

The R-xion: Stabilizing the Axion by means of Non-Anomalous Discrete R Symmetries.



Kai Schmitz

Kavli Institute for the Physics and Mathematics of the Universe (WPI)

Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Japan

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In collaboration with Keisuke Harigaya, Masahiro Ibe and Tsutomu T. Yanagida.

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Outline

- 1 The Strong CP Problem and the Peccei-Quinn Solution
- 2 Minimal Extension of the MSSM with a Peccei-Quinn Symmetry
- 3 Phenomenological Constraints and Observational Prospects
- 4 Conclusions

Axion Physics 101

[Peccei & Quinn '77; Weinberg '78; Wilczek '78]

The strong CP problem: Why no CP violation in strong interactions!?

- ▶ Axial QCD anomaly $\rightarrow \mathcal{L}_{\text{QCD}}^{\text{eff}} \supset \bar{\theta} \frac{\alpha_s}{8\pi} \text{Tr}[G_{\mu\nu} \tilde{G}^{\mu\nu}]$.
- ▶ Neutron EDM $d_n \simeq 5 \times 10^{-16} \bar{\theta} \text{ e cm} \lesssim 3 \times 10^{-26} \text{ e cm}$.
- ▶ Vacuum angle $\bar{\theta} \lesssim 10^{-10}$. Expectation $\bar{\theta} \sim \mathcal{O}(1)$. \Rightarrow Why so tiny?

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Peccei-Quinn solution: Promote $\bar{\theta}$ to dynamical DOF with VEV at 0.

- ▶ The axion: pseudo-NG boson of a spontaneously broken global $U(1)_{\text{PQ}}$.
- ▶ QCD instanton-induced effective potential after the QCD phase transition:

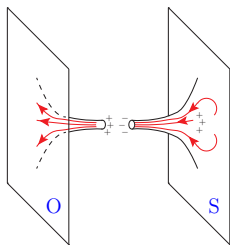
$$V_a = \Lambda_{\text{QCD}}^4 [1 - \cos(\bar{\theta} - a/f_a)], \quad \langle a \rangle = \bar{\theta} f_a.$$

No obvious reason why axion decay constant f_a should have an intermediate value. **But: interestingly enough: axion dark matter if f_a is of $\mathcal{O}(10^{12})$ GeV!**

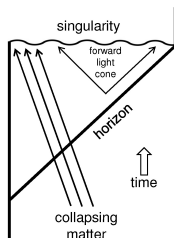
$$\Omega_a^0 h^2 \sim 0.5 \left(\frac{\bar{\theta}_i^2}{\pi^2/3} \right) \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}.$$

[Preskill, Wise & Wilczek '83;
Abbott & Sikivie '83;
Dine & Fischler '83]

However, just a Reformulation of the Original Question!



[Fig. from J.E. Kim, 1308.0344 [hep-th]]



[Fig. from quantumfrontiers.com (Caltech blog)]

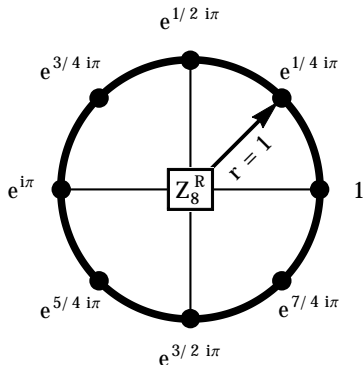
But: Any global symmetry is believed to be broken by quantum gravity effects!

[Kamionkowski & March-Russell '92; Barr & Seckel '92; Holman et al. '92; Banks & Seiberg '11]

- ▶ Why is $\bar{\theta}$ so small? → Why is the global PQ symmetry of such high quality?
- ▶ Answer: Approximate accidental $U(1)_{\text{PQ}}$ due to exact gauge symmetry.

Our idea: Protect PQ symmetry by means of gauged discrete R symmetry, Z_N^R .

An Anomaly-Free Discrete R Symmetry for the MSSM (I)



Chiral superfield $\Phi = (\phi, \psi) \rightarrow$
 $(\exp(\frac{2\pi i}{N} r) \phi, \exp(\frac{2\pi i}{N} (r-1)) \psi)$

Strong motivation for Z_N^R in SUSY phenomenology and model building:

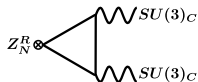
[Giudice & Masiero '88; Yanagida '97; Dine & Kehayias '10]

[Dimopoulos & Georgi '81; Sakai & Yanagida '82; Weinberg '82]

[Izawa & Yanagida '97]

- ▶ No large μ term $W_\mu = \mu H_u H_d$.
- ▶ No dangerous proton decay.
- ▶ No large $\langle W \rangle$ (i.e. negative Λ).
- ▶ Possibly remnant subgroup of continuous *stringy* $U(1)_R$ symmetry.
- ▶ If $U(1)_R$ gauged, remnant Z_N^R gauged and not broken by quantum gravity.

