Tsung-Dao Lee Institute

Axion Quality from Superconformal Dynamics

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Based on YN and M. Suzuki (TDLI), PLB 2021.

Strong CP Problem

QCD Lagrangian for strong interactions allows

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \widetilde{G}^a_{\mu\nu}$$

explicitly violating **CP** symmetry.

The physical strong CP phase : $\bar{\theta} \equiv \theta - \arg\det\left(M_u M_d\right)$

The current upper bound on the neutron electric dipole moment

$$\Rightarrow |\bar{\theta}| < 10^{-11}$$

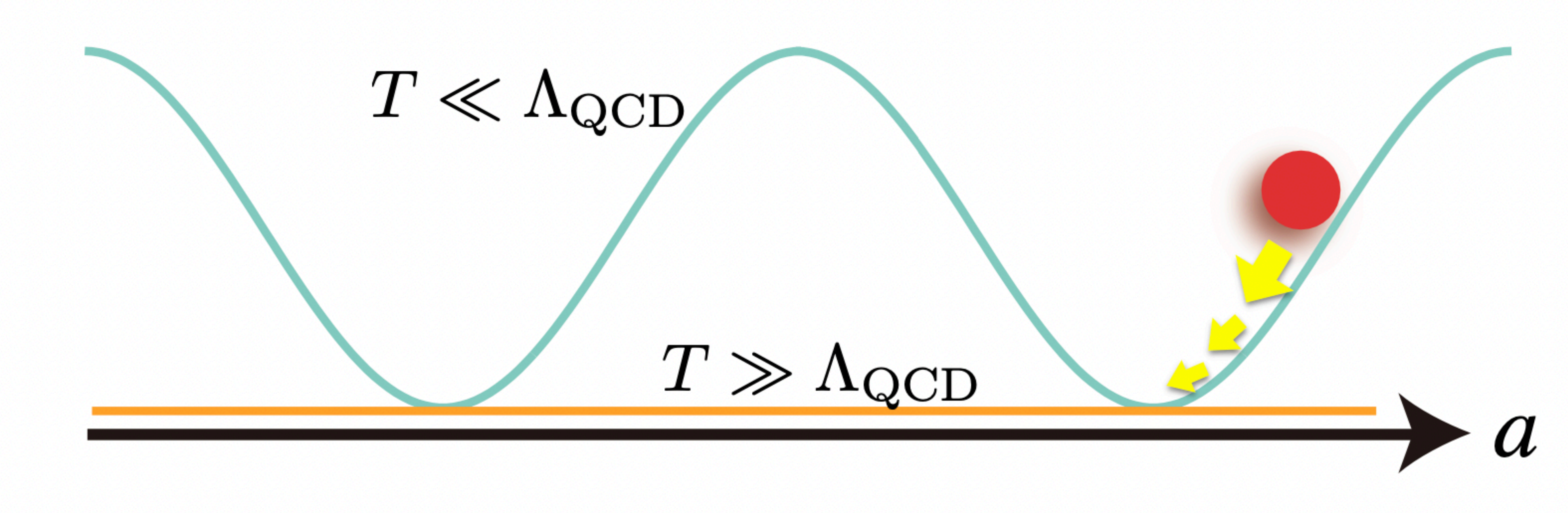
Why is $\bar{\theta}$ so small ??

Some shifts of $\bar{\theta}$ would not provide a visible change in our world.

Axion Solution

The most common explanation is **the Peccei-Quinn mechanism** that the strong CP phase is promoted to a dynamical variable.

$$\mathcal{L}_\theta = \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$



Fuminobu Takahashi slide

The axion a dynamically cancels the strong CP phase !

