Axion/ALPs in Particle Physics.

Andreas Ringwald

SFB Lecture
DESY
Hamburg, D
30 June 2017

[Baer,Choi,Kim,Roszkowski 10]
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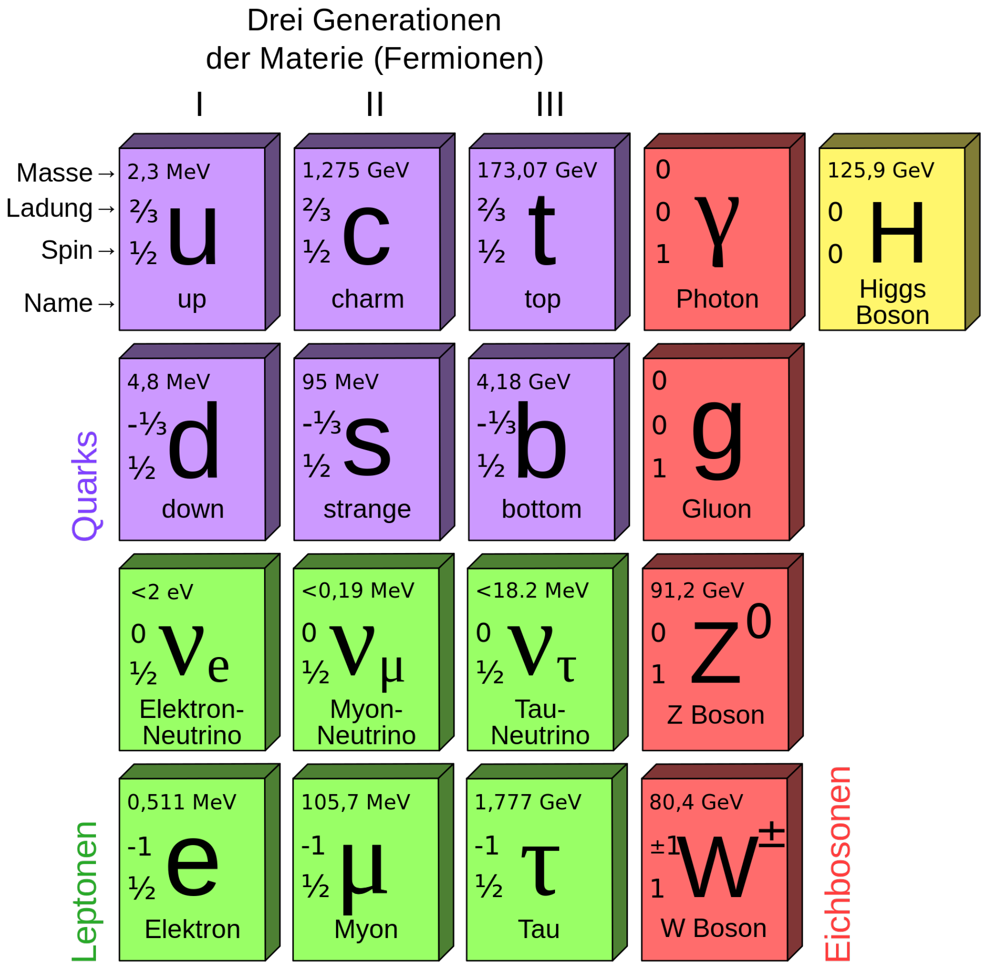
Strong Case for Physics Beyond the Standard Model

- Discovery of Higgs boson marks completion of SM particle content



Drei Generationen der Materie (Fermionen)

	I	II	III			
Masse→ Ladung→ Spin→ Name→	2,3 MeV ⅔ ½ u up	1,275 GeV ⅔ ½ c charm	173,07 GeV ⅔ ½ t top	0 0 1 γ Photon	125,9 GeV 0 0 H Higgs Boson	
Quarks	4,8 MeV -⅓ ½ d down	95 MeV -⅓ ½ s strange	4,18 GeV -⅓ ½ b bottom	0 0 1 g Gluon		
	<2 eV 0 ½ ν_e Elektron-Neutrino	<0,19 MeV 0 ½ ν_μ Myon-Neutrino	<18.2 MeV 0 ½ ν_τ Tau-Neutrino	91,2 GeV 0 1 Z^0 Z Boson		
Leptonen	0,511 MeV -1 ½ e Elektron	105,7 MeV -1 ½ μ Myon	1,777 GeV -1 ½ τ Tau	80,4 GeV ±1 1 $W^\pm$ W Boson		Eichbosonen

[wikipedia]

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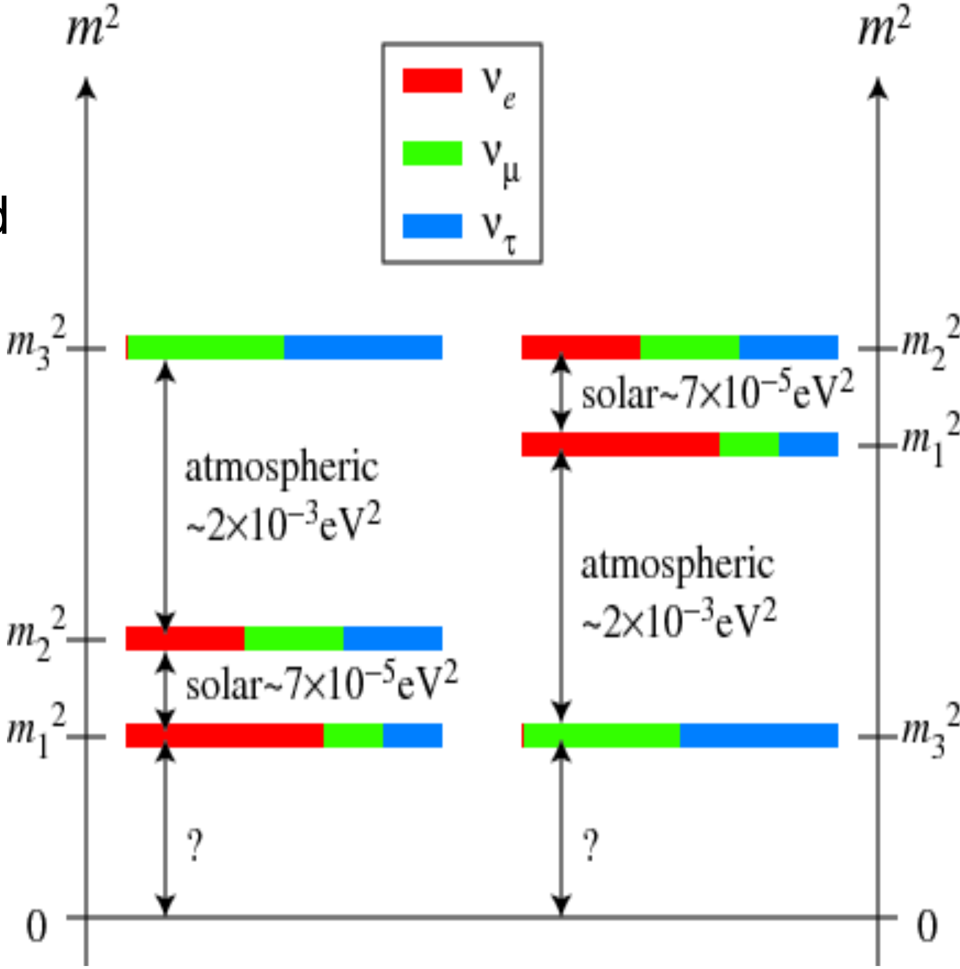
- Strong case for physics beyond SM (BSM) suggested by observations in particle physics, astrophysics and cosmology
  - Neutrino flavour oscillations



[King et al. 13]

