The R-xion: Peccei-Quinn Symmetry from a Gauged Discrete R Symmetry

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

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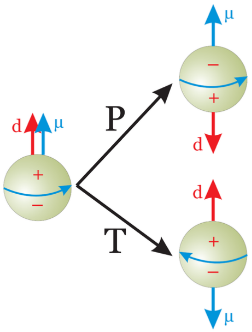
The Strong *CP* Problem



[Fig. from Wikipedia]

CP violation in strong interactions!?

- Axial QCD anomaly induces

$$\mathscr{L}_{\mathrm{QCD}}^{\mathrm{eff}} \supset \bar{\theta}\, \frac{\alpha_s}{8\pi} \mathrm{Tr}\left[G_{\mu\nu}\widetilde{G}^{\mu\nu}\right]$$

with QCD vacuum angle $\bar{\theta} = \theta + \arg\{\det M_q\}$.

- *CP* violation! E.g. neutron electric dipole moment:

$$d_n \simeq 5\times 10^{-16}\,\bar{\theta}\,\mathrm{e\ cm} \lesssim 3\times 10^{-26}\,\mathrm{e\ cm}\,.$$

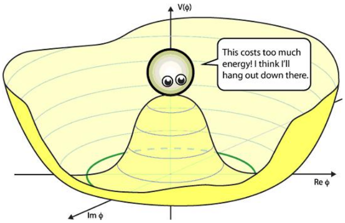
Observational constraint: $\bar{\theta} \lesssim 10^{-10}$. Expectation: $\bar{\theta} \sim \mathcal{O}(1)$. $\Rightarrow$ Why so tiny?

The Axion and the Peccei-Quinn Solution

One solution: Promote $\bar{\theta}$ to dynamical real scalar field with VEV at 0.
[Peccei & Quinn '77; Weinberg '78; Wilczek '78]

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

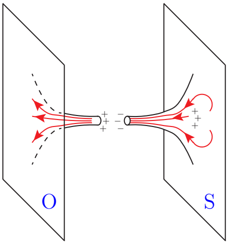
$$V_a = \Lambda_{\mathrm{QCD}}^4 \left[1 - \cos\left(\bar{\theta} - a/f_a\right)\right] \,, \quad \langle a \rangle = \bar{\theta} f_a \,.$$



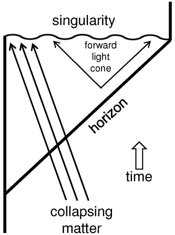
No *obvious* reason why axion decay constant f_a should have an intermediate value. But interestingly enough: axion dark matter if f_a is of $\mathcal{O}\left(10^{12}\right)\,\mathrm{GeV}$!
[Preskill, Wise & Wilczek '83; Abbott & Sikivie '83; Dine & Fischler '83]

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

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!

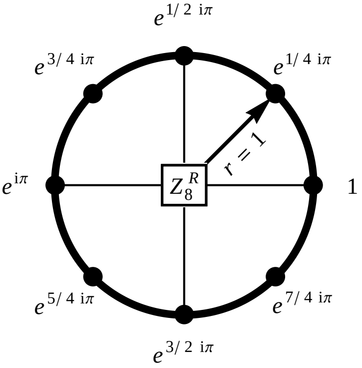
[Kamionkowski & March-Russell '92; Barr & Seckel '92; Holman et al. '92; Banks & Seiberg '11]

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

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

Outline

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



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

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

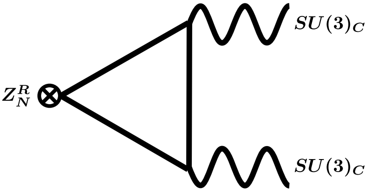
[Giudice & Masiero ’88; Yanagida ’97; Dine & Kehayias ’10]

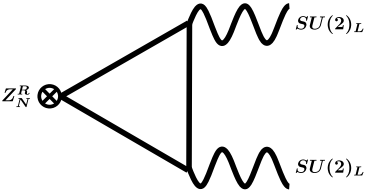
[Dimopoulos & Georgi ’81; Sakai & Yanagida ’82; Weinberg ’82]

[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 remanant 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:

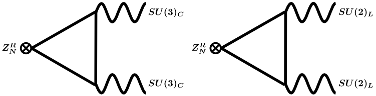
[Ibanez '93]

- Generation-independent Z_N^R with $N = 3, 4, 5, ..$ that commutes with $SU(5)$.
- $Z_N^R\,[SU(3)_C]^2$ and $Z_N^R\,[SU(2)_L]^2$ anomaly coefficients

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

- Given solely the MSSM particle content, only Z_3^R and Z_6^R anomaly-free.

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



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

- Introduce k pairs of vector-like quark & anti-quark fields:

$$Q_i \sim \mathbf{5}_i \,, \quad \bar{Q}_i \sim \mathbf{5}_i^* \,.$$

- R charges such that $k\left(r_Q + r_{\bar{Q}} - 2\right) \stackrel{(N)}{=} +6$. In most cases, $r_Q + r_{\bar{Q}} \neq 0, 2$.
- Renormalizable superpotential for the extra quark sector:

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

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:

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

- $n\,k$ 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.

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

- 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:

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

New singlet sector:

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

Coupling between the new matter and the singlet sector:

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

- Colour anomaly: $\mathcal{A}_{\rm PQ} = k\, q_{Q\bar{Q}} = k\,(-n)$. Remniscent 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.

