Automatic Peccei-Quinn symmetry

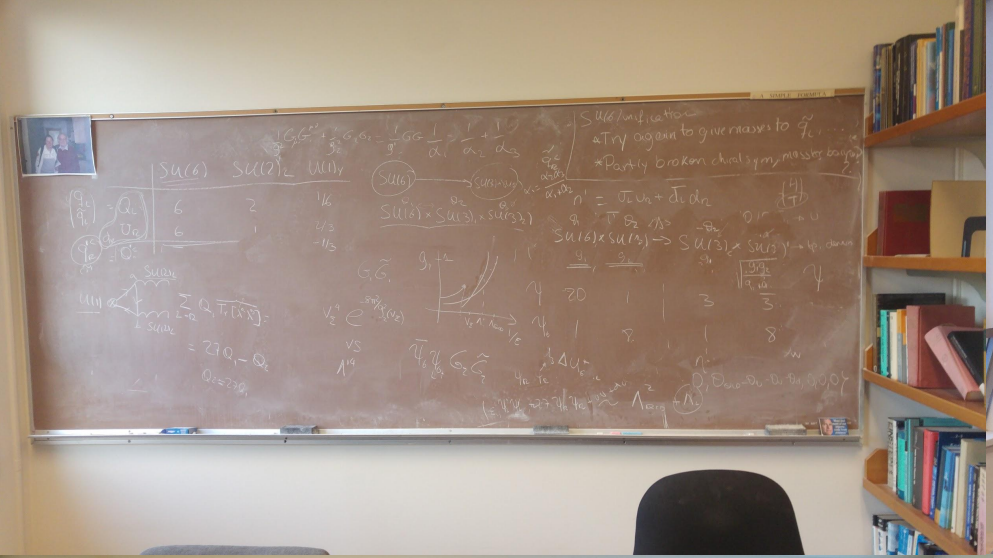
Pablo Quílez Lasanta

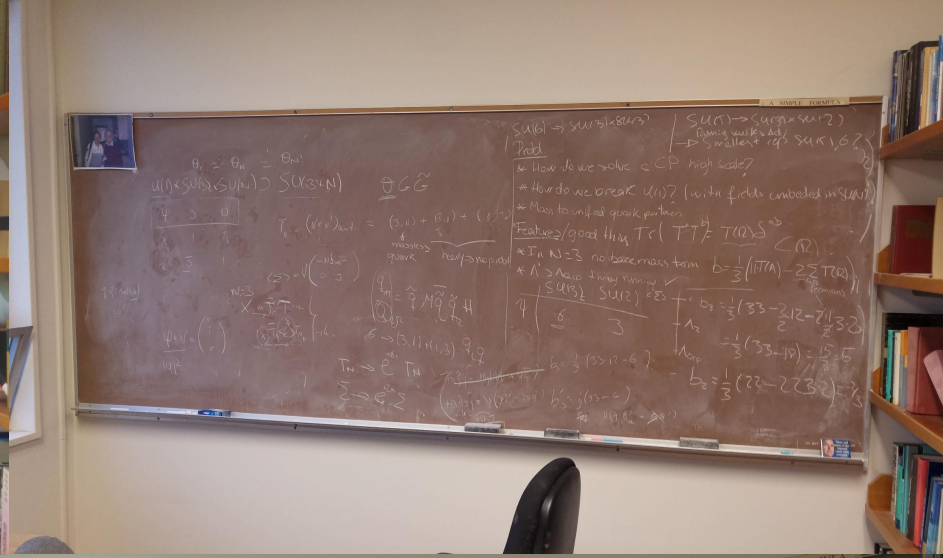
Based on **arXiv:1812.08174** Published in **Eur. Phys. J. C79** (2019) no.5, 369