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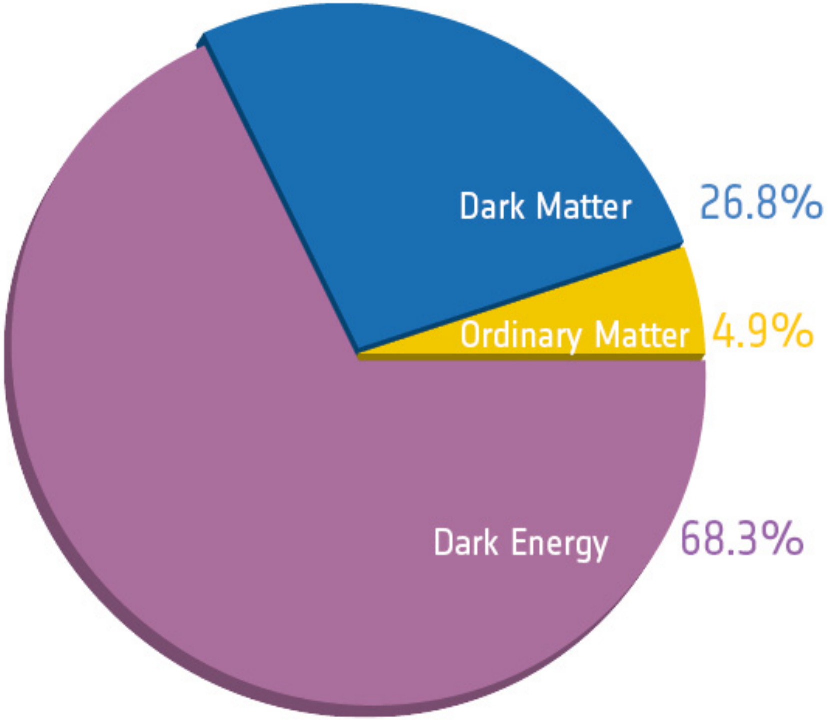

[PLANCK]

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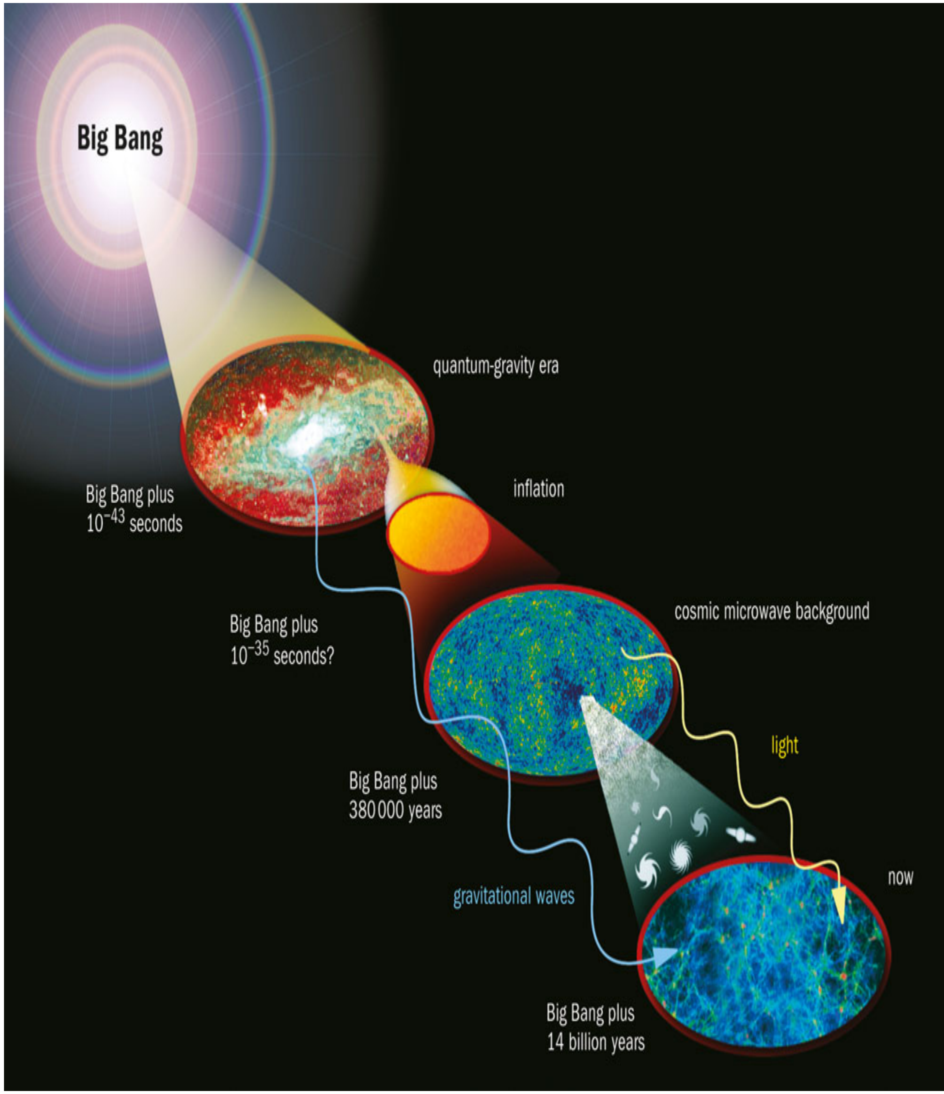

[physicsworld.com]

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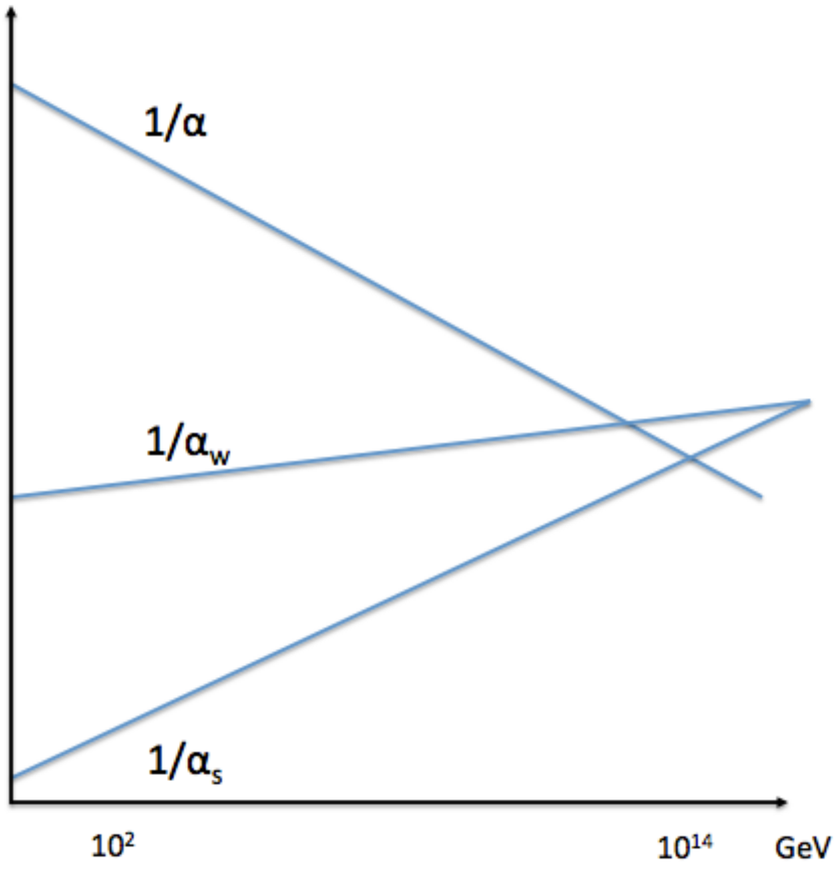
  - Unification?
  - Naturalness?
    - Cosmological constant (dark energy)
    - Hierarchy between weak scale and Planck scale
    - Non-observation of strong CP violation



[StackExchange]

Topological Theta Term and Strong CP Problem

- Most general gauge invariant Lagrangian of QCD:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

  - Parameters: strong coupling α_s, quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$ and theta angle θ [Belavin et al. \`75;´t Hooft 76;Callan et al. \`76;Jackiw,Rebbi \`76]

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violates P and T, and thus CP