An Anomaly-Free Discrete R Symmetry for the MSSM (II)



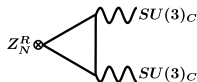
Rendering the Z_N^R symmetry anomaly-free: [Ibanez '93]

- ▶ Generation-independent; $N \geq 3$; commutes with $SU(5)$.
- ▶ $Z_N^R [SU(3)_C]^2$ and $Z_N^R [SU(2)_L]^2$ anomaly coefficients

$$\mathcal{A}_R^{(C)} \stackrel{(N)}{=} \mathcal{A}_R^{(L)} \stackrel{(N)}{=} -6.$$

$N \neq 3, 6 \Rightarrow$ Extra matter sector required. *Natural* consequence of gauged Z_N^R symmetry.

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- ▶ Introduce k pairs of vector-like quark & anti-quark fields: $Q_i \sim \mathbf{5}_i$, $\bar{Q}_i \sim \mathbf{5}_i^*$.
- ▶ R charges such that $k(r_Q + r_{\bar{Q}} - 2) \stackrel{(N)}{=} +6$. In most cases, $r_Q + r_{\bar{Q}} \neq 0, 2$.
- ▶ Renormalizable superpotential for the extra quark sector:

$$W_Q^{\text{ren}} = 0$$

Global $SU(k)_Q^V \times SU(k)_Q^A \times U(1)_Q^V \times U(1)_Q^A$ flavour symmetry.

Rendering the Extra Quark Flavours Massive

Couple new matter sector to SM singlet P that acquires VEV above the EW scale:

$$W_Q \supset \frac{\lambda_i}{M_{\text{Pl}}^{n-1}} P^n (Q\bar{Q})_i, \quad m_{Q_i} = \frac{\lambda_i}{M_{\text{Pl}}^{n-1}} \langle P \rangle^n, \quad n = 1, 2.$$

- ▶ nk possible values for r_P , the R charge of P , for each combination of N, n, k .
- ▶ Add singlets \bar{P} and X with $r_{\bar{P}} = -r_P$ and $r_X = 2$. Restrict to values of r_P s. t.

$$W_P^{\text{ren}} = \kappa X \left[\frac{\Lambda^2}{2} - P\bar{P} \right].$$

- ▶ True vacuum configuration at energies below the mass scale Λ :

$$\langle X \rangle \sim m_{3/2}, \quad \langle P \rangle = \frac{\Lambda}{\sqrt{2}} e^{A/\Lambda}, \quad \langle \bar{P} \rangle = \frac{\Lambda}{\sqrt{2}} e^{-A/\Lambda}.$$

Notice: new chiral multiplet $A = (\frac{1}{\sqrt{2}}(b + ia), \tilde{a})$ contains pseudo-scalar a .

Global Abelian Flavour Symmetries

New matter sector:

$$W_Q^{\text{ren}} = 0 \quad \Rightarrow \quad U(1)_Q^V \times U(1)_Q^A.$$

New singlet sector:

$$W_P^{\text{ren}} = \kappa X \left[\frac{\Lambda^2}{2} - P\bar{P} \right] \quad \Rightarrow \quad U(1)_P, \quad q_P = 1, \quad q_{\bar{P}} = -1.$$

Coupling between the new matter and the singlet sector:

$$W_Q \supset \frac{\lambda_i}{M_{\text{Pl}}^{n-1}} P^n (Q\bar{Q})_i \quad \Rightarrow \quad U(1)_P \times U(1)_Q^V \times U(1)_Q^A \rightarrow U(1)_{PQ} \times U(1)_Q^V.$$

- ▶ Colour anomaly: $\mathcal{A}_{PQ} = k q_{Q\bar{Q}} = k(-n)$. Reminiscent of KSVZ axion model.
- ▶ q_Q and $q_{\bar{Q}}$ eventually fixed by coupling to MSSM (e.g. $\bar{Q}\mathbf{10}H_d$ or $\bar{P}\bar{Q}\mathbf{10}H_d$).

Generation of the MSSM μ Term

$W_\mu = \mu H_u H_d$ forbidden by Z_N^R . Generated during / after R symmetry breaking.