Axion Solution

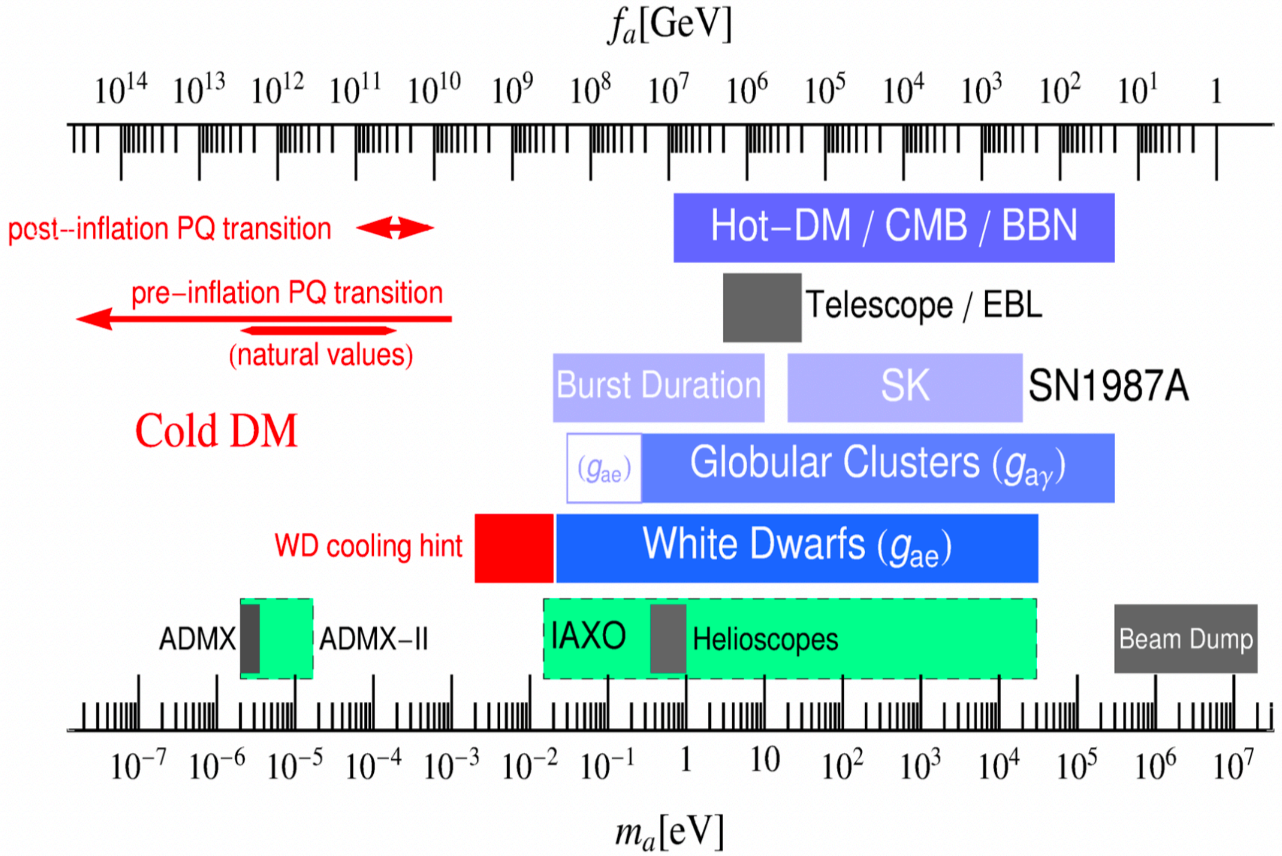
Axion is a pseudo-Nambu-Goldstone boson associated with spontaneous breaking of **a global U(1)PQ symmetry**.

Non-perturbative QCD effects break the U(1)PQ explicitly and generate the axion potential :

$$V(a) \sim m_\pi^2 f_\pi^2 \cos\left(\theta + \frac{a}{f_a}\right)$$

Astrophysical observations put a lower limit :

$$f_a \gtrsim 10^8\ \mathrm{GeV}$$



PDG

Axion Quality Problem

The small strong CP phase requires the U(1)$_{PQ}$ to be realized to an extraordinary high degree.

⇕

Quantum gravity effects do not respect such a global symmetry.

Planck suppressed U(1)$_{PQ}$-violating operators are expected.

$$\Delta V(\phi) \sim \frac{|\phi|^{k+3}}{M_{\rm Pl}^k}\phi + \mathrm{h.c.}$$

➡ Destroy the Peccei-Quinn mechanism.

$$\Delta V(a) \sim f_a^4 \left(\frac{f_a}{M_{\rm Pl}}\right)^k \cos\left(\frac{a}{f_a} - \varphi\right) \qquad \langle\phi\rangle \equiv \frac{f_a}{\sqrt{2}}$$

Axion Quality Problem

The small strong CP phase requires the $U(1)_{PQ}$ to be realized to an extraordinary high degree.

Quantum gravity ef ... nmetry.

Planck ... d.