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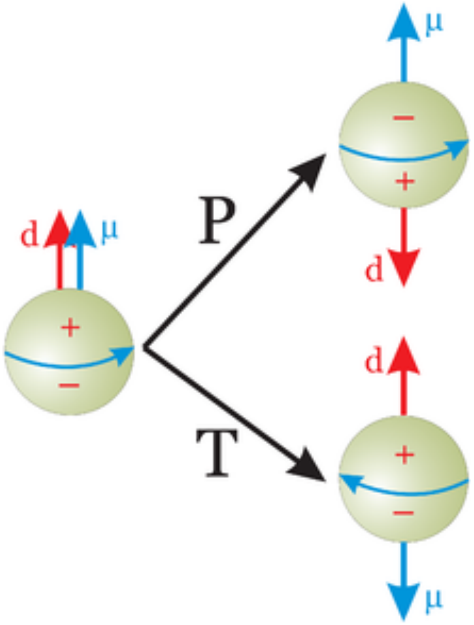

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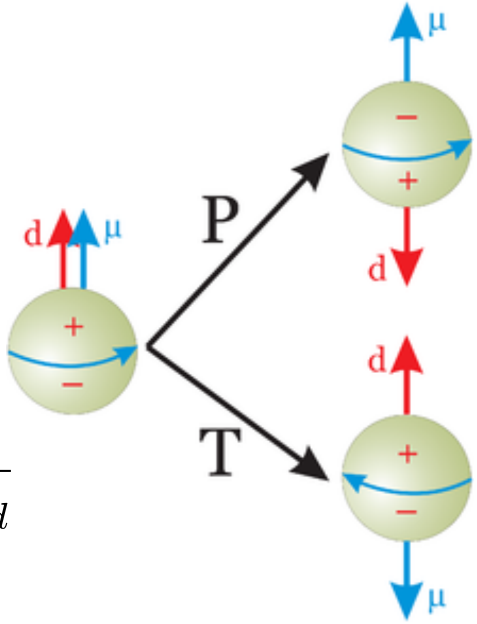
- Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment of neutron; prediction:

$$d_n \sim e\theta\, \frac{m_*}{m_n^2} \sim 6 \times 10^{-17}\ \theta\ e\,{\rm cm}; \qquad m_* = \frac{m_u m_d}{m_u + m_d}$$



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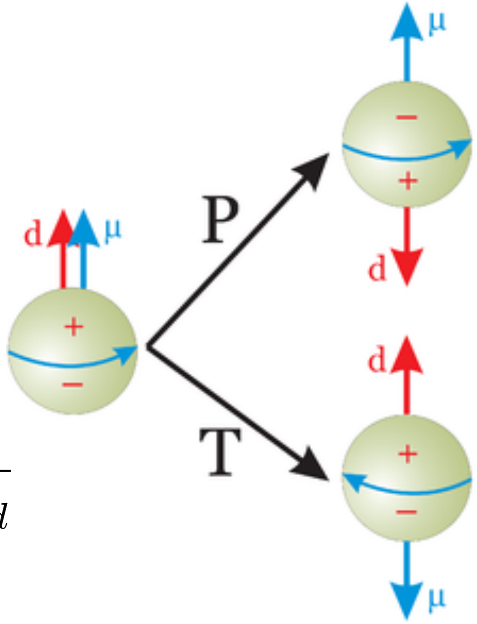
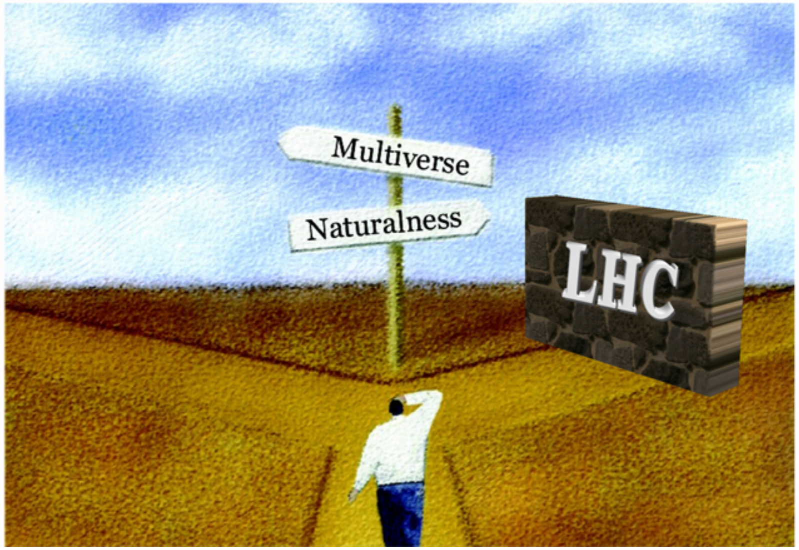
- Experiment: [Baker et al. 06]

$$|d_n| < 2.9\times 10^{-26}\ e\,{\rm cm} \Rightarrow |\theta| < 10^{-9}$$



Topological Theta Term and Strong CP Problem

- Naturalness?
  1. Cosmological constant (dark energy)
  2. Hierarchy between weak scale and Planck scale
  3. Non-observation of strong CP violation
- 1. and 2. can be „solved“ by anthropic selection in multiverse
- Fails for 3.!
  - No anthropic argument for $|\theta| < 10^{-9}$
- Dynamical solution of 3. most required!



[Quantamagazine]

Topological Theta Term and Strong CP Problem

- If θ were a dynamical field, its vacuum expectation value would be zero. Correspondingly: strong CP problem solved
  - Partition function in terms of Fourier series of Euclidean path integrals over gauge fields with fixed topological charge

$$Z(\theta) = \sum_{Q=-\infty}^{+\infty} \exp[i\theta Q] Z_Q, \qquad Q = \int d^4x \, \frac{\alpha_s}{8\pi} G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} \equiv \int d^4x \, q(x)$$

$$Z_Q = \int_Q [dG][dq][d\bar{q}] \exp\left[- \int d^4x \left\{ \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + i\bar{q}\gamma_\mu D_\mu q - \bar{q}_R \mathcal{M} q_L - \bar{q}_L \mathcal{M}^\dagger q_R \right\} \right]$$

  - Z_Q positive
  - Vacuum energy density in QCD

$$\epsilon_0(\theta) \equiv -\frac{1}{\mathcal{V}} \ln \left[\frac{Z(\theta)}{Z(0)} \right], \qquad -\pi \leq \theta \leq \pi$$

has absolute minimum at $\theta = 0$

[Vafa,Witten ´84]

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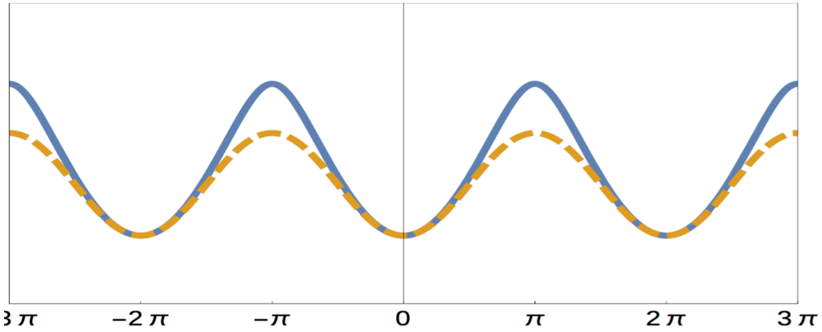


- Chiral EFT allows to calculate vacuum energy density: [Grilli di Cortona et al. `16]

$$\epsilon_0(\theta) \simeq m_\pi^2 f_\pi^2 \left[1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d} \right]$$