- ▶ $N = 4$: $K \supset g H_u H_d$. In combination with $\langle W \rangle = m_{3/2} M_{\text{Pl}}^2$ due to R breaking:

$$W \supset \frac{g}{M_{\text{Pl}}^2} \langle W \rangle H_u H_d = g m_{3/2} H_u H_d.$$

- ▶ $N \neq 4$: Similarly as in NMSSM, couple SM singlet S with $r_S = -2$ to $H_u H_d$.

$$W_S^{\text{ren}} = g_H H_u H_d S + m_{3/2}^2 S + g_X m_{3/2} X S + g_{X^2} X^2 S \quad (+m_S S^2) \quad (+\lambda_S S^3).$$

- ▶ In the PQ-breaking vacuum, S has VEV of the order of the gravitino mass,

$$\langle S \rangle = \mu / g_H \sim m_{3/2}.$$

Our model: MSSM + extra $\mathbf{5}$'s and $\mathbf{5}^*$'s. + singlets P, \bar{P}, X + singlet S .

Bounds on the Number of Extra Matter Multiplets

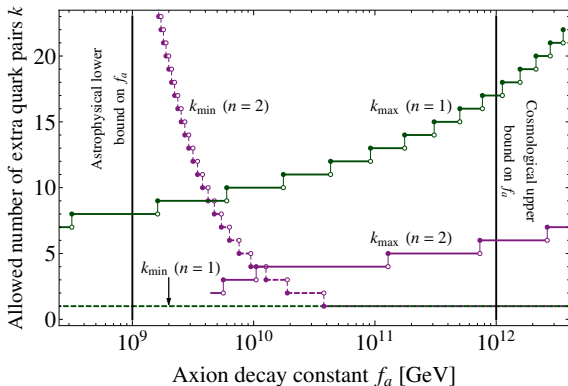
- Require unification of the SM gauge couplings at the perturbative level,

$$g_{\text{GUT}}(m_{Q_i}, k) \leq \sqrt{4\pi} \Rightarrow k_{\text{max}} = k_{\text{max}}(f_a, n),$$

- and consistency with direct searches for heavy vector-like down-type quarks,

[ATLAS, 14.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, assuming a dominant coupling to the third generation of SM quarks via the operator $\bar{Q} \mathbf{10} H_d$]

$$m_{Q_i} \propto |\mathcal{A}_{\text{PO}}|^n \propto k^n, \quad m_{Q_i} \geq M_{\text{O}}^{\text{min}} = 590 \text{ GeV} \Rightarrow k_{\text{min}} = k_{\text{min}}(f_a, n).$$



Solve RGEs incl. new matter fields. $\rightarrow k_{\text{max}}$.

k_{min} and k_{max} translate into lower bounds on the axion decay constant f_a .

Shifts in the QCD Vacuum Angle

Higher-dim. operators explicitly break the $U(1)_{\text{PQ}}$. Most relevant operators in W :

$$W \supset P^P S^S, \bar{P}\bar{P} S^S, m_{3/2}^m P^P X^X, m_{3/2}^m \bar{P}\bar{P} X^X, \quad r_P(p - \bar{p}) + 2(m + x - s) \stackrel{(N)}{=} 2.$$

Non-standard contributions to the axion potential (from F - and A -terms):

$$\Delta V_a = M^4 \cos\left(p \frac{a}{\sqrt{2}\Lambda}\right), \quad M = M(N, n, k, f_a, m_{3/2}, \langle S \rangle, \langle X \rangle)$$

These distortions of V_a induce shifts in the axion VEV, $\langle a \rangle = (\bar{\theta} + \Delta\bar{\theta}) f_a$:

$$\Delta\bar{\theta} \sim \frac{p}{|\mathcal{A}_{\text{PQ}}|} \frac{M^4}{\Lambda_{\text{QCD}}^4} \leq 10^{-10} \Rightarrow M^4 \leq 10^{-10} \frac{|\mathcal{A}_{\text{PQ}}|}{p} \Lambda_{\text{QCD}}^4 \Rightarrow f_a \leq f_a^{\text{max}}.$$

$$f_a \leq \min\{f_a^{\text{max},S}, f_a^{\text{max},X}\}.$$

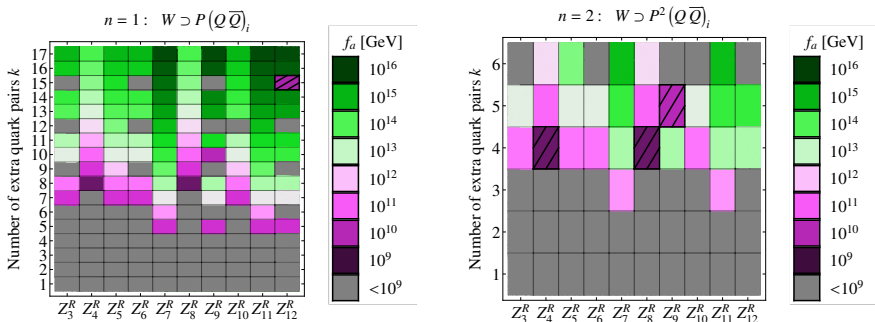
$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}.$$

(N, n, k, r_P) viable if window of viable f_a .

