Peccei-Quinn Genesis

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Eung Jin Chun, Hyun Min Lee, and Jun-ho Song
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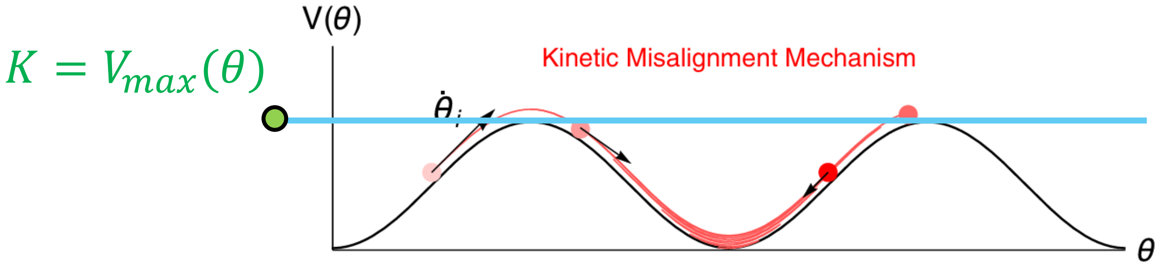
Presenter: Junho Song

Can minimal extension of KSVZ + seesaw mechanism explain following problems?

1. Flatness problem
2. Strong CP problem
3. Baryon asymmetry
4. axion dark matter abundance
5. Neutrino mass

Motivation

$$V = m_a(T)^2 v_a^2 \left(1 - \cos\left(\frac{a}{v_a}\right)\right)$$



Axiogenesis (arXiv:1910.02080v2):

Mechanism of spontaneous baryogenesis through the axion kinetic misalignment

Successful Cogenesis => $Y_\theta^{\mathrm{BAU}} \approx Y_\theta^{\mathrm{axion\ DM}}$

Assumption

Y_θ is constant

$$Y_\theta^{\mathrm{BAU}} \approx \mathcal{O}(100) \cdot Y_\theta^{\mathrm{axion\ DM}}$$

Where $2\, Y_\theta^{\mathrm{axion\ DM}} \cdot \mathrm{m_a} \approx 0.44\ \mathrm{eV}$

There are two ways:

1. For given $Y_\theta = Y_\theta^{\mathrm{BAU}}$, **dissipation** (For $\mathrm{T} < \mathrm{T_{EW}}$) decrease Y_θ up to $Y_\theta^{\mathrm{axion\ DM}}$

2. Introduce new source to get current baryon asymmetry given Small $Y_\theta^{\mathrm{axion\ DM}}$

$\Rightarrow$ Type 1 seesaw model

Key Idea to get BAU given (small) $Y_{\theta}^{\text{axion DM}}$

$n_{PQ,end}$

$\rho \cong v_a$ (transition to kination phase)

$$n_\theta = v_a^2 \dot{\theta}$$

$$\dot{\theta}(t) \propto a(t)^{-3}$$

Kinetic equilibrium rate ≫ chemical equilibrium rate

$$\Gamma_{\text{chemical}} \gg H \gg \left(\frac{T}{v_a}\right)^2 \Gamma_{\text{chemical}}$$

Relaxation rate for $\dot{\theta} \approx \left(\frac{T}{v_a}\right)^2 \cdot$ Relaxation rate for $n_{\Delta f}$

$n_{\Delta f}$ is fast variable

$\dot{\theta}$ is slow variable

$\Gamma_{\text{chemical}} \gg H$

(Quasi-equilibrium)

$$\dot{n}_{\Delta f} = 0$$

$$n_{\Delta f} = \frac{\mathcal{O}(1)}{6} \dot{\theta}(t) T^2 \propto a^{-5}$$

$$\sum_i \mu_i(t) = \mathcal{O}(1) \cdot \dot{\theta}(t) \longrightarrow \mu_i(t) \propto \dot{\theta}(t)$$

$\Gamma_{\text{chemical}} < H$

After decoupling of chemical interaction

$$n_{\Delta f} \propto \dot{\theta}(T_{dec}) a^{-3}$$

For (weak) **sphaleron process**, decoupling temperature T_{dec} is EW phase transition scale