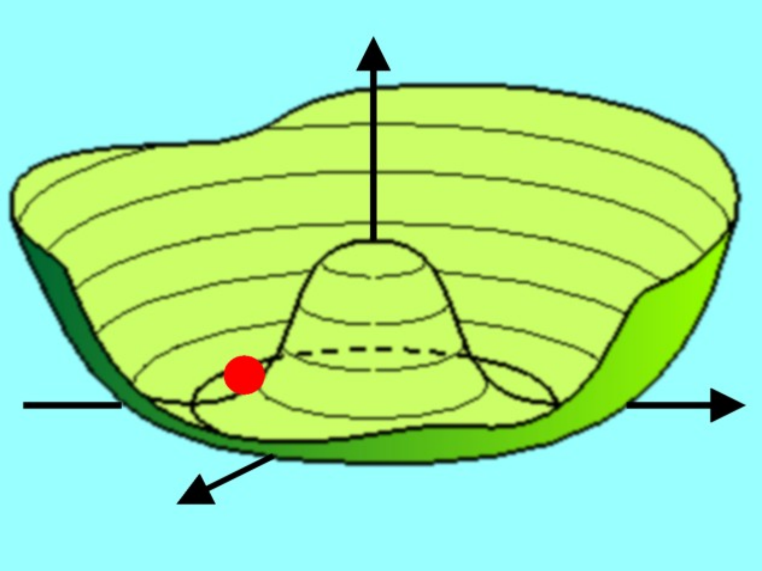
[Di Vecchia,Veneziano `80]

Axionic Solution of Strong CP Problem

- A singlet complex scalar field σ featuring a global $U(1)_{\rm PQ}$ symmetry is added to SM
- Symmetry is broken by vev $\langle\sigma\rangle = v_{\rm PQ}/\sqrt{2}$

$$\sigma(x) = \frac{1}{2}\left(v_{\rm PQ} + \rho(x)\right) {\rm e}^{{\rm i}A(x)/v_{\rm PQ}}$$

  - Excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Excitation of angle: NGB $m_A \ll v_{\rm PQ}$



[Raffelt]

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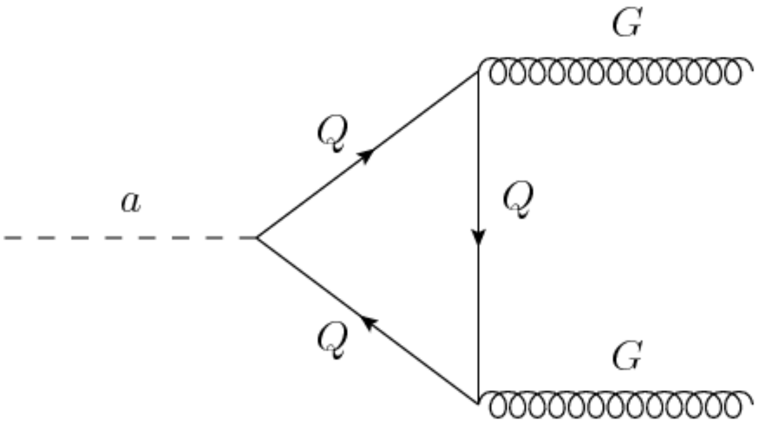
- Quarks (SM or extra) carry PQ charges such that $U(1)_{\rm PQ}$ is anomalously broken due to gluonic triangle anomaly

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} = -\frac{\alpha_s}{8\pi}\, N\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\, E\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



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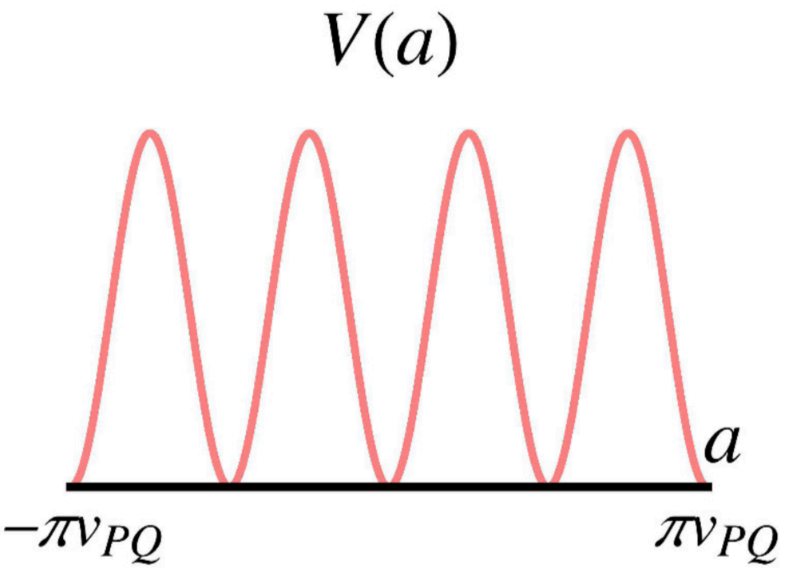

$$V(A) \simeq m_\pi^2 f_\pi^2 \left[1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos(NA/v_{\rm PQ})}}{m_u + m_d}\right]$$

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$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} = -\frac{\alpha_s}{8\pi}\, N\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\, E\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- No strong CP problem, since NGB field acts as x-dependent theta parameter:

[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

A ... Axion

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\frac{E}{N}\frac{A(x)}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu}; \qquad f_A = v_{\rm PQ}/N$$

QCD dynamics: $\langle A(x)\rangle = 0$

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- Add singlet complex scalar field σ featuring a global $U(1)_{\rm PQ}$ symmetry to Standard Model (SM)
- Parameters in most general scalar potential such that symmetry spontaneously broken in vacuum:

$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2} \right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2} \right) \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)$$

- For $\lambda_H, \lambda_\sigma > 0$ and $\lambda_{H\sigma}^2 < \lambda_H \lambda_\sigma$, minimum of potential attained at:

$$\langle H^\dagger H \rangle = v^2/2, \qquad \langle |\sigma|^2 \rangle = v_{\rm PQ}^2/2$$

- Expansion about VEV:

$$\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x) \right) e^{iA(x)/v_{\rm PQ}}$$

  - Excitation of modulus: $m_\rho = \sqrt{2\,\lambda_\sigma}\, v_{\rm PQ} + \mathcal{O}\left(\frac{v}{v_{\rm PQ}} \right)$
  - Excitation of angle (Nambu-Goldstone Boson (NGB)): $m_A = 0$
- Low energy effective field theory: SM + massless non-interacting NGB

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Add color-triplet, electroweak singlet fermion $Q = (Q_L, Q_R)$
- PQ scalar and exotic quark are assumed to transform under $U(1)_{\rm PQ}$ as

$$\sigma \to e^{i\alpha}\sigma\,, \qquad Q_L \to e^{i\alpha/2} Q_L\,, \qquad Q_R \to e^{-i\alpha/2} Q_R$$

- Invariant Lagrangian:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu \sigma^* \partial^\mu \sigma - V(H,\sigma) + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\overline{Q}_L \sigma Q_R$$

- After PQ symmetry breaking, integrate out modulus: $\left[\sigma(x) = \frac{v_{\rm PQ}}{\sqrt{2}} e^{iA(x)/v_{\rm PQ}}\right]$

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu A \partial^\mu A + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\frac{v_{\rm PQ}}{\sqrt{2}} e^{iA/v_{\rm PQ}} \overline{Q}_L Q_R$$

- Redefining fermion by local transformation,

$$Q_L \to e^{iA/2v_{\rm PQ}} Q_L; \quad Q_R \to e^{-iA/2v_{\rm PQ}} Q_R$$

we obtain:

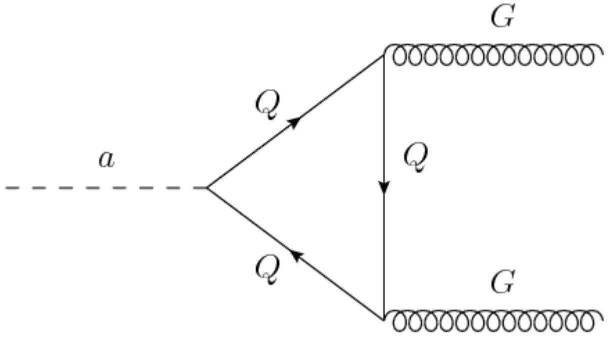
$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu A)^2 + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\frac{v_{\rm PQ}}{\sqrt{2}}\overline{Q}_L Q_R + \frac{1}{2}\frac{\partial_\mu A}{v_{\rm PQ}}\overline{Q}\gamma^\mu \gamma_5 Q$$