Superconformal dynamics !

$$\frac{\quad}{M_{\rm Pl}^k}\phi + \text{h.c.}$$

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Conformal Dynamics

The PQ breaking field marginally couples to **CFT sector fields**.

$$W_{\rm int} = \lambda \phi \mathcal{O}_{\rm CFT}$$

The PQ breaking field holds a large anomalous dimension.

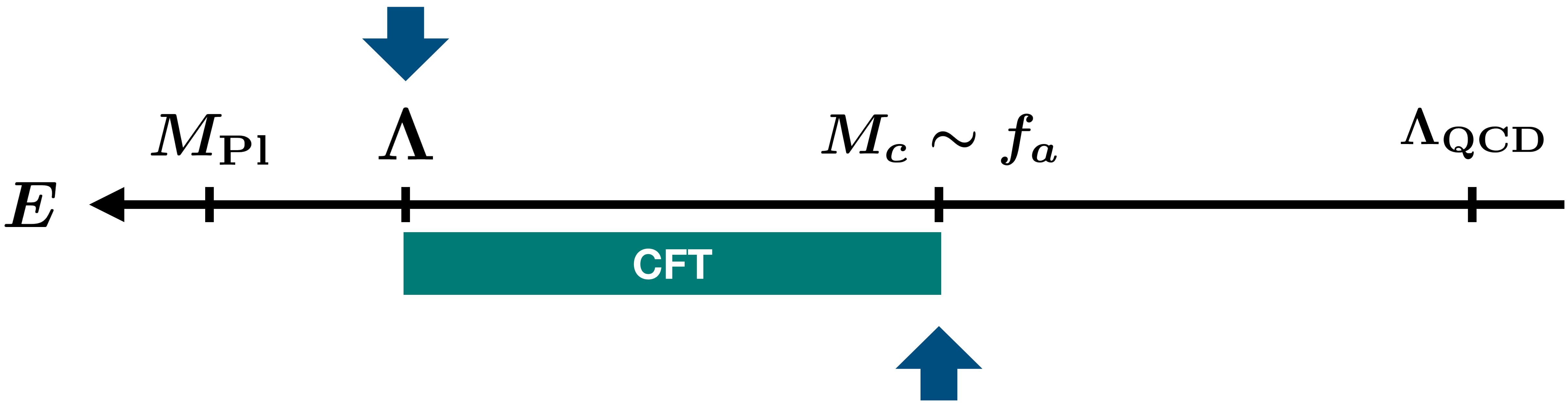
$$\Rightarrow \quad \epsilon_\phi \equiv Z_\phi^{-1/2}(\mu) = \left(\frac{\mu}{\Lambda}\right)^{\frac{\gamma_\phi}{2}} \ll 1$$

The $U(1)_{PQ}$-violating operators are significantly suppressed at low-energies :

$$\Delta W \sim \frac{\phi^k}{M_{\rm Pl}^{k-3}} \quad \rightarrow \quad \epsilon_\phi^k \frac{\phi^k}{M_{\rm Pl}^{k-3}}$$

Conformal Dynamics

The theory flows into a conformal fixed point.



PQ breaking drives conformal breaking.

All the CFT sector fields become massive.

Integrating out the CFT sector fields generates

$$\mathcal{L}_\theta = \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \widetilde{G}^a_{\mu\nu}$$

cf. The KSVZ axion model

The Model

A SUSY SU(N) gauge theory with N_f vector-like quarks :

$$Q_I, \bar{Q}_I \ (I = 1, \cdots, N_f) \quad N_f \text{ : even}$$

The theory is in **conformal window** : $\frac{3}{2}N < N_f < 3N$

PQ singlet chiral superfields : $\Phi, \bar{\Phi}$

$$W_Q = \lambda \Phi Q_m \bar{Q}_m + \bar{\lambda} \bar{\Phi} Q_k \bar{Q}_k$$

$$m = 1, \cdots, N_f/2 \qquad k = N_f/2 + 1, \cdots, N_f$$

The ordinary color is embedded in flavor symmetries :

$$\underline{SU(N_f/2)_1} \times SU(N_f/2)_2$$

$$\supset SU(3)_C$$

The Model

	Q_m	$\bar{Q}_m$	Q_k	$\bar{Q}_k$	Φ	$\bar{\Phi}$
$SU(N)$	N	$\overline{\mathrm{N}}$	N	$\overline{\mathrm{N}}$	1	1
$U(1)_{\mathrm{PQ}}\ (\mathrm{Z}_N)$	$+1$	0	-1	0	-1	$+1$
$U(1)_R$	$\frac{N_f-N}{N_f}$	$\frac{N_f-N}{N_f}$	$\frac{N_f-N}{N_f}$	$\frac{N_f-N}{N_f}$	$\frac{2N}{N_f}$	$\frac{2N}{N_f}$

- The $U(1)_{PQ}$ symmetry is not anomalous under the SU(N).