$\boldsymbol{Y_{\Delta f}}$ **(comoving net number density for f fermion) is conserved**

Key Idea to get BAU given (small) $Y_\theta^{\text{axion DM}}$

Including Seesaw mechanism

$n_{PQ,\text{end}}$

$$n_\theta = v_a^2 \dot{\theta}$$

$\rho \cong v_a$ (transition to kination phase)

$$\dot{\theta}(t) \propto a(t)^{-3}$$

Quasi-equilibrium

$$\dot{n}_{\Delta f} = 0$$

$$\sum_i \mu_i(t) = \mathcal{O}(1) \cdot \dot{\theta}(t)$$

$\Gamma_{\text{chemical}} \gg H$

$$n_{\Delta f} = \frac{\mathcal{O}(1)}{6} \dot{\theta}(t) T^2 \propto a^{-5}$$

$n_{\Delta f}$ is fast variable

$\dot{\theta}$ is slow variable

$\left(\frac{T}{v_a}\right)^2$ times slower

$\Gamma_{\text{chemical}} < H$

After decoupling of chemical interaction

$$n_{\Delta f} \propto \dot{\theta}(T_{\text{dec}}) a^{-3}$$

Key Idea to get BAU given (small) $Y_\theta^{\text{axion DM}}$

Including Seesaw mechanism

$n_{PQ,end}$

$n_\theta = v_a^2\dot{\theta}$

$\rho \cong v_a$ (transition to kination phase)

$\dot{\theta}(t) \propto a(t)^{-3}$

$\Gamma_{RHN} \gg H$

(In strong washout regime)

Inverse decay of RHN is active around $T{\sim}M_N$ and it is decoupled at $T{\sim}\mathcal{O}(0.1)\cdot M_N$

$\Gamma_{RHN} < H$

After decoupling of inverse decay of RHN

$$Y_{\Delta f,B-L} = \frac{n_{\Delta f}}{s} \sim \frac{\dot{\theta}(T_{B-L})}{T_{B-L}}$$

$\Gamma_{sph} \gg H$

$$\frac{Y_{\Delta f,B-L}}{Y_{\Delta f,sph}} \sim \left(\frac{T_{B-L}}{T_{EW}}\right)^2$$

$\Gamma_{sph} < H$

After decoupling of EW sphaleron

$$Y_{\Delta f,sph} = \frac{n_{\Delta f}}{s} \sim \frac{\dot{\theta}(T_{EW})}{T_{EW}}$$

For given same $Y_\theta = Y_\theta^{\text{axion DM}}$

If Inverse decay is decoupled when $T_{dec} \sim \mathcal{O}(10)\cdot T_{EW}$, Thus, we expect $M_N = \mathcal{O}(10)$ **TeV**

Charge asymmetry arrangement in t-dep background

In the minimal extension of **KSVZ** with **seesaw model**,

$$-y_Q \Phi Q Q^c - \frac{1}{2} y_N \Phi N N + \text{h.c.} \quad \text{where} \quad \Phi = \frac{v_a}{\sqrt{2}} e^{i\theta}$$

⬇

Under $\mathrm{U(1)_{PQ}}$ local transformation,

$$\partial_\mu \theta \, J^\mu_{PQ} \;\rightarrow\; \dot{\theta} \, J^0_{PQ} \quad \text{where} \quad \partial_\mu \theta = (\dot{\theta}, 0, 0, 0)$$

Energy shifting between particle and anti-particle,
$\mathrm{E} \rightarrow \mathrm{E} \pm (\mathrm{PQ\ charge}) \cdot \dot{\theta}$

⬇

$$f_l(p) \simeq e^{-\frac{E+\mu}{T}} \qquad \mu_i \rightarrow \mu_i - q_i^{PQ} \dot{\theta}$$

	Φ	$\mathrm{N_R}$	Q	ℓ_{L}	$\mathrm{e_R}$	The other
$\mathrm{q_i^{PQ}}$	1	-1/2	-1/2	-1/2	-1/2	0