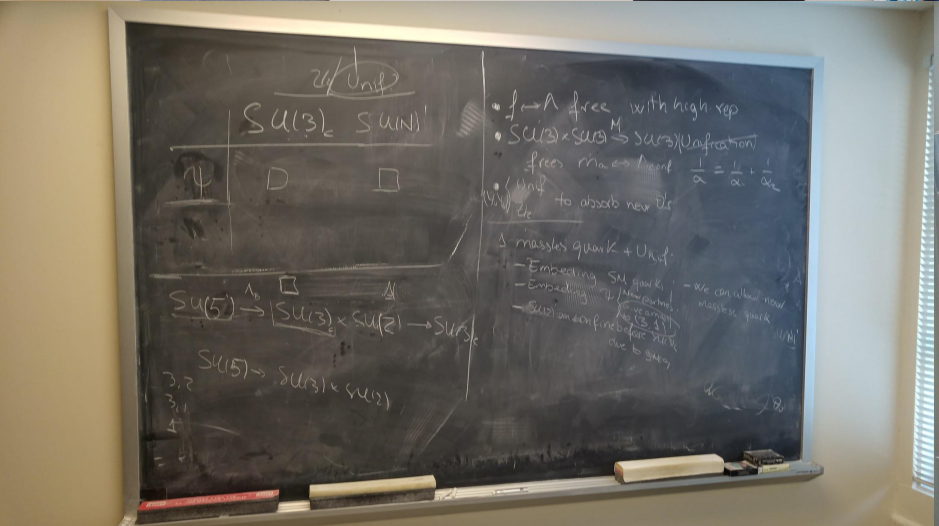
In collaboration with: M.B. Gavela, M. Ibe , T. T. Yanagida

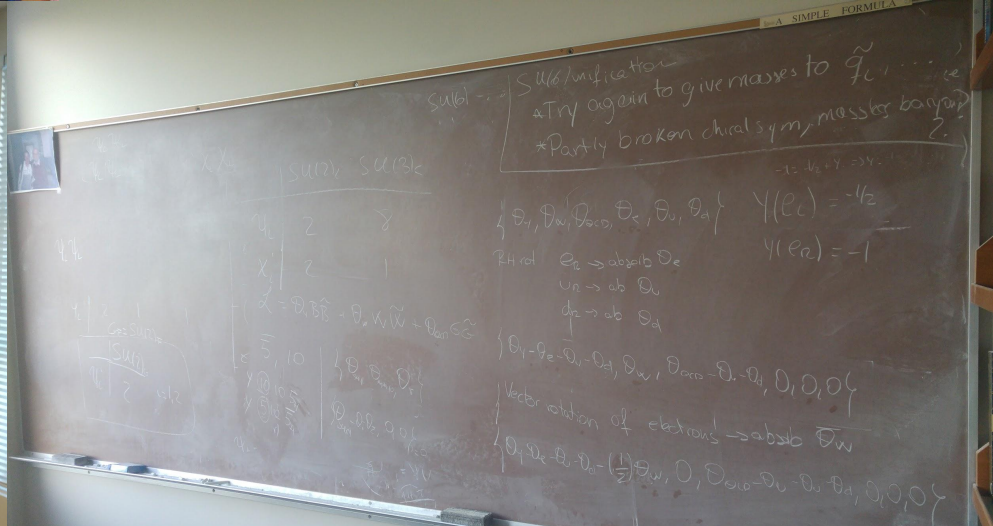
Mary K Fest - Berkeley

September 21st, 2019


A SIMPLE FORMULA
SU(6)/unification
*Try again to give masses to
*Partly broken chiral sym, massless bosons
SU(6) → SU(3)×SU(3)
SU(6)×SU(3)×SU(3)
SU(6)×SU(3) → SU(3)
SU(3) → SU(2)
U(1)
27Q_e − Q_e
Q_e = 27Q_e


A SIMPLE FORMULA
SU(6) → SU(3)×SU(3)
Prob
* How do we solve CP high scale?
* How do we break U(1) (with fields embedded in SU(N))
* Mass to unified quark partners
Feature 2/good thing
* Tr N = 3 no bare mass term
* Λ > Λ_QCD time running
SU(3)
SU(2)
SU(7) → SU(3)×SU(2)
Prance musk × Ad
→ smallest rep SU(3,6)


SU(5)/U_unif
SU(3)_c
SU(N)'
D
SU(5) → SU(3) × SU(2) → SU(3)_c
SU(5) → SU(3) × SU(2)
f → Λ free with high rep
SU(3) × SU(3) → SU(3) (Unification)
free mass → heavy
U_unif
U_e
to absorb new U's
Δ massless quark + U_unif
- Embedding SM quark
- Embedding new quarks
- Suppression confined before 2TeV due to QCD
- we can allow new massless quark


