Gravity safe, electroweak natural axionic solution to strong CP and SUSY μ problems in the LHC era with determination of the PQ scale

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arXiv : 1810.03713 with : H. Baer and V. Barger
arXiv : 1902.10748 with : K.J. Bae, H. Baer and V. Barger
arXiv : 1905.00443 with : H. Baer, V. Barger, H. Serce, K. Sinha and R.W. Deal

May 16, 2019

Outline

1. Motivation
2. Hybrid Models
3. PQ scale from landscape ?
4. Summary

Outline

Motivation

Till today, though, the Standard Model (SM) is the most celebrated and established theory, there are several reasons to expect new physics beyond SM. Some of these are as follows :

- The Higgs mass instability problem in the EW sector
- The lack of a DM candidate
- The strong CP problem

and several others.

Weak Scale Supersymmetry (WSS) is one of the most attractive ways to deal with the first problem. And the third problem can be solved by introducing **Peccei-Quinn (PQ) Symmetry**.

Both WSS and PQ symmetry contribute to build up the entire Dark Matter content of the universe.

- But SUSY also have some drawbacks, one of which is the **SUSY μ problem**.
- Though PQ symmetry solves the strong CP problem, it is a global symmetry and global symmetries are not compatible with inclusion of quantum gravity and hence the theory suffers from **gravity-spoliation problem**.

In this paper, we review twenty previously devised solution to the μ problem.
Later we shall introduce two hybrid models which would simultaneously solve both strong CP and the SUSY μ problem, beside being gravity safe. We shall also try to predict the most probable PQ scale in the context of these two models.

Naturalness problem

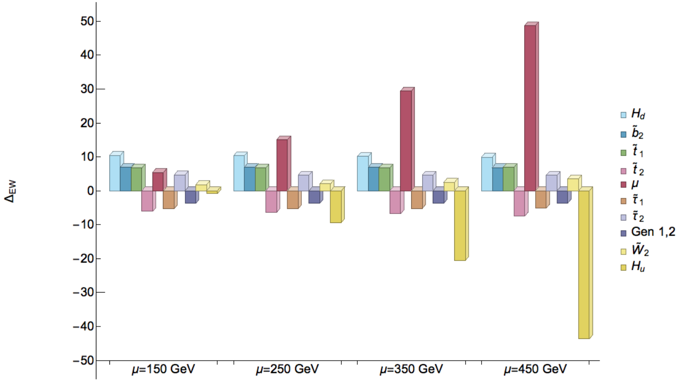

Figure 1: Top ten contributions to $\Delta_{EW} = max_i|C_i|/(M_Z^2/2)$ from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV. [*arXiv : 1702.06588*]

SUSY μ problem

- $\mu \approx$ **100 - 350 GeV** phenomenologically.
- The MSSM superpotential contains term $\mu H_u H_d$ which leads to $\mu \approx m_P$.

This is the famous SUSY μ problem

- A promising approach to solve the SUSY μ problem is to first forbid μ, perhaps via some symmetry, and then re-generate it of order the scale of soft SUSY breaking terms.
- However, present LHC limits suggest the soft breaking scale m_{soft} lies in the multi-TeV regime whilst naturalness requires $\mu \sim m_{W,Z,h} \sim 100$ GeV so that a Little Hierarchy (LH) appears with $\mu \ll m_{soft}$.

Solutions to the SUSY μ problem

model	Admit LH?	strong CP?	Gravity Safe?	see-saw?
GM	small λ_μ	×	$--$	$SNSS$
CM	small λ_μ	×	$--$	$SNSS$
R-sym	$(v_i/m_P)^{n_i}$	×	?	$SNSS$
$\mathbb{Z}_4^R$	small λ_μ	×	$--$	$SNSS$
Instanton	small $e^{-S_{cl}}$	×	$--$	$SNSS$
G_2MSSM	$\langle S_i \rangle / m_P \ll 1$	×	$--$	$SNSS$
NMSSM	small λ_μ	×	$--$	$SNSS$
nMSSM	small λ_μ	×	$--$	$SNSS$
$\mu\nu$SSM	small λ_μ	×	$--$	$bRPV$
$U(1)'$ (CDEEL)	small λ_μ	×	$--$	$SNSS$
sMSSM	small λ_μ	×	$--$	$SNSS$