KSVZ axion model with type 1 seesaw

$$-\mathcal{L}_{\text{Yukawa}} = y_u q u^c H + y_d q d^c \tilde{H} + y_e l e^c \tilde{H} + y_\nu l N H + h.c.$$

$$-\mathcal{L}_{\text{anomaly}} = \frac{c_S}{32\pi^2} \frac{a}{v_a} G\tilde{G} + \frac{c_W}{32\pi^2} \frac{a}{v_a} W\tilde{W}$$

$$-\mathcal{L}_{\text{KSVZ}} = y_Q \Phi Q Q^c + \frac{1}{2} y_N \Phi N N + h.c.$$

Chemical potential (Equilibrium) relations for obtaining $\mathrm{Y_{B-L}}$

$$\left.\begin{aligned}
&\mu_{q_i} + \mu_{u_i^c} + \mu_H = c_S \frac{m_d^2}{m_u^2 + m_d^2} \dot{\theta}\, \delta_{i1} \\
&\mu_{q_i} + \mu_{d_i^c} - \mu_H = c_S \frac{m_u^2}{m_u^2 + m_d^2} \dot{\theta}\, \delta_{i1} \\
&\textstyle\sum_i \left(2\mu_{q_i} + \mu_{u_i^c} + \mu_{d_i^c}\right) = c_S \dot{\theta}.
\end{aligned}\right\} \quad \Gamma_{y_{u_1,d_1}} \ll \Gamma_{y_{u_{2,3},d_{2,3}}}, \Gamma_{SS,WS}$$

$$\mu_{l_i} + \mu_{e_i^c} - \mu_H = 0,$$

$$\mu_{l_i} + \mu_H = x_l \dot{\theta},$$

$$\textstyle\sum_i \left(3\mu_{q_i} + \mu_{l_i}\right) = c_W \dot{\theta}$$

+ hypercharge neutrality $\qquad c_B = -0.13$

$$\Rightarrow \quad \mu_{B-L} = \frac{1}{33}\left(28 c_W - c_S \frac{57 m_u^2 - 15 m_d^2}{m_u^2 + m_d^2} - 153 x_l\right)\dot{\theta}$$

Origin of non-zero Υ_θ: PQ pole inflation

(*JHEP* 05 (2024) 295, arXiv: 2310.17710v2)

Can Υ_θ be arbitrary large?

Set up

$$V_E = V_{\rm PQC} + V_{\rm PQV}$$

$$V_{\rm PQC} = \frac{\lambda_\Phi}{4}(\rho^2 - v_a^2)^2$$

$$V_{\rm PQV} = \frac{|\lambda_n|}{\sqrt{2^{n-2}}}\frac{\rho^n}{M_P^{n-4}}\cos(n\theta + \delta)$$

Setting EFT Lagrangian at Planck scale

Peccei-Quinn field ($U(1)_{PQ}$ complex scalar field) is non-minimally coupled to gravity in Jordan frame.

$$\Omega(\Phi) = 1 - 2\zeta\frac{|\Phi|^2}{M_P^2}$$

$$g_{J.\mu\nu} = g_{E,\mu\nu}/\Omega$$ Weyl transformation

$$\Phi = \frac{1}{\sqrt{2}}\rho\, e^{i\theta}$$ Polar representation

Einstein frame

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{M_P^2}{2}R + \frac{1 + \zeta(6\zeta - 1)\frac{\rho^2}{M_P^2}}{2(1 - \zeta\frac{\rho^2}{M_P^2})^2}(\partial_\mu\rho)^2 + \frac{\rho^2(\partial_\mu\theta)^2}{2(1 - \zeta\frac{\rho^2}{M_P^2})} - V_E$$

Inflation

$$V_E = V_{\rm PQC} + V_{\rm PQV}$$

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{M_P^2}{2}R + \frac{1+\zeta(6\zeta-1)\frac{\rho^2}{M_P^2}}{2(1-\zeta\frac{\rho^2}{M_P^2})^2}(\partial_\mu\rho)^2 + \frac{\rho^2(\partial_\mu\theta)^2}{2(1-\zeta\frac{\rho^2}{M_P^2})} - V_E$$