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

$$\mathcal{L} \supset \frac{1}{2}\left(\partial_\mu A\right)^2 + \frac{i}{2}\overline{Q}\partial_\mu\gamma^\mu Q - y\frac{v_{\rm PQ}}{\sqrt{2}}\overline{Q}_L Q_R + \frac{1}{2}\frac{\partial_\mu A}{v_{\rm PQ}}\overline{Q}\gamma^\mu\gamma_5 Q$$

- Coupling of axion with exotic color-triplet gives rise to effective interaction with gluons via triangle anomaly:

$$\mathcal{L} \supset -\frac{1}{2}\frac{A}{v_{\rm PQ}}\partial_\mu\left(\overline{Q}\gamma^\mu\gamma_5 Q\right) = -\frac{\alpha_s}{8\pi}\frac{A}{v_{\rm PQ}}G^c_{\mu\nu}\tilde{G}^{c\,\mu\nu}$$



- Integrating out heavy color-triplet, end up with effective theory at scales much below PQ scale $v_{\rm PQ}$, but above QCD scale $\Lambda_{\rm QCD}$:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu A\,\partial_\mu A - \frac{\alpha_s}{8\pi}\frac{A}{v_{\rm PQ}}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

Dine-Fischler-Srednicki-Zhitnitskyi (DFSZ) Model

[Zhitnitsky 80;Dine,Fischler,Srednicki 81]

- Type II Higgs Doublet Model:

$$\mathcal{L}_Y = Y_{ij}\bar{q}_{iL}H_d d_{jR} + \Gamma_{ij}\bar{q}_{iL}\tilde{H}_u u_{jR} + h.c.$$

- Fields are supposed to transform under PQ symmetry as:

$$\begin{aligned} \sigma &\to e^{i\alpha}\sigma\,, \\ H_d &\to e^{iX_d\alpha}H_d\,, \\ H_u &\to e^{-iX_u\alpha}H_u\,, \\ d_{iR} &\to e^{-iX_d\alpha}d_{iR}\,, \\ u_{iR} &\to e^{-iX_u\alpha}u_{iR} \end{aligned}$$

- Yukawa interactions as well as most general scalar potential,

$$V(\sigma) = -\mu_\sigma^2|\sigma|^2 + \lambda_\sigma|\sigma|^4 + \lambda_3 H_d^\dagger H_u\sigma^2$$

invariant, if $X_u + X_d = 2$

- Anomalous divergence of PQ current:

$$\partial^\mu J_\mu^{\rm PQ} = -6\,\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - 16\,\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Dine-Fischler-Srednicki-Zhitnitskyi (DFSZ) Model

- Low energy effective Lagrangian below EW, but above QCD scale:

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{\alpha_s}{8\pi}\frac{A}{f_A} G^c_{\mu\nu}\tilde{G}^{c,\mu\nu} - \frac{\alpha}{8\pi}\frac{8}{3}\frac{A}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu A}{f_A}\sum_f C_f \overline{f}\gamma^\mu\gamma_5 f$$

$$f_A = \frac{v_{\rm PQ}}{6}; \qquad C_{Ae} = C_{Ad} = \frac{\sin^2\beta}{3}; \qquad C_{Au} = \frac{\cos^2\beta}{3}; \qquad \tan\beta = \frac{v_u}{v_d}$$

- In contrast to KSVZ model:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu A\,\partial_\mu A - \frac{\alpha_s}{8\pi}\frac{A}{v_{\rm PQ}} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

Axion Couplings to SM at Energies Below QCD Scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2} m_A^2 A^2 - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A} A\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{Af}}{f_A}\partial_\mu A\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Axion mass: $m_A = 57.0(7)\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$ [Weinberg ´78; ... Borsanyi et al. \`16]

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- Couplings of axion to SM suppressed by powers of

$$f_A = v_{\mathrm{PQ}}/N \gg v = 246\,\mathrm{GeV}$$

rendering the axion „invisible“

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

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rendering the axion „invisible“

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85]
- Nucleon couplings: [Grilli di Cortona et al. `16]

$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3) C_{Au} - 0.39(2) C_{Ad} - 0.038(5) C_{As} \\ &\quad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3) C_{Ad} - 0.39(2) C_{Au} - 0.038(5) C_{As} \\ &\quad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At} \end{aligned}$$

- Electron coupling very model dependent

Axion Couplings to SM at Energies Below QCD Scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2} m_A^2 A^2 - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\, A\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Axion mass: $m_A = 57.0(7)\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$ [Weinberg ´78; ... Borsanyi et al. `16]
- Couplings of axion to SM suppressed by powers of

$$f_A = v_{\mathrm{PQ}}/N \gg v = 246\,\mathrm{GeV}$$

rendering the axion „invisible“ [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

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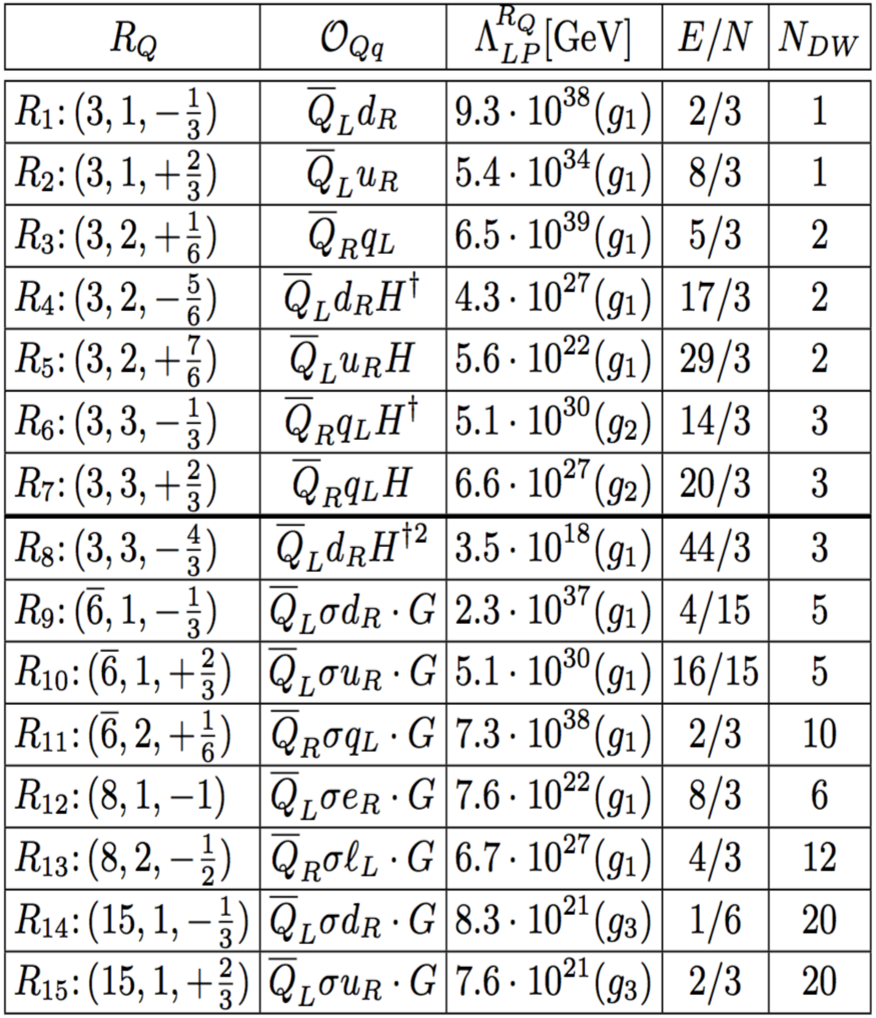
Axion Couplings to SM at Energies Below QCD Scale

- Range of couplings?
- KSVZ-type axion models: anomaly originates from heavy fermions Q in representation $R_Q = (\mathcal{C}_Q, \mathcal{I}_Q, \mathcal{Y}_Q)$ under $SU(3)_C \times SU(2)_I \times U(1)_Y$
- Fifteen cases survive phenomenological requirements
  - sufficiently short lived to avoid issues with long-lived strongly interacting relics
  - no Landau poles induced below Planck scale