model	admit LH?	strong CP?	gravity safe?	see-saw?
$U(1)'$ (HPT)	small λ_μ	$\times$	$--$	$bRPV$
KN	$v_{PQ} < m_{hidden}$	$\surd$	?	$SNSS$
CKN	$\Lambda < \Lambda_h$	$\surd$	?	$SNSS$
BK/EWK	$\lambda_\mu \sim 10^{-10}$	$\surd$	?	$SNSS$
HFD	$v_{PQ} < m_{hidden}$	$\surd$	$\surd$	$SNSS$
MSY/CCK/SPM	$v_{PQ} < m_{hidden}$	$\surd$	$\times$	$RadSS$
CCL	small λ_μ	$\surd$	$\surd$	several
MBGW	small λ_μ	$\surd$	$\mathbf{Z}_{22}$	$SNSS$
Hybrid CCK/SPM	small λ_μ	$\surd$	$\mathbf{Z}_{24}^{R}$	$SNSS$

Table 1: : Summary of twenty solutions to the SUSY μ problem and how they 1. admit a Little Hierarchy (LH), 2. solve the strong CP problem ($\surd$) or not ($\times$), 3. are expected gravity-safe and 4. Standard neutrino see-saw (SNSS) or other.

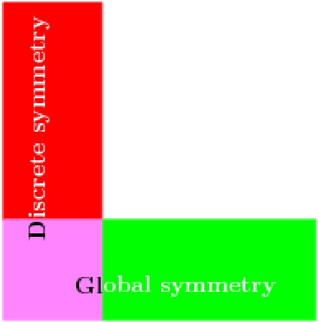

Figure 2: Kim diagram where the column represents an infinite sequence of lagrangian terms obeying gravity-safe discrete symmetry while the row represents an infinite sequence of terms obeying the global symmetry. The green region terms are gravity-unsafe while red region violates the global symmetry. The lavender terms are gravity-safe and obey the global symmetry.

Fundamental R symmetries

- R-symmetries are characterized by the fact that superspace co-ordinates θ carry non-trivial R-charge : $+1$ being the simplest case.
- For the Lagrangian $\mathcal{L} \ni \int W d^2\theta$ to be invariant under $\mathbb{Z}_N^R$ symmetry, the superpotential W must carry R-charge $= 2 \text{ mod } |N|$

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multiplet	$\mathbb{Z}_4^R$	$\mathbb{Z}_6^R$	$\mathbb{Z}_8^R$	$\mathbb{Z}_{12}^R$	$\mathbb{Z}_{24}^R$
H_u	0	4	0	4	16
H_d	0	0	4	0	12
Q	1	5	1	5	5
U^c	1	5	1	5	5
E^c	1	5	1	5	5
L	1	3	5	9	9
D^c	1	3	5	9	9
N^c	1	1	5	1	1

Table 2: : These R-symmetries were shown to be anomaly-free and consistent with GUT by *Lee et al.* in *arXiv : 1102.3595*

$\mathbb{Z}_{24}^R$ discrete symmetry

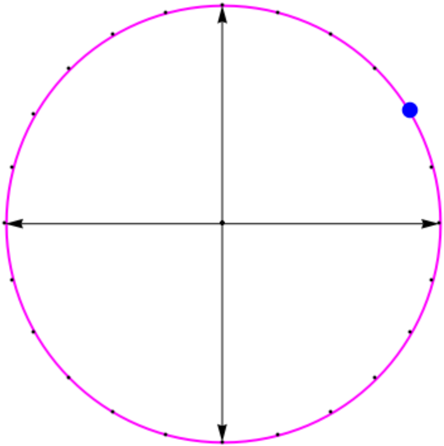

Figure 3: All terms in superpotential (W) must have R charge : $Q_R(W) = 2 + 24\text{n}$; (n=integer)

