^2\right]$$

  so that $g_{a\gamma}$ cannot be hierarchically larger than $g_{A\gamma}$ in the model.

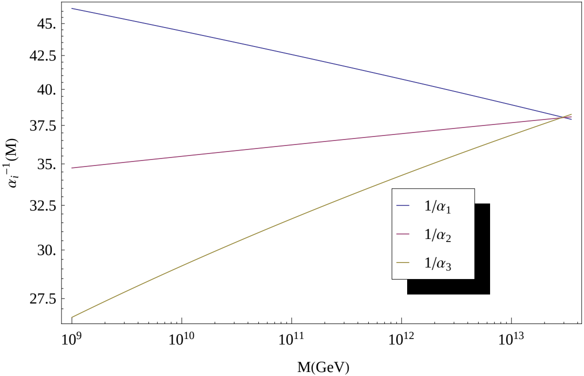
$Z_{13} \otimes Z_5 \otimes Z_5'$ model with two pseudo Nambu-Goldstone bosons.

Benchmarks for this model



$Z_{13} \otimes Z_5 \otimes Z'_5$ model with two pseudo Nambu-Goldstone bosons.

- The field content is such that the model has gauge coupling unification at $M_U \sim 10^{13}$ GeV, near to intermediate scale.



- Proton is stabilized by the same discrete symmetries which protects the axion/ALP.
- Free from domain wall problem.
- Embedding on SU (5) GUT group is possible [AD, Franco, Pleitez 07].

$Z_{11} \otimes Z_9 \otimes Z_7$ model with axion and two photophilic ALPs.

Photophilic model: only one ALP field coupling to $\frac{\alpha_s}{8\pi} G\tilde{G}$
$\Rightarrow f_A$ and f_{a_i} ($g_{a_i\gamma}$ and $g_{A\gamma}$) are not connected
$Z_{11} \otimes Z_9 \otimes Z_7$ model has the scales f_A, f_{a_1} and f_{a_2}

- BSM: 3 scalar singlets σ_i; 1 vectorial quark (Q_L, Q_R);
  2 noncolored vectorial charged fermions (E_{bL}, E_{bR});
  3 right-handed neutrinos N_{iR}.

	q_L	u_R	d_R	L	l_R	N_R	H	Q_L	Q_R	σ_1	σ_2	E_{1L}	E_{1R}	σ_3	E_{2L}	E_{2R}
$\mathbb{Z}_7$	1	ω_7^3	ω_7^4	1	ω_7^4	ω_7^3	ω_7^3	ω_7^5	ω_7^3	ω_7	1	ω_7^5	ω_7^4	ω_7^1	ω_7^5	ω_7^3
$\mathbb{Z}_9$	1	ω_9^5	ω_9^4	ω_9^6	ω_9	ω_9^2	ω_9^5	1	ω_9^8	ω_9^5	ω_9	ω_9^6	1	1	ω_9^1	ω_9^5
$\mathbb{Z}_{11}$	1	ω_{11}^3	ω_{11}^8	ω_{11}^2	ω_{11}^{10}	ω_{11}^5	ω_{11}^3	ω_{11}^9	ω_{11}^7	ω_{11}	1	1	ω_{11}^{10}	1	ω_{11}^{10}	ω_{11}^9

- Three accidental $U(1)_{PQ_1} \otimes U(1)_{PQ_2} \otimes U(1)_{PQ_3}$.

	q_L	u_R	d_R	L	l_R	N_R	H	Q_L	Q_R	σ_1	σ_2	E_{1L}	E_{1R}	σ_3	E_{2L}	E_{2R}
K_ψ	0	0	0	$-1/2$	$-1/2$	$-1/2$	0	1	-1	1	0	1	0	0	0	-1
X_ψ	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0
Z_ψ	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

$Z_{11} \otimes Z_9 \otimes Z_7$ model with axion and two photophilic ALPs.

- BSM Yukawa Lagrangian invariant under $Z_{11} \otimes Z_9 \otimes Z_7$ and $U(1)_{PQ_1} \otimes U(1)_{PQ_2} \otimes U(1)_{PQ_3}$