A SIMPLE FORMULA
SU(6)/unification
*Try again to give masses to
*Partly broken chiral sym, massless bosons
SU(2)_c
SU(3)_c
RH rot
e_R → absorb θ_e
u_R → ab θ_u
d_R → ab θ_d
Vector rotation of electrons → absorb θ_W

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Strong CP and axions

The axion solution

- ➔ Strong CP: Why is $\bar{\theta}$ so small? $\bar{\theta} \lesssim 10^{-10}$
- ➔ Introduce a $U(1)_{PQ}$ symmetry (classically exact): [Peccei+Quinn 77]
  - ◆ Spontaneously broken $\longrightarrow$ pGoldstone Boson: AXION
  - ◆ Anomalous: explicitly broken by QCD instantons $\longrightarrow$ massive
- ➔ If $\bar{\theta}$ were a scalar field, its vev would be zero [Vafa+Witten, 84]

$$\bar{\theta}\,\frac{\alpha_s}{8\pi}G\tilde{G} \quad \longrightarrow \quad \left(\bar{\theta} - \frac{a}{f_a}\right)\frac{\alpha_s}{8\pi}G\tilde{G}$$

Massless quark solution and dynamical axion

Massless quark solution

➔ Under a axial rotation: $U(1)_A: \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset -m_q \bar{q} q - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow -m_q \bar{q} e^{i\alpha\gamma_5} q - (\theta - \alpha) \frac{\alpha_s}{8\pi} G\tilde{G}$$

Massless quark solution

- Under a axial rotation: $U(1)_A: \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset -\cancel{m_q \bar{q} q} - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow -\cancel{m_q \bar{q} e^{i\alpha\gamma_5} q} - (\theta - \alpha) \frac{\alpha_s}{8\pi} G\tilde{G}$$

- If $m_q = 0$, the phase θ can be fully reabsorbed $\Longrightarrow$ **Strong CP Problem solved!**

- No different from usual PQ solution

- Most economical option: Massless up quark, disfavored by lattice data [Manohar et al 16, PDG]

Dynamical Axion

[Choi+Kim 85]

- ➔ New confining group $\tilde{\Lambda} \gg \Lambda_{QCD}$
- ➔ Two massless quarks ⇔ two $\theta' s$
- ➔ $SU(\tilde{N})$ Confines + Chiral Symmetry Breaking:

	$SU(3)_c$	$SU(\tilde{N})$
ψ	$\square$	$\square$
χ	1	$\square$

$$U(4)_L \times U(4)_R \xrightarrow[\langle\bar{\chi}\chi\rangle]{\langle\bar{\psi}\psi\rangle} U(4)_V$$

pseudo-Goldstone Bosons (pGB): $16 = 8 + 3 + \bar{3} + 1 + 1$

The η' becomes the dynamical axion

Dynamical Axion

[Choi+Kim 85]

➔ New c

➔ Two m

➔ $SU(\tilde{N}$

pseudo

$SU(2)$	$SU(\tilde{N})$
	$\square$
	$\square$

$\xrightarrow[\langle\bar{\chi}\chi\rangle]{\langle\bar{\psi}\psi\rangle} U(4)_V$

Just another UV completion of the invisible axion...

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

... but composite

The η becomes the dynamical axion

Invisible Axion drawbacks

➔ The $U(1)_{PQ}$ symmetry is imposed

$$\mathcal{L} \supset -m\cancel{\bar{\psi}}\psi - m\cancel{\bar{\chi}}\chi$$

Invisible Axion drawbacks

➔ The $U(1)_{PQ}$ symmetry is imposed

$$\mathcal{L} \supset -m\bar{\psi}\psi - m\bar{\chi}\chi$$

➔ PQ quality: Quantum gravity operators

$$g_5 \frac{|\Phi|^4 (\Phi + \Phi^*)}{M_{\text{Planck}}}$$

[Giddings+Strominger 88]
[Lee 88]
[Abbot+Wise 89]
[Coleman+Lee 90]
[Holman et al 92]
[Kallosh+Linde+Linde+Susskind 95]