From CMB normalization, $\frac{\lambda_\Phi}{\zeta^2} \simeq 4\times 10^{-10}$

Inflation is driven by **pole** at the kinetic term of **radial mode**

Inflationary Prediction

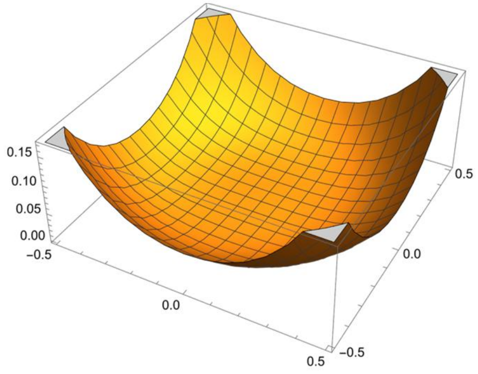
During inflation, $\rho \to \frac{M_P}{\sqrt{\zeta}}$ $\quad \rho \simeq \frac{M_P}{\sqrt{\zeta}}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)$ It gives flat potential

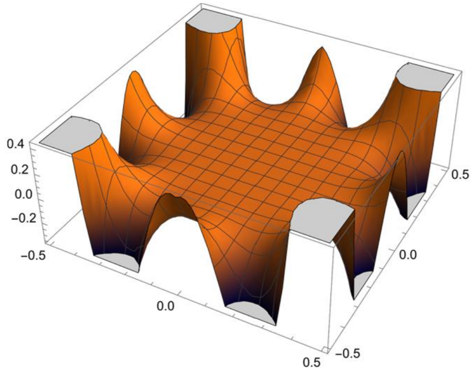
(Canonical form)

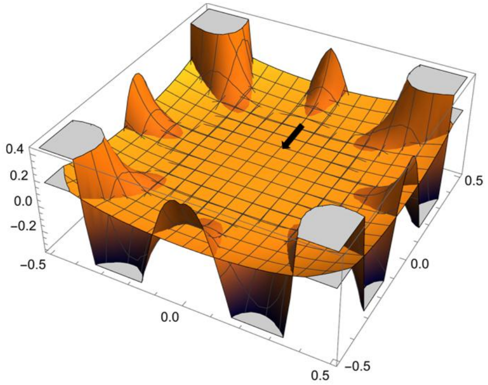
For $N=60$, $\quad n_s \cong 0.9667$, $\quad r \cong 0.0033$

Assumption: Inflation is realized via slow-roll of the radial mode in the V_{PQC}

For n=8, and $10^2 \times \lambda_\Phi = \lambda_{\rm n}$







$$V_{\rm PQC} = \frac{\lambda_\Phi}{4}(\rho^2 - v_a^2)^2 \qquad V_{\rm PQV} = \frac{|\lambda_n|}{\sqrt{2^{n-2}}}\frac{\rho^n}{M_P^{n-4}}\cos(n\theta+\delta)$$

$\varepsilon_\phi > \varepsilon_\theta$ (Inflaton slow rolls along radial direction)

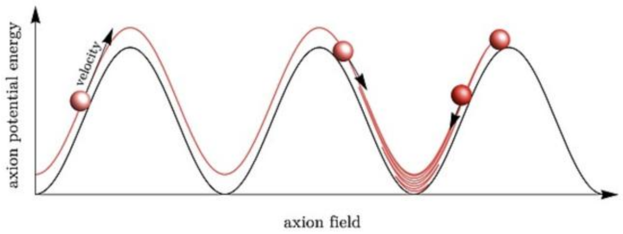
We have two conditions:

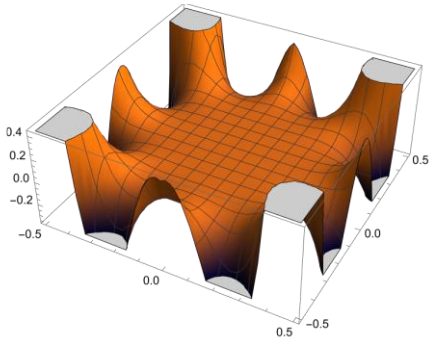
$$V_{\rm PQC} > V_{\rm PQV}, \quad \frac{\partial V_{\rm PQC}}{\partial\phi} > \frac{\partial V_{\rm PQV}}{\partial\phi}$$

$$n_{\theta,e} \approx -\frac{1}{3H}\frac{\partial V_{\rm PQV}}{\partial\theta}\bigg|_{\rho=\rho_e}$$