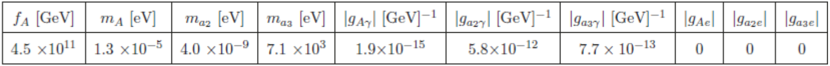
$$\mathcal{L}_Y^{BSM} = F_{ij}\overline{L}_i\widetilde{H}_N N_{jR} + y_{ij}\overline{(N_{iR})^c}\sigma_1 N_{jR} + y_i\frac{\sigma_1}{M_{\mathrm{Pl}}}\overline{q}_{iL}HQ_R$$
$$+ y_Q\frac{\sigma_1^2}{M_{\mathrm{Pl}}}\overline{Q}_L Q_R + k_i\frac{\sigma_2}{M_{\mathrm{Pl}}}\overline{L}_i HE_R + k_{ij;bc}\frac{\sigma_i\sigma_j}{M_{\mathrm{Pl}}}\overline{E}_{bL}E_{cR}$$

- Lowest dimension operators violating $U(1)_{PQ_2}$, and $U(1)_{PQ_3}$

$$\mathcal{L} \supset \frac{g}{M_{Pl}^5}(\sigma_2)^9 \quad \Longrightarrow \quad m_{a_2} \simeq 10^{-7}\mathrm{eV}\,|g|^{1/2}\left(\frac{v_2}{10^9\mathrm{GeV}}\right)^{7/2}$$

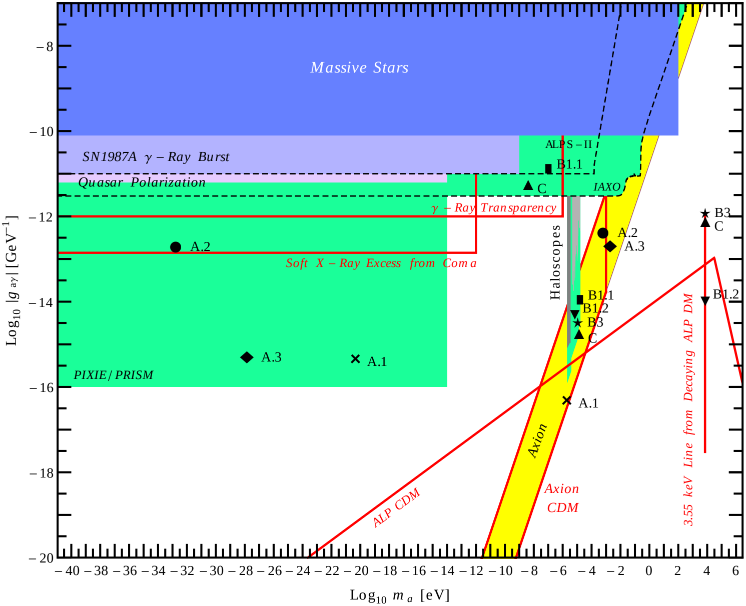
$$\mathcal{L} \supset \frac{g'}{M_{Pl}^3}(\sigma_3)^7 \quad \Longrightarrow \quad m_{a_3} \simeq 7.1\,\mathrm{keV}\,|g'|^{1/2}\left(\frac{v_3}{1.8\times 10^9\mathrm{GeV}}\right)^{5/2}$$

- For $v_1 = 9\times 10^{11}$ GeV, $v_2 = 4\times 10^9$ GeV, $v_1 = 3\times 10^9$ GeV



f_A [GeV]	m_A [eV]	m_{a_2} [eV]	m_{a_3} [eV]	$\lvert g_{A\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{a_2\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{a_3\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{Ae}\rvert$	$\lvert g_{a_2e}\rvert$	$\lvert g_{a_3e}\rvert$
4.5×10^{11}	1.3×10^{-5}	4.0×10^{-9}	7.1×10^{3}	1.9×10^{-15}	5.8×10^{-12}	7.7×10^{-13}	0	0	0

$Z_{11} \otimes Z_9 \otimes Z_7$ model with axion and two photophilic ALPs.



[AD, Machado, Nishi, Ringwald, Vaudrevange, 1403.5760]

Conclusions

- Discrete symmetries can the protect the solution of the strong CP problem and axion/ALP masses.
- Plenitude of hidden complex scalar fields in certain compactifications in string theory [Witten 84; Cicoli, Goodsell, Ringwald 12], with a multitude of discrete symmetries exact at the perturbative level.
- Models with intermediate scales in the range 10^9 GeV$\lesssim f_A, f_a \lesssim 10^{13}$ GeV, can have couplings $g_{A\gamma}, g_{a\gamma}$ and masses m_A, m_a in which the axion is a dark matter candidate, also with ALPs explaining:
  - Anomalous transparency of the Universe for VHE photons.
  - Soft X-ray excesses from coma cluster.
  - 3.55 keV line from Andromeda and galaxy clusters.
- Upcoming experiments with Haloscopes, Light-shinning-through-a-wall experiments, Helioscopes can probe models with intermediate scales for axion/ALP.