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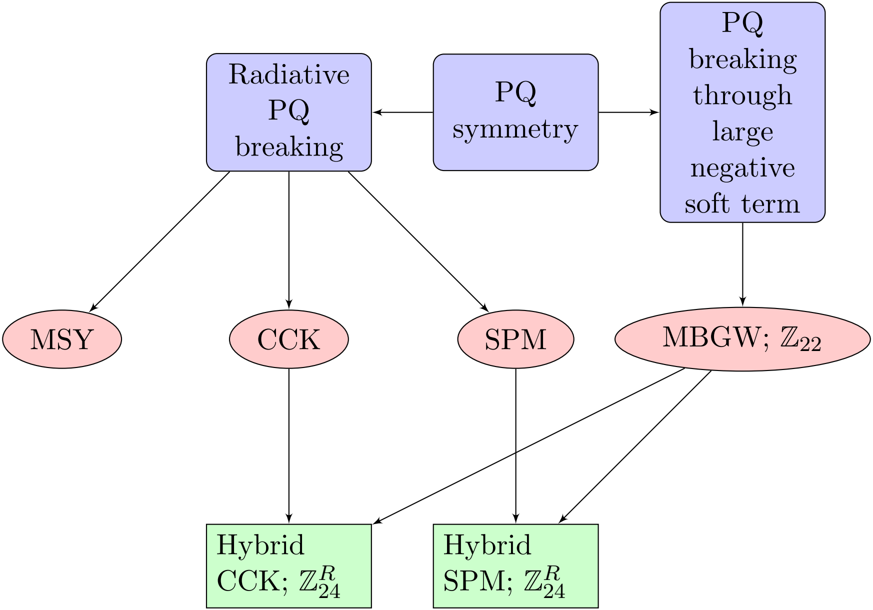
Hybrid Models



Radiative PQ breaking

PQ symmetry

PQ breaking through large negative soft term

MSY

CCK

SPM

MBGW; $\mathbb{Z}_{22}$

Hybrid CCK; $\mathbb{Z}_{24}^R$

Hybrid SPM; $\mathbb{Z}_{24}^R$

Hybrid CCK

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} X^2 H_u H_d \tag{1}$$

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{24}^RCharges	5	5	9	9	5	1	16	12	-1	5
PQ Charges	1	0	0	1	0	0	-1	-1	1	-3

$$V = [f A_f \frac{\phi_X^3 \phi_Y}{m_P} + h.c.] + m_X^2 |\phi_X|^2 + m_Y^2 |\phi_Y|^2 + \frac{f^2}{m_P^2} [9\phi_X^4 \phi_Y^2 + \phi_X^6] \tag{2}$$

- The lowest order PQ violating terms in the superpotential are $\mathbf{X^8Y^2/m_P^7}$, $\mathbf{X^4Y^6/m_P^7}$ and $\mathbf{Y^{10}/m_P^7}$ which implies the lowest order PQ breaking term in the scalar potential is suppressed by $\mathbf{1/m_P^8}$.

- Thus the PQ symmetry arises as an accidental approximate global symmetry from the fundamental discrete $\mathbb{Z}_{24}^R$ symmetry.

Hence, this model is gravity-safe.

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- This has been mentioned earlier by *Lee et al.* in *arXiv : 1102.3595*, but the PQ and $\mathbb{Z}_{24}^R$ breaking mechanism was conjectured to be radiative.
- Here PQ and $\mathbb{Z}_{24}^R$ symmetry is broken through a large negative soft term A_f.

Hybrid CCK

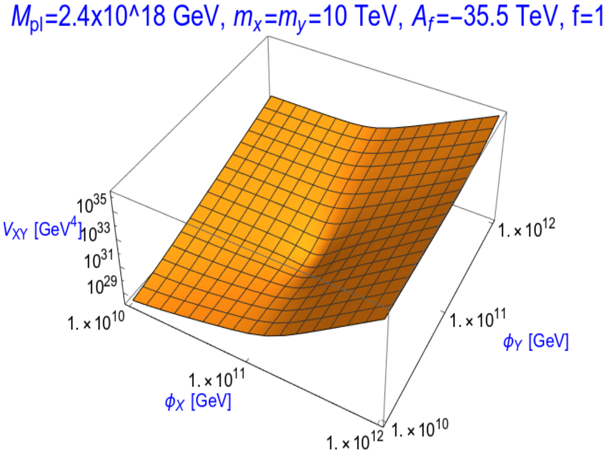

Figure 4: Scalar potential V_{hyCCK} versus ϕ_X and ϕ_Y for $m_X = m_Y \equiv m_{3/2} = 10$ TeV, $f = 1$ and $A_f = -35.5$ TeV.