R_Q	$\mathcal{O}_{Qq}$	$\Lambda_{LP}^{R_Q}[\mathrm{GeV}]$	E/N	N_{DW}
$R_1: (3, 1, -\frac{1}{3})$	$\overline{Q}_L d_R$	$9.3 \cdot 10^{38}(g_1)$	2/3	1
$R_2: (3, 1, +\frac{2}{3})$	$\overline{Q}_L u_R$	$5.4 \cdot 10^{34}(g_1)$	8/3	1
$R_3: (3, 2, +\frac{1}{6})$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$	5/3	2
$R_4: (3, 2, -\frac{5}{6})$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$	17/3	2
$R_5: (3, 2, +\frac{7}{6})$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	29/3	2
$R_6: (3, 3, -\frac{1}{3})$	$\overline{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30}(g_2)$	14/3	3
$R_7: (3, 3, +\frac{2}{3})$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$	20/3	3
$R_8: (3, 3, -\frac{4}{3})$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	44/3	3
$R_9: (\overline{6}, 1, -\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$2.3 \cdot 10^{37}(g_1)$	4/15	5
$R_{10}: (\overline{6}, 1, +\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$5.1 \cdot 10^{30}(g_1)$	16/15	5
$R_{11}: (\overline{6}, 2, +\frac{1}{6})$	$\overline{Q}_R \sigma q_L \cdot G$	$7.3 \cdot 10^{38}(g_1)$	2/3	10
$R_{12}: (8, 1, -1)$	$\overline{Q}_L \sigma e_R \cdot G$	$7.6 \cdot 10^{22}(g_1)$	8/3	6
$R_{13}: (8, 2, -\frac{1}{2})$	$\overline{Q}_R \sigma \ell_L \cdot G$	$6.7 \cdot 10^{27}(g_1)$	4/3	12
$R_{14}: (15, 1, -\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$8.3 \cdot 10^{21}(g_3)$	1/6	20
$R_{15}: (15, 1, +\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$7.6 \cdot 10^{21}(g_3)$	2/3	20

[Di Luzio, Mescia, Nardi 16]

Axion Couplings to SM at Energies Below QCD Scale

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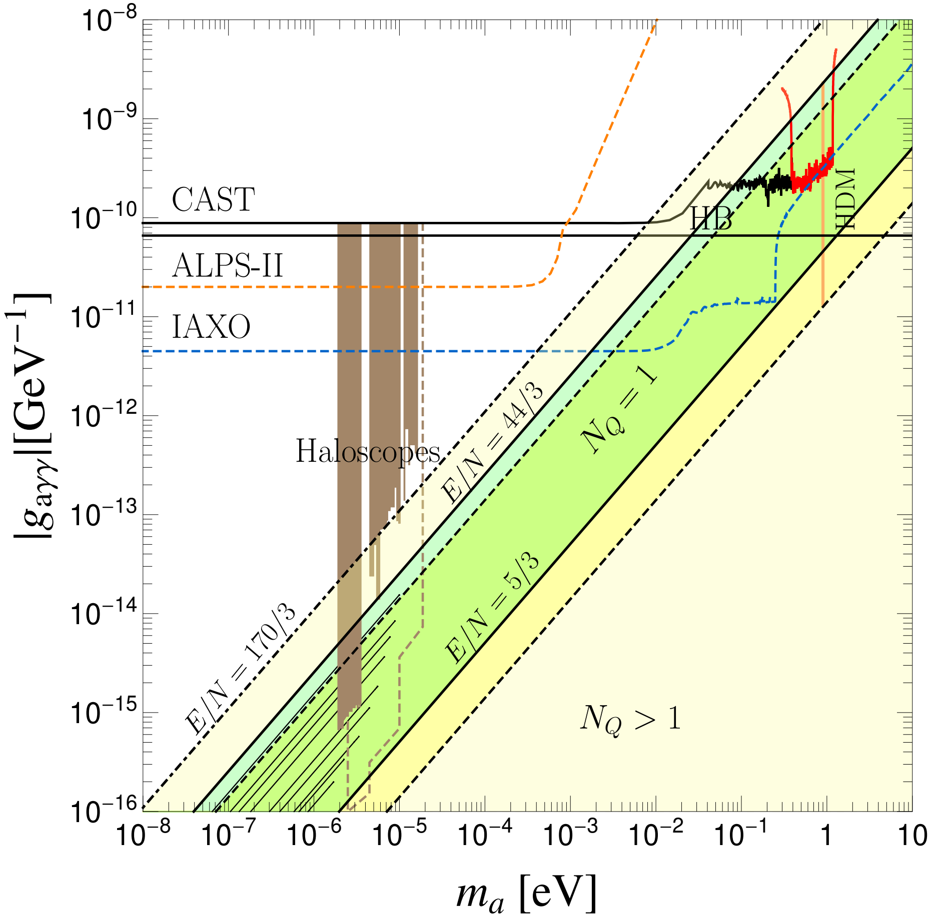
- More than one order of magnitude range in

$$g_{A\gamma} \equiv C_{A\gamma}/(2\pi f_A)$$



[Di Luzio, Mescia, Nardi 16]

A Minimal Model of Particle Physics and Cosmology

- Unify PQ U(1) symmetry with lepton symmetry: add three right-handed SM-singlet neutrinos to KSVZ like model [Shin 87; Dias et al. `14]

$$\mathcal{L} \supset - \Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$

$$+ y \tilde{Q} \sigma Q + y_{Q_{d\,i}} \sigma Q d_i + h.c. \Big]$$

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

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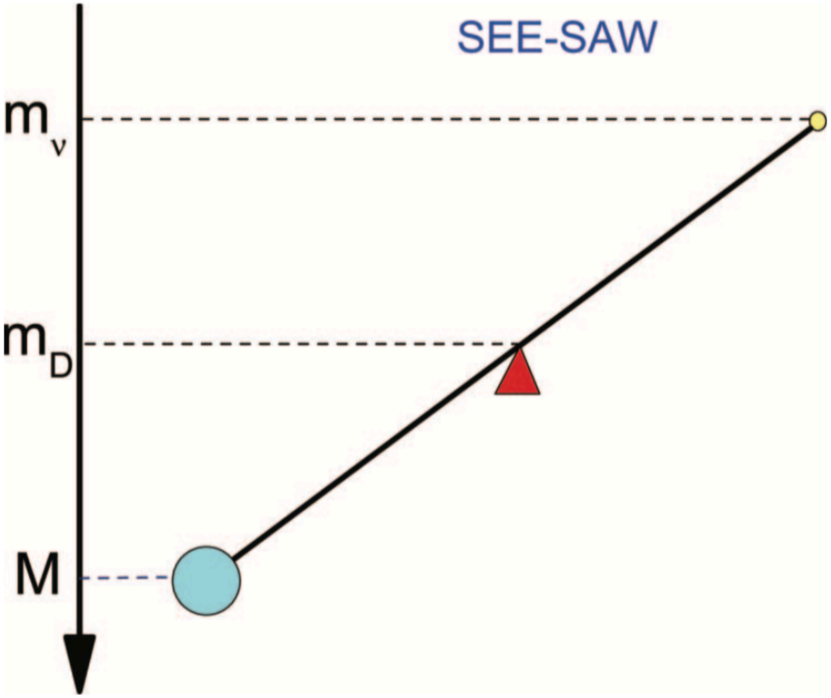
1. No strong CP problem
2. See-saw explanation of active neutrino masses

$$m_\nu = 0.04\,\mathrm{eV} \left(\frac{10^{11}\,\mathrm{GeV}}{v_\sigma} \right) \left(\frac{-F\,Y^{-1}\,F^{T}}{10^{-4}} \right)$$



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SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