➡ Axion does not couple to the SU(N) gauge field so that no new axion potential is generated.

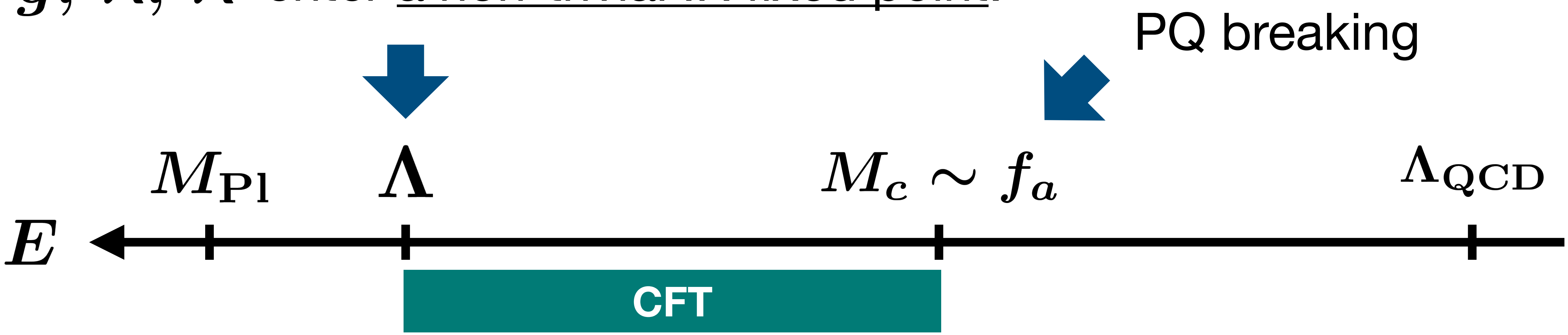
- Anomaly coefficient : $A_{U(1)_{\mathrm{PQ}}-SU(3)_C-SU(3)_C} = N$

➡ $\mathrm{Z}_N \subset U(1)_{\mathrm{PQ}}$ is **an anomaly-free discrete symmetry.**

It ensures the $U(1)_{PQ}$ at the renormalizable level.

Anomalous Dimension

$g, \lambda, \bar{\lambda}$ enter a non-trivial IR fixed point.

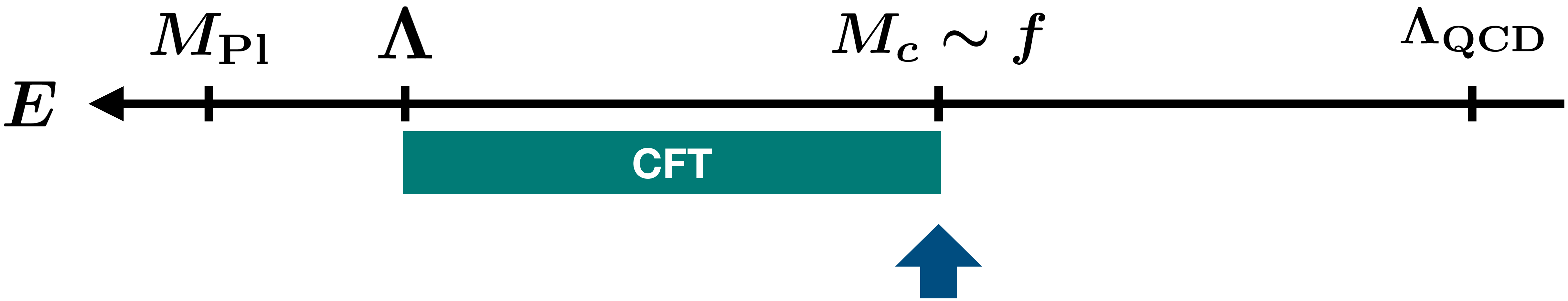


Anomalous dimension is determined by **the U(1)$_R$ charge**.