Invisible Axion drawbacks

➔ The $U(1)_{PQ}$ symmetry is imposed

$$\mathcal{L} \supset -m\cancel{\bar{\psi}}\psi - m\cancel{\bar{\chi}}\chi$$

➔ PQ quality: Quantum gravity operators

$$g_5 \frac{|\Phi|^4 (\Phi + \Phi^*)}{M_{\text{Planck}}}$$

➔ Possible solution: Accidental axions

[Randall 92]
[Dobrescu 97]
[Butter+Gaillard 05]
[Redi+Sato 16]
[Fukuda et al 17]
[Ibe et al 18]
[Lillard+Tait 18]
[Gavela+Ibe+PQ+Yanagida 18]

Automatic Peccei-Quinn Symmetry

M.B. Gavela, M. Ibe, P.Q, T. T. Yanagida

Dynamical axion with automatic and protected PQ due to chiral SU(5)

Automatic PQ

	$SU(5)$	$SU(3)_c$
$\psi_{\bar{5}}$	$\bar{\mathbf{5}}$	$\mathbf{R}$
ψ_{10}	$\mathbf{10}$	$\mathbf{R}$

LH

➔ Free from gauge anomalies

- Analogous to usual SU(5) GUT: **5*** + **10**
- **R** is a pseudoreal representation

Automatic PQ

	$SU(5)$	$SU(3)_c$	$U(1)_{PQ}$
$\psi_{\bar{5}}$	$\bar{\mathbf{5}}$	$\mathbf{8}$	-3
ψ_{10}	$\mathbf{10}$	$\mathbf{8}$	$+1$

➔ Free from gauge anomalies

- Analogous to usual SU(5) GUT: **5*** + **10**
- **8** is a pseudoreal representation

➔ Automatically we get a $U(1)_{PQ}$:

- Mass terms are automatically forbidden!
- Analogous to usual B-L in SU(5) GUT

Automatic PQ

➔ Free from gauge anomalies

SU(5) GUT: **5*** + **10**

presentation

$\psi_{\bar{5}}$

ψ_{10}

➔

When $U(1)_{PQ}$ is spontaneously broken

=> composite axion

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

... but automatic and protected.