Axion Quality Problem

$$V_{\text{eff}}(a) = V_0 - \Lambda_{\text{QCD}}^4 \cos\left(\bar{\theta} + c_S \frac{a}{v_a}\right) + \underbrace{\frac{\lambda_n}{\sqrt{2^n}} M_P^4 \left(\frac{v_a}{M_P}\right)^n \cdot 2\cos\left(n\frac{a}{v_a} + \delta\right)}_{V_{\text{PQV}}(|\phi|=v_a,a)}$$





V_{PQV} is Planck suppressed

Mass of axion at the minimum of $V_{eff}(a)$ can be shifted from V_{PQV}

$$\delta m_a^2 \equiv n^2 \frac{|\lambda_n|}{\sqrt{2^{n-2}}} \frac{v_a^{n-2}}{M_P^{n-4}} \lesssim 10^{-10} \frac{n}{N_{DW}} m_a^2$$

$$|\theta_{\text{eff}}| = \left|\bar{\theta} + c_S \frac{\langle a \rangle}{v_a}\right| < 10^{-10}$$

Neutron EDM bound

It gives constraint V_{PQV} that kicks the axion initially

Post Inflation dynamics, and Reheating

After the end of inflation, PQ charge is **conserved**

$$V_{\rm PQV} = \frac{|\lambda_n|}{\sqrt{2^{n-2}}} \frac{\rho^n}{M_P^{n-4}} \cos(n\theta + \delta)$$

$$V_{\rm PQC} = \frac{\lambda_\Phi}{4}(\rho^2 - v_a^2)^2$$

$\rho_e \approx \frac{0.732}{\sqrt{\zeta}} M_P$ $\qquad n_{\theta,e} = n_{\theta,e}(n, \lambda_n)$

$\rho_c \equiv \frac{M_P}{\sqrt{6\zeta}}$

$\rho < \rho_c \Rightarrow$ canonical normalized field

Radiation (like)

$$n_\theta(\phi) = n_{\theta,e}\, c_N^{-\frac{3}{4}} \left(\frac{V_{\rm PQC}(\phi)}{V_{\rm PQC}(\rho_e)}\right)^{\frac{3}{4}}$$

Radiation like Redshift

We assume that **reheating** occurs when $v_a < \rho \ll \frac{M_p}{\sqrt{6\zeta}}$

Reheating

$v_a \simeq \rho$

PQ charge comoving number density

$$Y_\theta \equiv \frac{n_\theta(T_{RH})}{s(T_{RH})} \simeq 2.5 \times 10^7\, c_N^{-\frac{3}{4}} \frac{n_{\theta,e}}{M_P^3}$$