$$Z_\Phi = \left(\frac{M_c}{\Lambda}\right)^{-\gamma_\Phi} \qquad \gamma_\Phi = 6\frac{N}{N_f} - 2$$

Canonical normalization : $\Phi = \left(\frac{M_c}{\Lambda}\right)^{\gamma_\Phi/2} \hat{\Phi}$

Axion Potential



$\Phi, \bar{\Phi}$ obtain nonzero VEVs.

$$W_Q = \lambda \Phi Q_m \bar{Q}_m + \bar{\lambda} \bar{\Phi} Q_k \bar{Q}_k$$

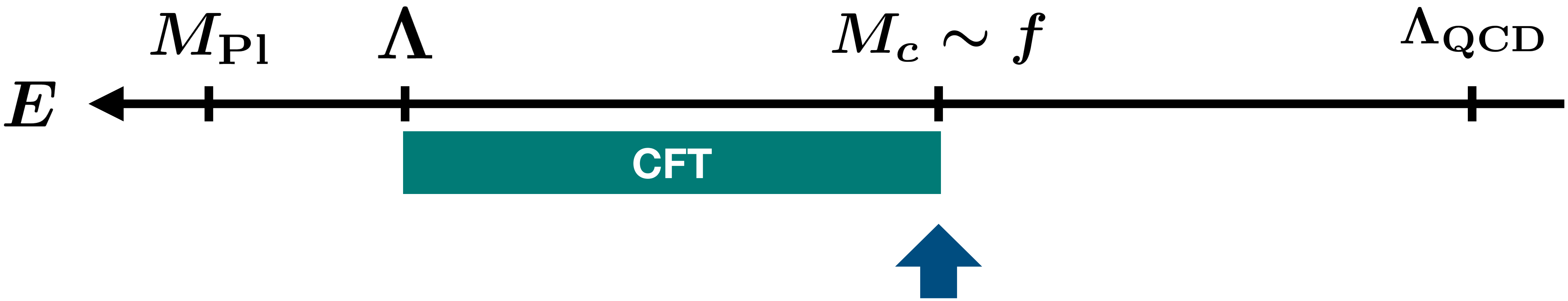
➡ <u>All the new quarks become massive.</u>

Integrating out the quarks ➡ $\mathcal{L}_{\rm eff} \supset N \frac{a}{F_a} \frac{g_c^2}{32\pi^2} G\tilde{G}$

$$F_a/N = \sqrt{2} f/N$$

Axion potential : $V \sim m_\pi^2 f_\pi^2 \cos\left(N \frac{a}{F_a}\right)$ $\quad m_\pi^2 f_\pi^2 = (0.1\,{\rm GeV})^4$

Hidden Glueballs



$\Phi, \bar{\Phi}$ obtain nonzero VEVs.

$$W_Q = \lambda \Phi Q_m \bar{Q}_m + \bar{\lambda} \bar{\Phi} Q_k \bar{Q}_k$$

➡ All the new quarks become massive.

The model becomes **a SU(N) pure Yang-Mills theory**.

It confines just below the conformal breaking scale.

➡ Heavy **SU(N) glueballs** and their superpartners.

Emergent PQ

The most dangerous operator respecting the **Z_N** symmetry :

$$W_{\not{\rm PQ}} \sim \frac{\Phi^N}{M_{\rm Pl}^{N-3}} \sim \left(\frac{M_c}{\Lambda}\right)^{\frac{N\gamma_\Phi}{2}} \frac{\hat{\Phi}^N}{M_{\rm Pl}^{N-3}}$$

The scalar potential in supergravity $V \supset -3WW^*/M_{\rm Pl}^2$

$$W = m_{3/2} M_{\rm Pl}^2$$

$$\Rightarrow \quad V_{\not{\rm PQ}} = \left(\frac{M_c}{\Lambda}\right)^{\frac{N\gamma_\Phi}{2}} \frac{\kappa_{\not{\rm PQ}}\, m_{3/2} \hat{\Phi}^N}{M_{\rm Pl}^{N-3}}$$

$\kappa_{\not{\rm PQ}}$

: model dependent coefficient

The $U(1)_{\rm PQ}$-violating axion potential :