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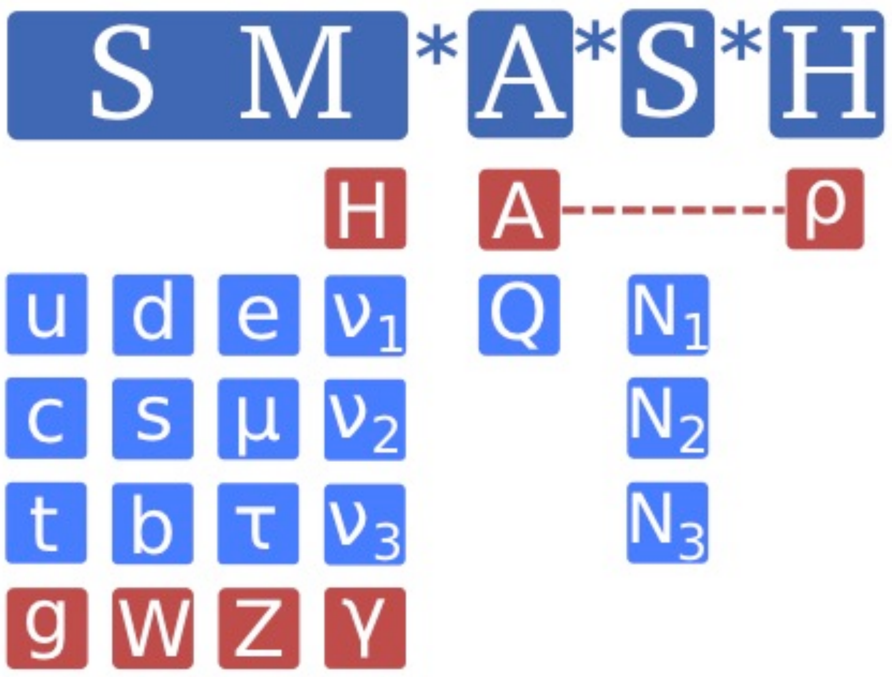
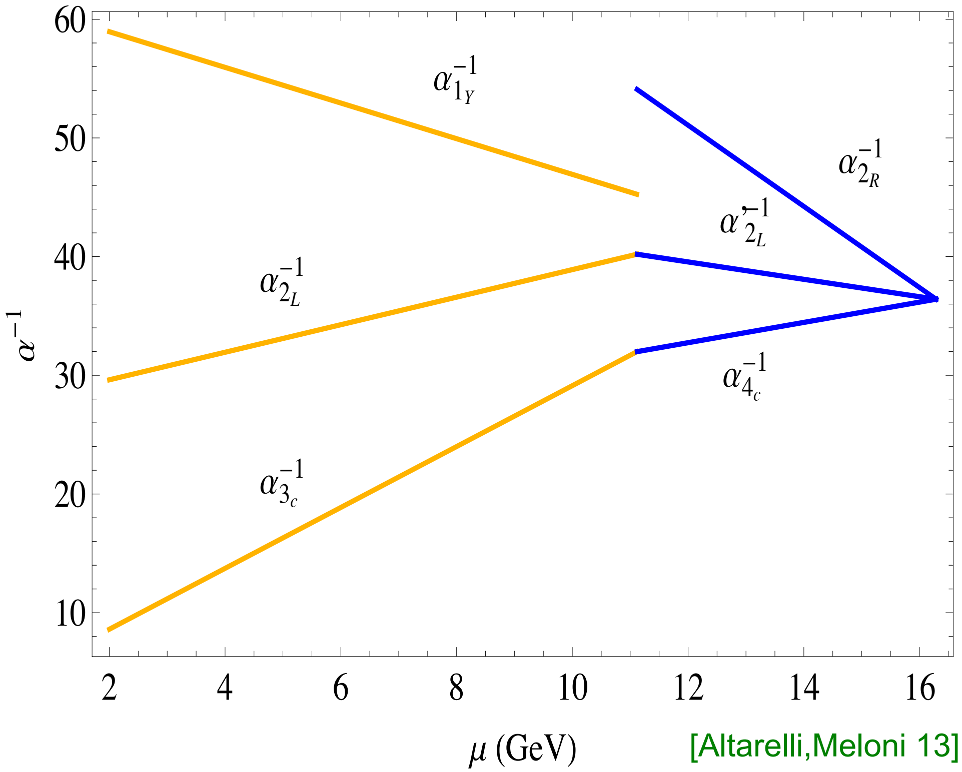
3. Axion dark matter
4. Explains matter-anti-matter asymmetry by thermal leptogenesis
5. Higgs portal inflation



Axion in SO(10) GUT

- SO(10) GUT automatically features right-handed sterile neutrinos
  - Neutrino masses and mixing
  - Baryogenesis via leptogenesis
- PQ extension of SO(10) GUT may in addition provide
  - Solution of strong CP problem
  - Axion dark matter
- In non-SUSY SO(10) GUT, intermediate SSB step required:



[Altarelli,Meloni 13]

$$SO(10) \xrightarrow{M_{\rm GUT}-210_H} SU(4)_C\, SU(2)_L\, SU(2)_R \xrightarrow{M_{\rm I}-126_H,45_H} SU(3)_C\, SU(2)_L\, U(1)_Y \xrightarrow{M_Z-10_H} SU(3)_C\, U(1)_Y$$

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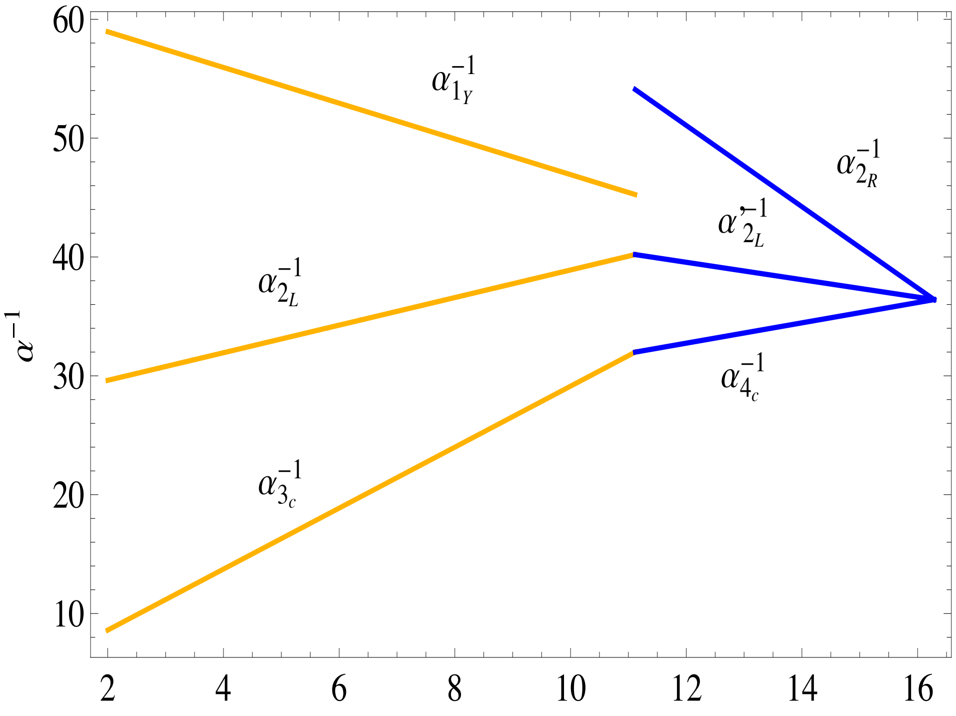

μ (GeV)

[Altarelli,Meloni 13]

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[Holman,Lazarides,Shafi 83]

- Imposing PQ symmetry,

$$16_{\psi(j)} \to e^{i\alpha} 16_{\psi(j)}\ ,\ 10_H \to e^{-2i\alpha} 10_H\ ,\ 45_H \to e^{4i\alpha} 45_H\ ,\ \overline{126}_H \to e^{-2i\alpha}\overline{126}_H\ ,\ 210_H \to 210_H$$

predicts $f_A \sim M_{\rm I}/(3\,g) \sim 10^{11}\,{\rm GeV}$

[Ernst,AR,Tamarit in prep.]