Hybrid CCK

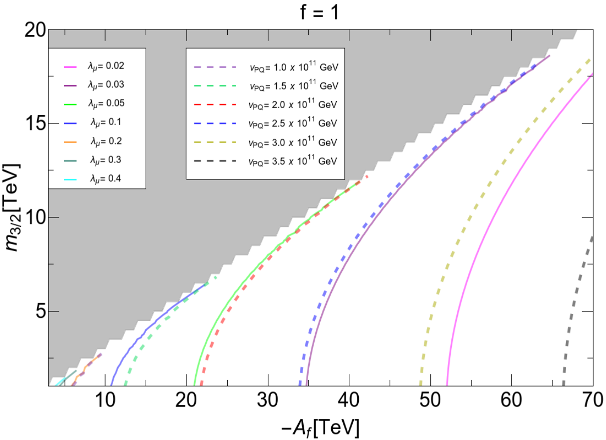

Figure 5: Representative values of λ_μ required for $\mu = 200$ GeV in the $m_{3/2}$ vs. $-A_f$ plane of the hyCCK model for $f = 1$. We also show several contours of v_{PQ}.

Benefits of $\mathbb{Z}_{24}^R$ symmetry

- When $\mathbb{Z}_{24}^R$ symmetry is imposed as the fundamental symmetry in a supersymmetric model, it forbids the μ term and the effective μ term is generated $\sim m_{weak}$ thereby solving the SUSY μ problem
- $\mathbb{Z}_{24}^R$ symmetry also forbids the R-parity violating operators. Hence, R-parity is no longer an ad-hoc symmetry as it results from $\mathbb{Z}_{24}^R$ fundamental symmetry.
- $\mathbb{Z}_{24}^R$ symmetry also forbids the dimension 5 proton decay operator.
- The global PQ symmetry emerges accidentally as an approximate global symmetry from the $\mathbb{Z}_{24}^R$ symmetry, thereby solving the strong CP problem beside protecting the model from the gravity-spoliation problem.

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Prediction of PQ scale from landscape?

- What is the origin of mass scales ? Why is C.C $\sim 10^{-120}\ m_P^4$? String landscape solves the C.C. problem. Why $m_{weak} << m_P$? Where do m_{SUSY} lie ?
- Some earlier analyses by Douglas explored a statistical approach to the magnitude of the SUSY breaking scale where it was found that, in case of F-term SUSY breaking, the magnitude of soft terms $m_{soft} \sim m_{3/2} \sim m_{hidden}^2/m_P$ enjoy a linearly increasing statistical distribution in the landscape $\sim m_{soft}^{2n_F+n_D-1}$
- A mild statistical draw with $n_F = 1$ and $n_D = 0$ $(2n_F + n_D - 1 = 1)$ on the soft terms provides $m_h \sim 125$ GeV while pushing $m_{sparticles}$ beyond LHC reach.
- Agrawal et al. have computed that if the weak scale is increasing by a factor of 2-5 beyond its measured value, then nuclear physics is modified in ways that are unlikely to lead to a livable universe.

- A general consideration of string theory landscape imply a mild statistical draw towards large soft SUSY breaking terms. Can we apply the same reasoning to these well-motivated hybrid models to understand the magnitude of the PQ breaking scale from landscape considerations ?
- Considering mixed axion-WIMP DM, $f_a \sim 10^{11}$-10^{12} GeV so as to meet the measured value of $\Omega h^2 \leq 0.12$
- However, in these hybrid models the relevant soft term is -A_f whose larger values become more probable due to the mild statistical pull. As -A_f gets larger, f_a also increases.

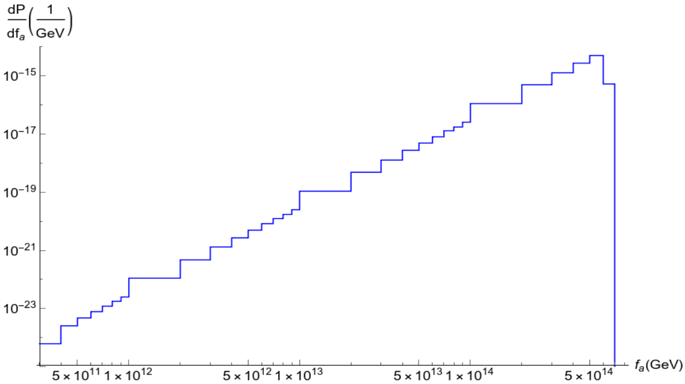

Figure 6: Probability Distribution in f_a with an n=1 statistical pull from the landscape.