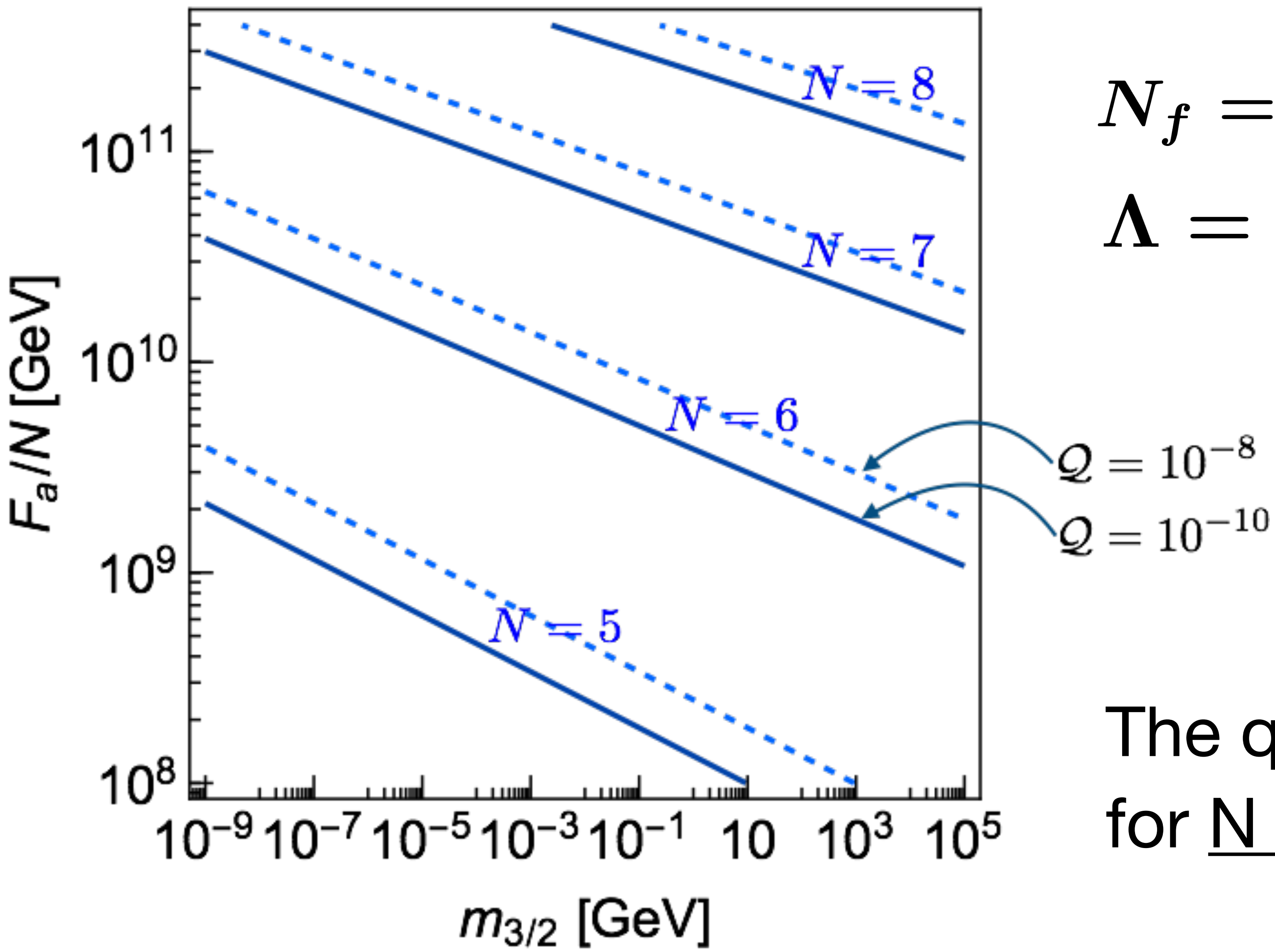
Arbitrary !

$$V_{\not{\rm PQ}} \supset \left(\frac{M_c}{\Lambda}\right)^{N(3N/N_f - 1)} \frac{\kappa_{\not{\rm PQ}}\, m_{3/2} F_a^N}{M_{\rm Pl}^{N-3}} \cos\left(N\frac{a}{F_a} + \varphi\right)$$

Emergent PQ

Axion quality factor : $V_{\not{PQ}} \equiv \mathcal{Q}\, m_\pi^2 f_\pi^2 \cos\left(N\frac{a}{F_a}+\varphi\right)$