- ▶ We scan 1950 combinations of N, n, k and r_P for $m_{3/2} = \langle S \rangle = \langle X \rangle = 1 \text{ TeV}$.

Phenomenologically Viable Scenarios

- ▶ Upper bounds on f_a due to the requirement that $\Delta\bar{\theta} \leq 10^{-10}$.
- ▶ Shaded squares: $\Delta\bar{\theta} \leq 10^{-10}$ satisfied, but $g_{\text{GUT}} > \sqrt{4\pi}$.



Large landscape of viable scenarios. \Rightarrow Works for any Z_N^R symmetry!

$f_a^{\text{max}} \gtrsim 10^{12} \text{ GeV}$ in some cases. \Rightarrow Axion dark matter possible!

The PQ Symmetry from a Gauged Discrete R Symmetry

Problem: Anomalous global $U(1)_{\text{PQ}}$, required for the axion solution of the strong CP problem, expected to be broken by quantum gravity effects.

Idea: Approximate accidental $U(1)_{\text{PQ}}$ due to exact gauged discrete R symmetry.

- ▶ New matter sector in order to render the Z_N^R anomaly-free, Q_i & \bar{Q}_i .
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Phenomenological constraints on model parameters N, n, k, r_P, f_a based on:

$$M_Q \geq 590 \text{ GeV}, \quad g_{\text{GUT}} \leq \sqrt{4\pi}, \quad \bar{\theta} < 10^{-10}, \quad 10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}.$$

Result: Large # of viable solutions. (Lower bounds on $\bar{\theta}$ in case of axion DM.)

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Thank you for your attention!

Supplementary Material

Higgs and Neutralino Phenomenology

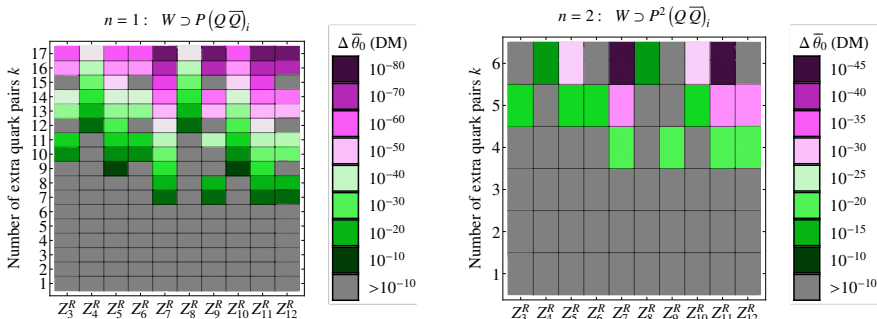
Same low-energy phenomenology as in the PQ-NMSSM and the nMSSM:

[Jeong, Shoji & Yamaguchi '12] [Panagiotakopoulos & Tamvakis '99; Panagiotakopoulos & Pilaftsis '01]

- ▶ Singlino \tilde{S} receives mass only from mixing with $\tilde{H}_{u,d}^0$. \Rightarrow Lightest neutralino.
- ▶ Contributions to m_{h^0} of a few GeV from singlino loops, if $\tilde{H}_{u,d}^0$ are light.
- ▶ BR ($h^0 \rightarrow \tilde{S}\tilde{S}$) large at small $\tan\beta$. \Rightarrow Soon tested at LHC-13 / LHC-14.

Lower Bounds on the QCD Vacuum Angle

- ▶ Assume dark matter to be made out of axions. \Rightarrow Set $f_a = 10^{12}$ GeV.
- ▶ What is the expected $\Delta\bar{\theta}$ in the scenarios that allow for this value of f_a ?



$\Delta\bar{\theta}$ typically not within experimental reach. **But:** 10 scenarios with $\Delta\bar{\theta} \gtrsim 10^{-15}$.

Particularly interesting: Z_4^R plus 6 new quark pairs with TeV-scale masses:
No CP problem, axion DM, no singlet S , TeV-scale vector quarks, $\Delta\bar{\theta} \gtrsim 10^{-15}$, ...