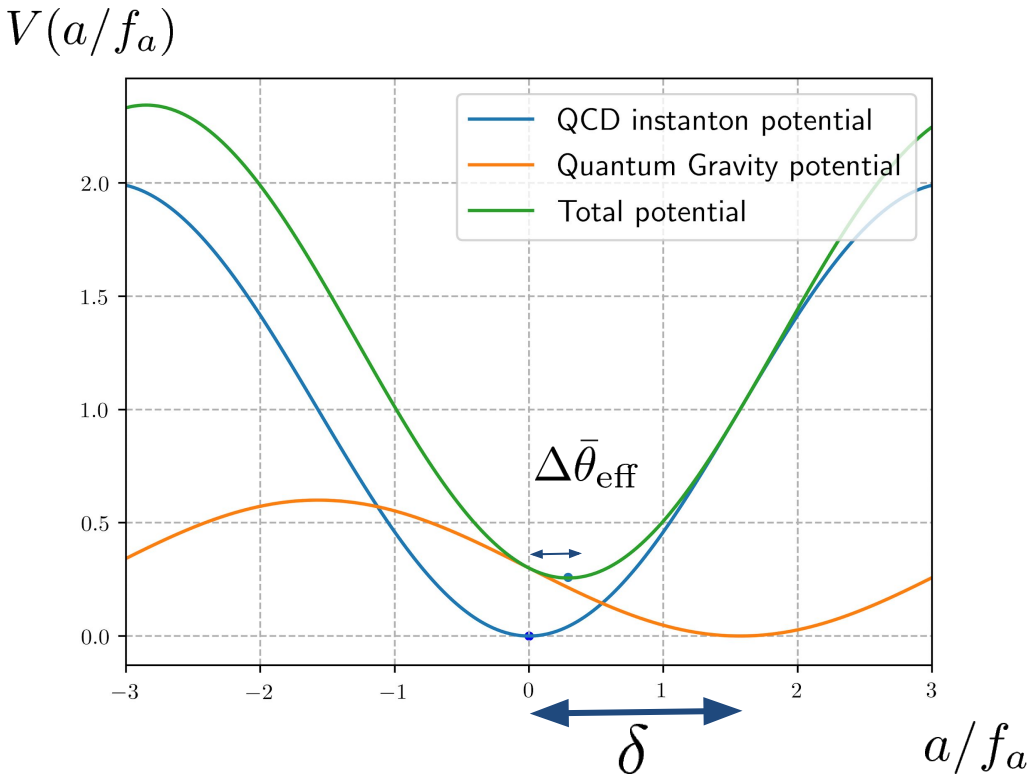
◆ Analogous to usual B-L in SU(5) GUT

PQ quality

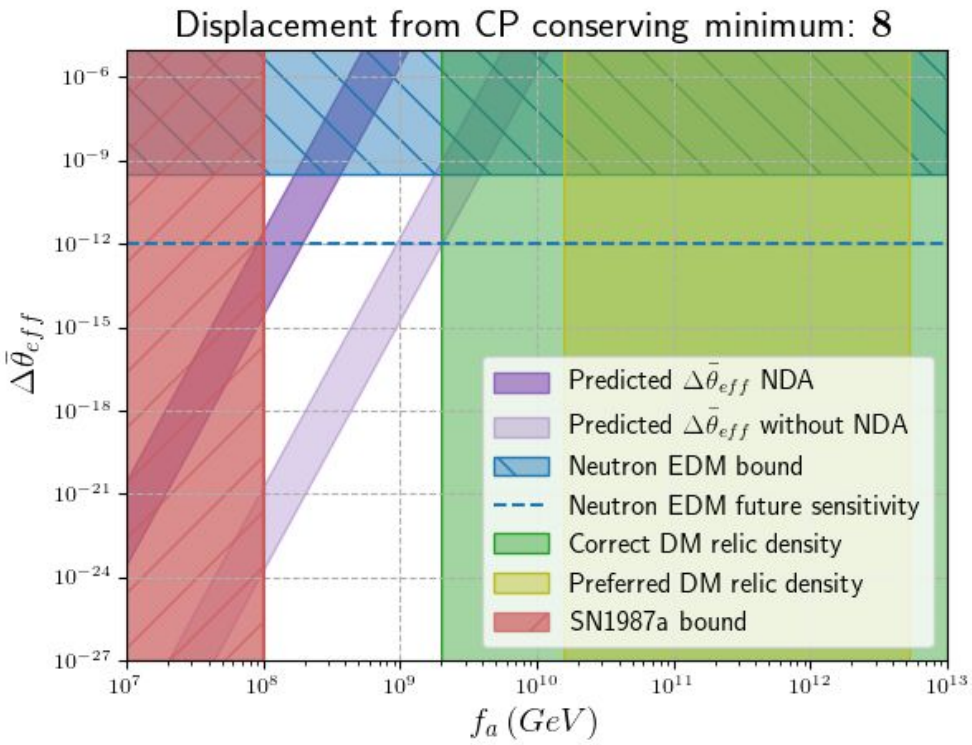
➔ Lowest dim PQV operator has d=9:

$$\mathcal{L}_{\not{PQ}} = c\,\frac{1}{4\pi}\,\frac{1}{M_{\rm Pl}^5}\,\frac{1}{2!\,4!}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}$$

$$|\Delta\bar{\theta}_{eff}| = |c\sin(\delta)|\,\frac{2\,(4\pi)^2}{4!}\left(\frac{N}{5}\right)^8\frac{f_a^9}{M_{Pl}^5\,\Lambda_{\rm QCD}^4}$$



Automatic PQ



Automatic PQ: Global chiral symmetry

➔ SU(5) confines at a high scale $\Lambda_5 \gg \Lambda_{\rm QCD}$

	$SU(5)$	$SU(3)_c$	$U(1)_{PQ}$
$\psi_{\bar{5}}$	$\bar{\mathbf{5}}$	$\mathbf{8}$	-3
ψ_{10}	$\mathbf{10}$	$\mathbf{8}$	$+1$

➔ The global chiral symmetry at high energies:

$$SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{5^*} \times U(1)_{10} \to SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{PQ=B-L}\,.$$

Automatic PQ: Global chiral symmetry

➔ SU(5) confines at a high scale $\Lambda_5 \gg \Lambda_{\rm QCD}$

$\psi_{\bar{5}}$

ψ_{10}

Are chiral symmetries spontaneously broken after confinement?