- $N = 4$: $K \supset g H_u H_d$. $\Rightarrow$ R breaking $\rightarrow$ $W \supset \frac{g}{M_{\rm Pl}^2}\langle W\rangle H_u H_d = g\, m_{3/2} H_u H_d$.
- $N \neq 4$: Couple standard model singlet S with $r_s = -2$ to $H_u H_d$.

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

- In the PQ-breaking vacuum: $\langle S\rangle = \mu / g_H \sim m_{3/2}$.

Same low-energy phenomenology as 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.
- $\mathrm{BR}\left(h^0 \rightarrow \tilde{S}\tilde{S}\right)$ large at small $\tan\beta$. $\Rightarrow$ Soon tested at LHC-13 / LHC-14.

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

Outline

Bounds on the Number of Extra Matter Multiplets

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

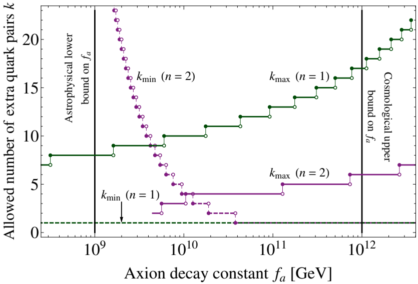
$$g_{\rm GUT}(m_{Q_i}, k) \leq \sqrt{4\pi} \;\Rightarrow\; k_{\rm max} = k_{\rm max}\left(f_a, n\right) ,$$

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

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

$$m_{Q_i} \propto \left|\mathcal{A}_{\rm PQ}\right|^n \propto k^n , \quad m_{Q_i} \geq M_Q^{\rm min} = 590\,\mathrm{GeV} \;\Rightarrow\; k_{\rm min} = k_{\rm min}\left(f_a, n\right) .$$

Solve RGEs including the new matter:



$k_{\rm min}$ and $k_{\rm max}$ translate into lower bounds on the axion decay constant f_a:

$$g_{\rm GUT}\left(f_a^{\rm min,p}, n, k\right) = \sqrt{4\pi} ,$$
$$M_Q\left(f_a^{\rm min,m}, n, k\right) = M_Q^{\rm min} .$$

$$\max\left\{f_a^{\rm min,p}, f_a^{\rm min,m}\right\} \leq f_a .$$

$$f_a^{\rm min,i} = f_a^{\rm min,i}(k, n) , \quad \mathrm{i} = \mathrm{p}, \mathrm{m} .$$

Shifts in the QCD Vacuum Angle

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

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

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

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

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

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

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

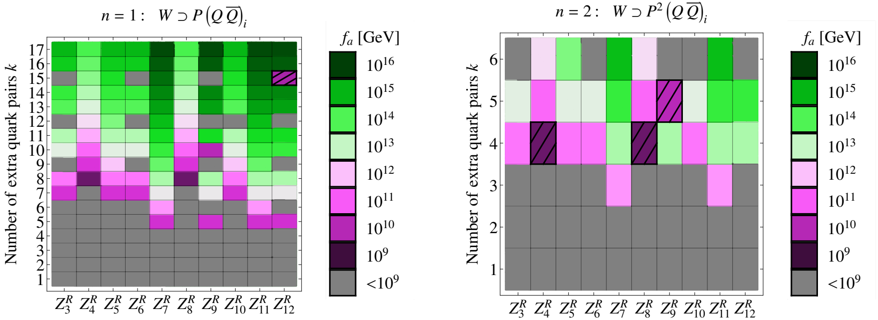
$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}\,.$$

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

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

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 $g_{\text{GUT}} > \sqrt{4\pi}$.

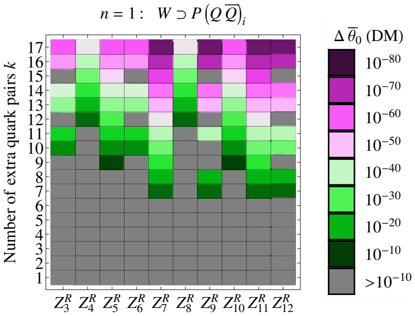


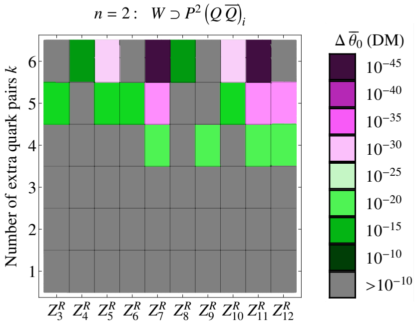
Large landscape of viable scenarios. $\Rightarrow$ Works for any Z_N^R symmetry!

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

Lower Bounds on the QCD Vacuum Angle

- Assume dark matter to be made out of axions. $\Rightarrow$ Set $f_a = 10^{12}\,\mathrm{GeV}$.
- 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, $\Delta\bar{\theta} \gtrsim 10^{-15}$, ...

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

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

- New matter sector in order to render the Z_N^R anomaly-free, Q_i & $\bar{Q}_i$.
- New singlet sector in order to provide masses to the new matter, P, $\bar{P}$ & X.
- Singlet S to generate the MSSM μ term.

Phenomenological constraints on N, n, k, r_P, f_a based on:

- Lower bound on the mass of heavy down-type quarks, $M_Q^{\rm min} = 590\,\mathrm{GeV}$.
- SM gauge coupling unification at the perturbative level, $g_{\rm GUT} \leq \sqrt{4\pi}$.
- Not too large a shift in the QCD vacuum angle, $\bar{\theta} < 10^{-10}$.
- f_a within astrophysically viable window, $10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$.

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

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Thank you for your attention!