at reheating, $V_{\rm PQC}(\phi_{\rm RH}) = \frac{g_* \pi^2}{30} T_{\rm RH}^4$

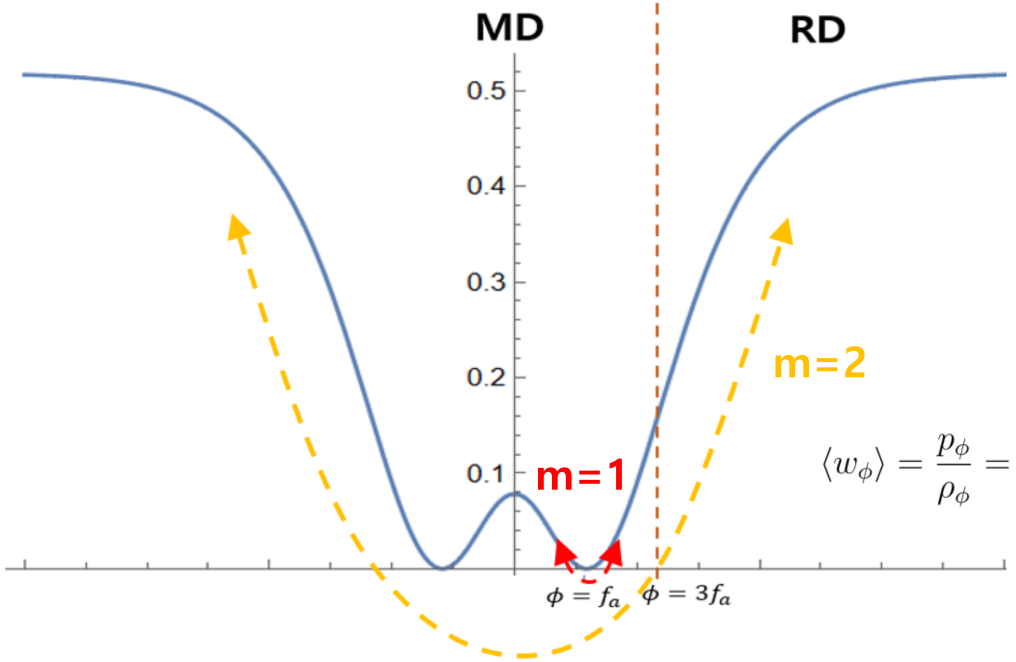
⋮ ⋮

In the PQ pole inflation, $Y_{\theta,\max} \approx 100$

Reheating (for KSVZ)

Inflaton oscillates around minimum in $V_{\rm PQC} = \frac{\lambda_\Phi}{4}(\phi^2 - v_a^2)^2$

Heavy quark mass, $m_Q(t) = \frac{y_Q}{\sqrt{2}}\phi(t)$, **also oscillates**



$\langle w_\phi \rangle = \frac{p_\phi}{\rho_\phi} = \frac{m-1}{m+1}$

for the **KSVZ** model, $\Gamma_\phi = \Gamma(\phi \to \bar{Q}Q) + \Gamma(\phi \to \bar{N}N)$

$\mathrm{M_N} = \mathrm{M_N}(\mathrm{v_a})$ ➡ $\Gamma(\phi \to \bar{N}N)$ is determined

Reheating is realized by $\Gamma(\phi \to \bar{Q}Q)$
And reheating temperature is bounded by $\Gamma(\phi \to \bar{N}N)$