- Hence we conclude that setting the PQ scale via anthropics is highly unlikely. This conclusion cannot be negated by adopting a tiny axion misalignment angle θ_i because WIMPs are also overproduced at large f_a.
- Instead, requiring -A_f to be of order the gravity-mediation scale $m_{3/2} \sim$ 10-100 TeV places the mixed axion-neutralino dark matter abundance into the intermediate scale sweet zone where $f_a \sim 10^{11}$-10^{12} GeV.

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Summary

- The MBGW model and the several DFSZ axionic extensions of the MSSM which generate PQ breaking radiatively as a consequence of SUSY breaking are inconsistent with gravity-safe $\mathbb{Z}_N^R$ symmetries which are consistent with GUTs.
- The MBGW model does turn out to be gravity safe under $\mathbb{Z}_{22}$ discrete gauge symmetry but this fundamental symmetry is inconsistent with GUTs.
- We have found two models : **hybrid CCK model** and **hybrid SPM model** which are gravity-safe under $\mathbb{Z}_{24}^R$ symmetry.
- The $\mathbb{Z}_{24}^R$ symmetry forbids the μ term, the RPV operators and the proton decay operators. Besides, the global PQ symmetry emerges accidentally as an approximate global symmetry from the $\mathbb{Z}_{24}^R$ symmetry.
- In these models, we are able to obtain $\mu \approx 200$ GeV as required by naturalness.

- The landscape pull towards large soft terms also pulls the PQ scale as large as possible. Unless this is tempered by rather severe (unknown) cosmological or anthropic bounds on the density of dark matter, then we would expect a far greater abundance of dark matter than is observed. This conclusion cannot be negated by adopting a tiny axion misalignment angle θ_i because WIMPs are also overproduced at large f_a.
- Instead, requiring -A_f to be of order the gravity-mediation scale $m_{3/2} \sim$ 10-100 TeV places the mixed axion-neutralino dark matter abundance into the intermediate scale sweet zone where $f_a \sim 10^{11}$-10^{12} GeV.

THANK YOU

QUESTIONS ?

Back Up Slides

Δ_{EW}, Δ_{HS}, Δ_{BG}

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The Electroweak Measure Δ_{EW}

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{3}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{4}$$

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Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \tag{5}$$

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \tag{6}$$

where Λ is a high energy scale up to which MSSM is valid. Λ can be as high as m_{GUT} or even m_P.

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where Λ is a high energy scale up to which MSSM is valid. Λ can be as high as m_{GUT} or even m_P.
A simple fix for Δ_{HS} is to regroup the dependent terms as follows :

$$m_h^2 \approx \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) \tag{7}$$

This regrouping now leads back to Δ_{EW} measure because now $(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) = m_{H_u}^2(Weak)$.

SUSY μ problem

- The Higgs mass instability problem in EW sector can be solved by introducing weak scale supersymmetry where the Higgs mass quadratic divergences all cancel leaving only mild log divergences
- However, due to lack of appearance of superpartners in LHC, it seems that the superpartners are too heavy to be visible and that might mean that SUSY is unnatural/fine-tuned.
- But before declaring SUSY to be in a fine-tuning crisis, it was pointed out that if $\Delta_{EW} < 30$, then we can still dwell in the natural domain. The Electroweak fine-tuning parameter (Δ_{EW}) is defined as

  $$\Delta_{EW} = max_i |C_i| / (M_Z^2/2) \tag{8}$$

  Where, C_i is any one of the parameters on the RHS of the following equation :

  $$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{9}$$

- $\mu \approx$ **100 - 350 GeV** phenomenologically.
- The MSSM superpotential contains term $\mu H_u H_d$ which leads to $\mu \approx m_p$.

This is the famous SUSY μ problem

- A promising approach to solve the SUSY μ problem is to first forbid μ, perhaps via some symmetry, and then re-generate it of order the scale of soft SUSY breaking terms.
- However, present LHC limits suggest the soft breaking scale m_{soft} lies in the multi-TeV regime whilst naturalness requires $\mu \sim m_{W,Z,h} \sim 100$ GeV so that a Little Hierarchy (LH) appears with $\mu \ll m_{soft}$.