➔ The global chiral symmetry at high energies:

$$SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{5^*} \times U(1)_{10} \to \boxed{SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{PQ=B-L}\,.}$$

Confinement VS Chiral symmetry breaking

➔ There are two options:

- Global symmetries are spontaneously broken ⇒ (pseudo)- **Goldstone bosons** arise.
- Global symmetries remain unbroken ⇒ **massless baryons** arise, and

't Hooft anomaly matching conditions are fulfilled.

$$SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{PQ=B-L}$$

Confinement VS Chiral symmetry breaking

$$\boxed{SU(8)_{5^*} \times SU(8)_{10}} \times U(1)_{PQ=B-L}$$

Impossible to match anomalies:
It has to be spontaneously broken

Confinement VS Chiral symmetry breaking

$$SU(8)_{5^*} \times SU(8)_{10} \times \boxed{U(1)_{PQ=B-L}}$$

Possible to match anomalies. Two options:

1. No chiral SB ⇒ Massless coloured baryon phenomenologically excluded χ = 10 5* 5*
2. Chiral SB ⇒ pGB, **AXION**

Conclusions

- ➔ A simple dynamical (composite) axion model where the PQ symmetry arises **automatically** is constructed.
- ➔ Based on a confining group **SU(5) with chiral fermions** in pseudoreal representations of colour.
- ➔ Presents an **inherent protection** from possibly dangerous gravitational effects.

Thank you!

Confinement VS Chiral symmetry breaking

➔ Global anomalies at high energies in terms of quarks

$$
\begin{aligned}
[SU(8)_{\bar{5}}]^3 : &\quad 5 \times A(\square) = 5\,, \\
[SU(8)_{10}]^3 : &\quad 10 \times A(\square) = 10\,, \\
U(1)_{PQ} \times [SU(8)_{\bar{5}}]^2 : &\quad 5 \times 2\,T(\square) Q_{\bar{5}} = -15\,, \\
U(1)_{PQ} \times [SU(8)_{10}]^2 : &\quad 10 \times 2\,T(\square) Q_{10} = 10\,, \\
[U(1)_{PQ}]^3 : &\quad 8\left(5\,(Q_{\bar{5}})^3 + 10\,(Q_{10})^3\right) = -1000\,.
\end{aligned}
$$

➔ Global anomalies at low energies in terms of bound states:

$$
\begin{aligned}
[SU(8)_{\bar{5}}]^3 : &\quad 8\,(n_{28}\,A(\mathbf{28}) + n_{36}\,A(\mathbf{36})) = 32(n_{28} + 3n_{36})\,, \\
[SU(8)_{10}]^3 : &\quad 28\,n_{28}\,A(\mathbf{8}) + 36\,n_{36}\,A(\mathbf{8}) = 4(7\,n_{28} + 9\,n_{36})\,, \\
U(1)_{PQ} \times [SU(8)_{\bar{5}}]^2 : &\quad 8\,PQ(\chi)\,(n_{28}\,2\,T(\mathbf{28}) + n_{36}\,2\,T(\mathbf{36})) = -80(3\,n_{28} + 5n_{36})\,, \\
U(1)_{PQ} \times [SU(8)_{10}]^2 : &\quad PQ(\chi)\,(28\,n_{28}\,2\,T(\mathbf{8}) + 36\,n_{36}\,2\,T(\mathbf{8})) = -20(7n_{28} + 9n_{36})\,, \\
[U(1)_{PQ}]^3 : &\quad 8\,(28n_{28} + 36n_{36})\,\left(PQ(\chi)\right)^3 = -4000\,(7n_{28} + 9n_{36})\,.
\end{aligned}
$$