From the sudden decay approximation, $\Gamma_\phi \cong \mathrm{H}$

reheating temperature is

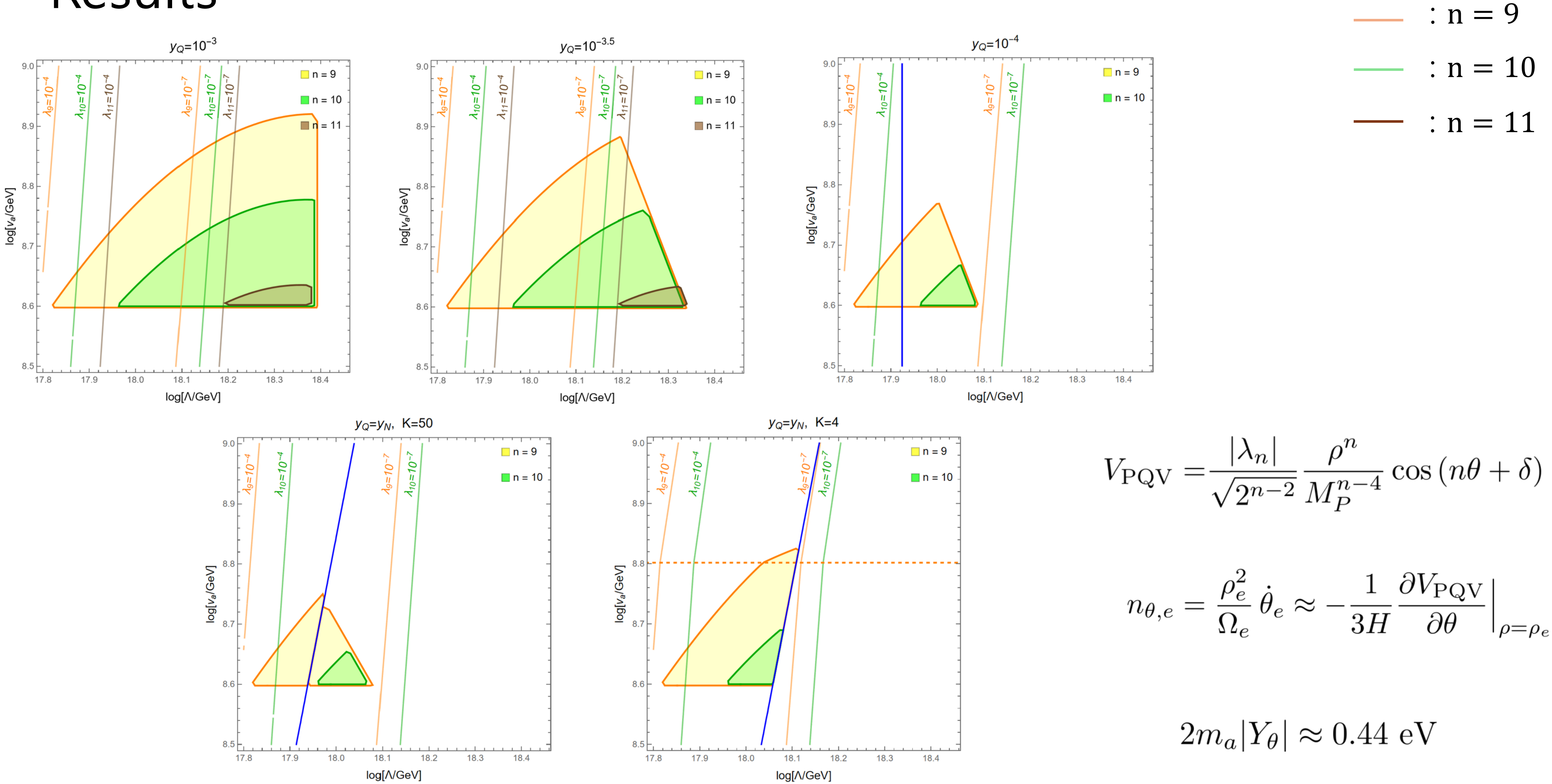
$$T_{\rm RH} \simeq 1.5 \times 10^6 \ \mathrm{GeV} \left(\frac{y_{f,\rm eff}}{10^{-4}}\right)^2 \left(\frac{\lambda_\Phi}{10^{-11}}\right)^{1/4}$$

If $(E_\phi = wn) > (m_Q(t) = \frac{y_Q}{\sqrt{2}}\phi(t))$ during one oscillation,
$\phi \to \bar{Q}Q$ is Kinematically allowed

$y_Q < \sqrt{\lambda_\phi}$ — $E_\phi > m_Q(t)$ is always satisfied

$y_Q > \sqrt{\lambda_\phi}$ $\quad y_c < y^Q_{\rm eff,k=4}$ — $E_\phi > m_Q(t)$ is only satisfied around $\phi \cong 0$