Fundamental R symmetries

- One way to realize PQ symmetry as an approximate global symmetry (so that the model does not suffer the gravity spoliation problem) is to assume a discrete R symmetry– which may emerge from compactification of 10-d Lorentzian spacetime in string theory– as a more fundamental symmetry of which the PQ symmetry emerges as an accidental approximate global symmetry.
- R-symmetries are characterized by the fact that superspace co-ordinates θ carry non-trivial R-charge : +1 being the simplest case.
- For the Lagrangian $\mathcal{L} \ni \int W d^2\theta$ to be invariant under Z_N^R symmetry, the superpotential W must carry R-charge :

$$Q_R(W) = 2 \bmod |N|$$

Radiative PQ breaking scenarios

- **MSY Model** (H. Murayama, H. Suzuki and T. Yanagida)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{MSY}}{m_P}XYH_uH_d \tag{10}$$

- **CCK Model** (K.Choi, E.J. Chun and J.E. Kim)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{CCK}}{m_P}X^2H_uH_d \tag{11}$$

- **SPM Model** (S.P. Martin)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{SPM}}{m_P}Y^2H_uH_d \tag{12}$$

Unfortunately, none of these radiative PQ breaking theories are consistent with the above mentioned R symmetries and hence suffer from the gravity spoilation problem.

- Either the Z_N^R charges of the multiplets are such that all the three terms in W_{PQ} are not allowed OR the model is not gravity-safe i.e., some PQ violating terms arise in the superpotential, just because they are allowed under the Z_N^R fundamental symmetry and the contribution of these terms in the scalar potential are suppressed by $1/m_p^7$ or less.
- Let such a PQV term in W_{PQ} be $\lambda_3 \; X^p Y^q / m_p^{p+q-3}$. Then the most dangerous PQV term in the scalar potential comes from the interference between $\lambda_3 \; X^p Y^q / m_p^{p+q-3}$ and $f \; X^3 Y / m_p$ when constructing the scalar potential as follows :

$$V_F = \left| \frac{\partial W}{\partial X} \right|^2_{X=\phi_X ; Y=\phi_Y} + \left| \frac{\partial W}{\partial Y} \right|^2_{X=\phi_X ; Y=\phi_Y} \tag{13}$$

  Hence, to obtain the PQV term in the scalar potential to be suppressed by $1/m_p^8$ or more, we need p+q $\geq$ 10
- For eg : SPM under Z_6^R symmetry : A PQV term like $M^2 Y$ is always present, thereby making the model gravity unsafe.

MBGW Model

This model was proposed by K.S. Babu, I. Gogoladze and K. Wang (mentioned previously by S.P. Martin and thus labelled **MBGW Model**)

$$W_{PQ} \ni \lambda_\mu \frac{X^2 H_u H_d}{m_P} + \lambda_2 \frac{X^2 Y^2}{m_P} \tag{14}$$

- This model turns out to be gravity-safe if the fundamental symmetry is considered to be a $\mathbf{Z}_{22}$ **discrete gauge symmetry**.

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{22}Charges	3	19	1	11	15	11	22	18	13	20
PQ Charges	1	0	0	1	0	0	-1	-1	1	-1

- However, the disadvantage of using a discrete gauge symmetry is that the charge assignments are inconsistent with SU(5) or SO(10) GUTs which may be expected at some level as a more ultimate theory.
- According to *Krauss and Wilczek*, a discrete gauge symmetry $\mathbf{Z}_M$ might arise if a field of charge Me condenses at some very high mass scale and condensation of a field having charge as high as 22 might not be very plausible because the resulting theory might be inconsistent with a UV completion in string theory.
- This model does not turn out to be gravity safe under any of the R symmetries mentioned before.

Hybrid Models

- These Models are obtained by adopting a hybrid approach between the radiative breaking models and the MBGW model.
- In the radiative breaking models a Majorana neutrino scale is generated as the PQ field X gets VEV, however in these hybrid models the see saw term MN^cN^c is allowed but it is not generated through PQ breaking– similar to MBGW model.
- In the radiative breaking models intermediate PQ and Majorana neutrino scales develop as a consequence of intermediate scale SUSY breaking, while in the MBGW model and in these hybrid models PQ breaking is triggered by large negative soft terms instead of radiative breaking.