Axion-Like Particles (ALPs)

- Extending the SM by further well-motivated global symmetries may lead to even more Nambu-Goldstone bosons:
  - Global lepton number symmetry: Majoron [Chikashige et al. 78; Gelmini,Roncadelli 80]
  - Global family symmetry: Familon [Wilczek 82; Berezhiani,Khlopov 90]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C'_{ig}}{f_{a'_i}}\, a'_i\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C'_{i\gamma}}{f_{a'_i}}\, a'_i\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C'_{a'_i f}}{f_{a'_i}}\, \partial_\mu a'_i\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Then the particle corresponding to the excitation of the field combination

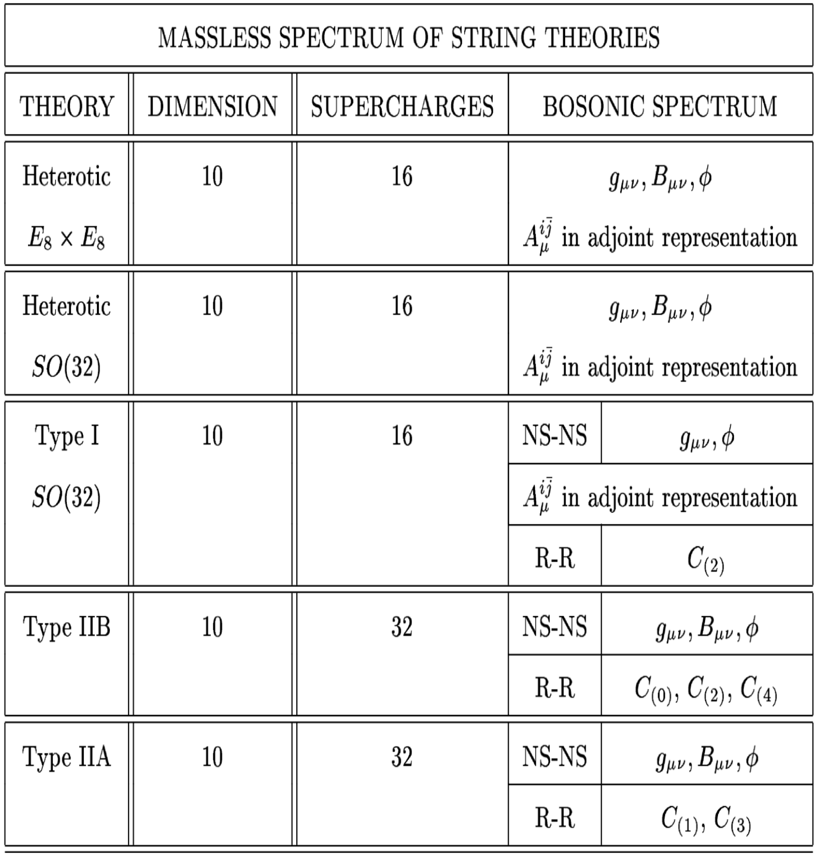
$$\frac{A(x)}{f_A} \equiv \frac{C'_{ig}}{f_{a'_i}}\, a'_i(x)$$

  is the axion

- Particle excitations of the fields orthogonal to this field combination are called Axion-Like-Particles (ALPs)
- String theory suggests a plenitude of ALPs [Witten 84; Conlon 06; Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10; Cicoli,Goodsell,AR 12]

Axion-Like Particles (ALPs)

- 4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs
  - KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string



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_μ^{ij} in adjoint representation	
Heterotic $SO(32)$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ A_μ^{ij} in adjoint representation	
Type I $SO(32)$	10	16	NS-NS	$g_{\mu\nu}, \phi$
			A_μ^{ij} 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]

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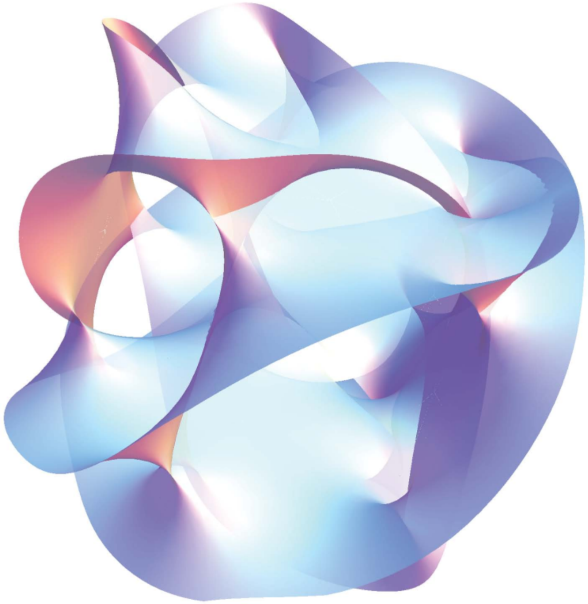
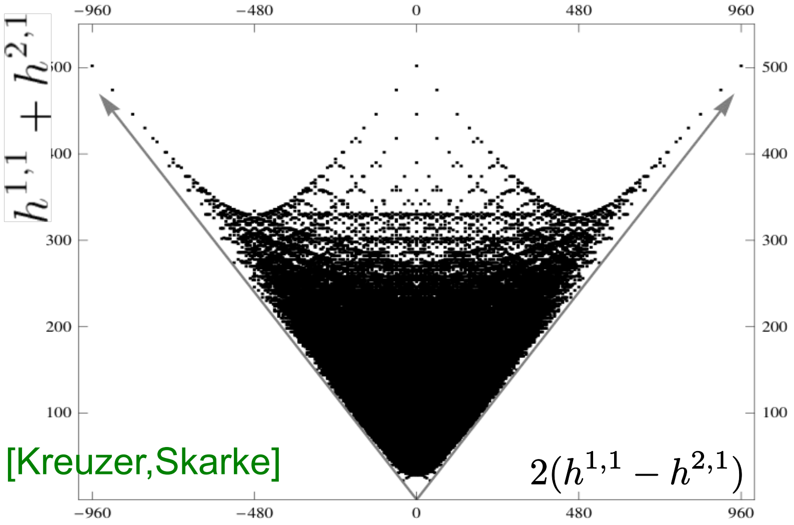
  - KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string
    - shift symmetry from gauge invariance in 10D; # ALPs depends on topology;
    - SB scale of order the string scale, i.e. GUT scale, 10^{16} GeV ,in the heterotic string case; typically lower, the intermediate scale, 10^{11} GeV , in IIB compactifications realising brane worlds with large extra dimensions [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli, Goodsell, AR 12]





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

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- 4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs
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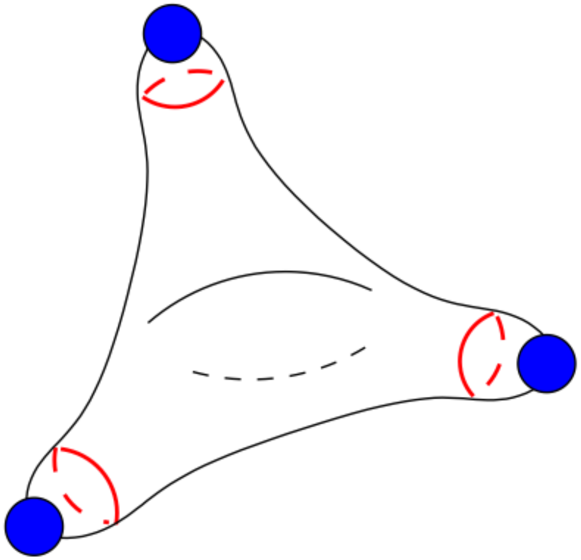
  - NGBs from accidental PQ symmetries appearing as low energy remnants of discrete symmetries from compactification, SB scale decoupled from string scale [Lazarides,Shafi 86; Choi et al. 09; Dias et al. 14]



- Discrete symmetries in orbifold compactifications of heteroric string:
  - $\mathbb{Z}_6 \times \mathbb{Z}_3 \times \mathbb{Z}_2 \times \mathbb{Z}_2$ 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]

Summary

- Unlike other naturalness problems (cosmological constant, weak scale), smallness of theta can not be justified by anthropic reasoning
- Plenty of UV extensions of SM can provide an axionic solution of the strong CP problem
- Strong CP problem solved for any value of decay constant
- Axion mass in terms of decay constant very well determined
- Couplings to photons and nucleons somewhat, to electrons strongly model-dependent
- Next Friday: Axion/ALPs in Astrophysics and Cosmology
- Suggest phenomenologically interesting ranges for decay constant