Results

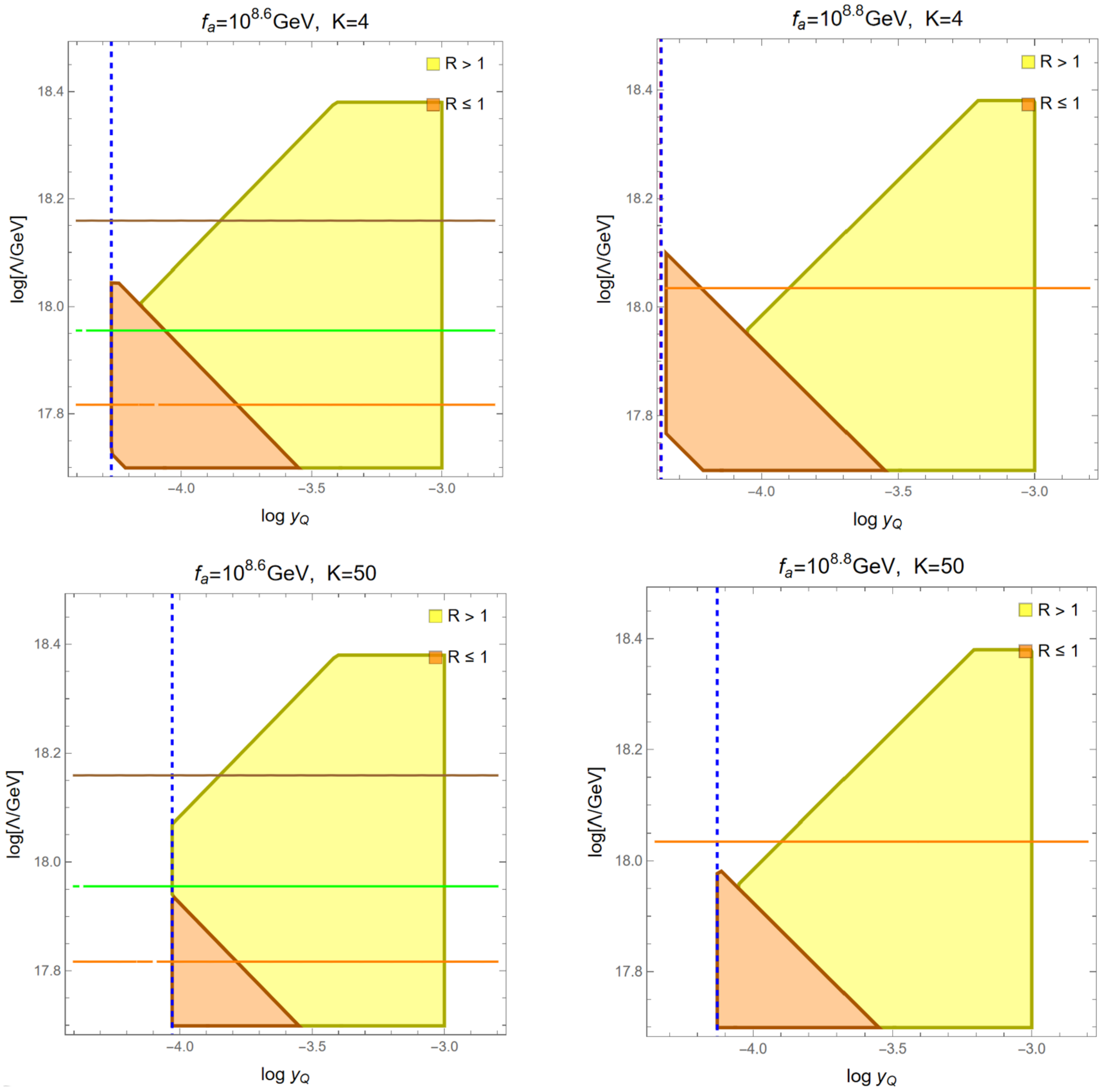


$$V_{\mathrm{PQV}} = \frac{|\lambda_n|}{\sqrt{2^{n-2}}} \frac{\rho^n}{M_P^{n-4}} \cos(n\theta + \delta)$$

$$n_{\theta,e} = \frac{\rho_e^2}{\Omega_e} \dot{\theta}_e \approx -\frac{1}{3H} \frac{\partial V_{\mathrm{PQV}}}{\partial \theta}\Big|_{\rho=\rho_e}$$

$$2m_a |Y_\theta| \approx 0.44 \text{ eV}$$

Results



: n = 9

: n = 10

: n = 11

$$V_{\mathrm{PQV}} = \frac{|\lambda_n|}{\sqrt{2^{n-2}}} \frac{\rho^n}{M_P^{n-4}} \cos(n\theta + \delta)$$

$$\mathcal{R} = \left(\frac{2m_f(\phi_0)}{E_\phi} \right)^2$$

Blue dotted line: $y_Q = \sqrt{3} y_N$

Summary

- PQ genesis solves the 4 problems
- Non-zero PQ charge is the source to get baryon asymmetry and axion DM abundance
- We require limited $f_a = (4\sim9) \times 10^8$GeV for successful cogenesis

Thank you!