Experimental upper bound requires $\mathcal{Q} \lesssim 10^{-10}$



$N_f = 2N,\ M_c = F_a,\ \kappa_{\not{PQ}} = 1$

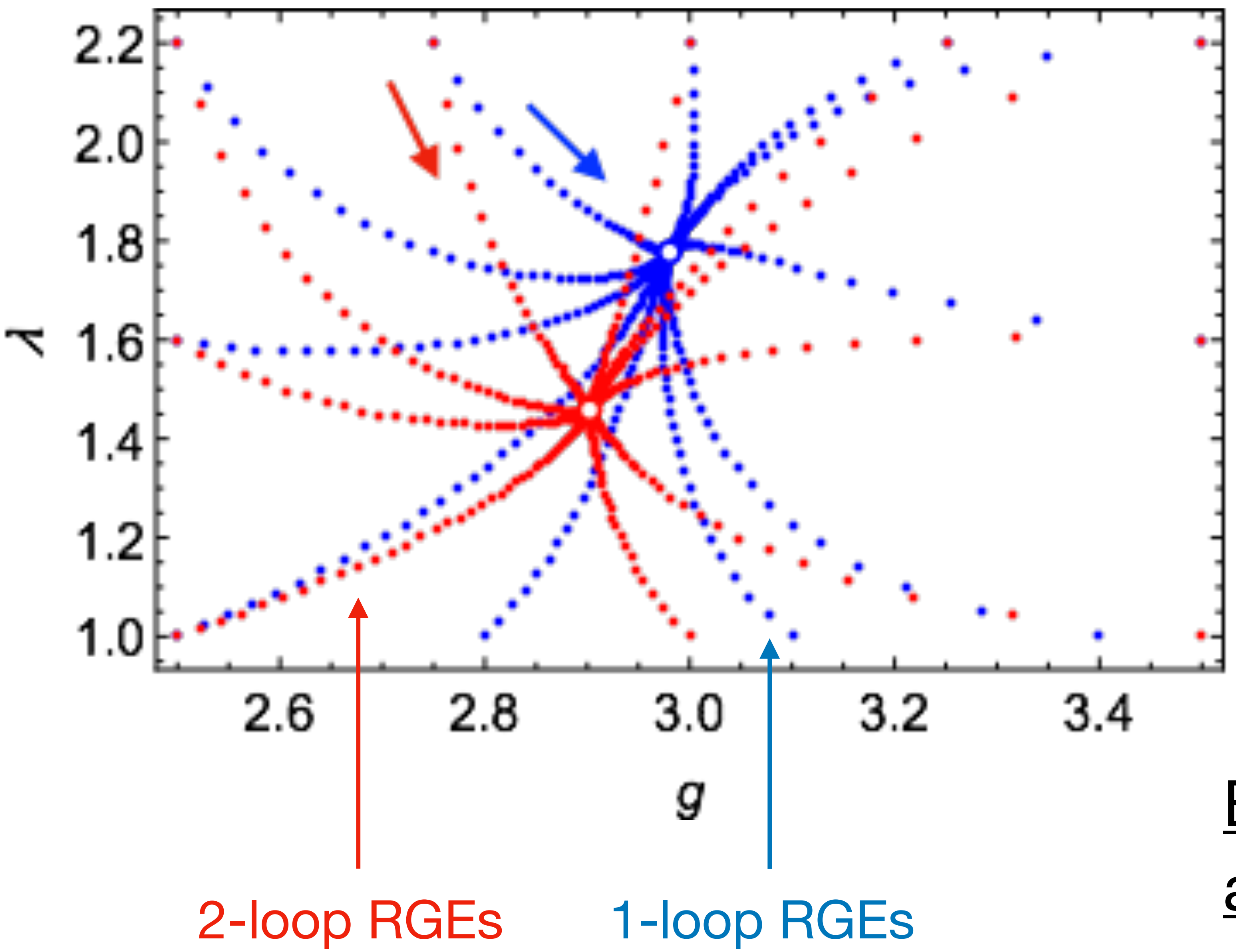
$\Lambda = 0.1\, M_{\rm Pl}$

The quality problem is solved for N = 5 or larger !

The IR fixed Point

Check the existence of the IR fixed point for $g,\ \lambda,\ \bar{\lambda}$

RG flows from Λ_0 to $\mu = 10^{-9}\Lambda_0$



$N = 5 \quad N_f = 10$

$\bar{\lambda} = 2$ at Λ_0

The effect of SU(3)c gauge coupling is <u>ignored</u>.

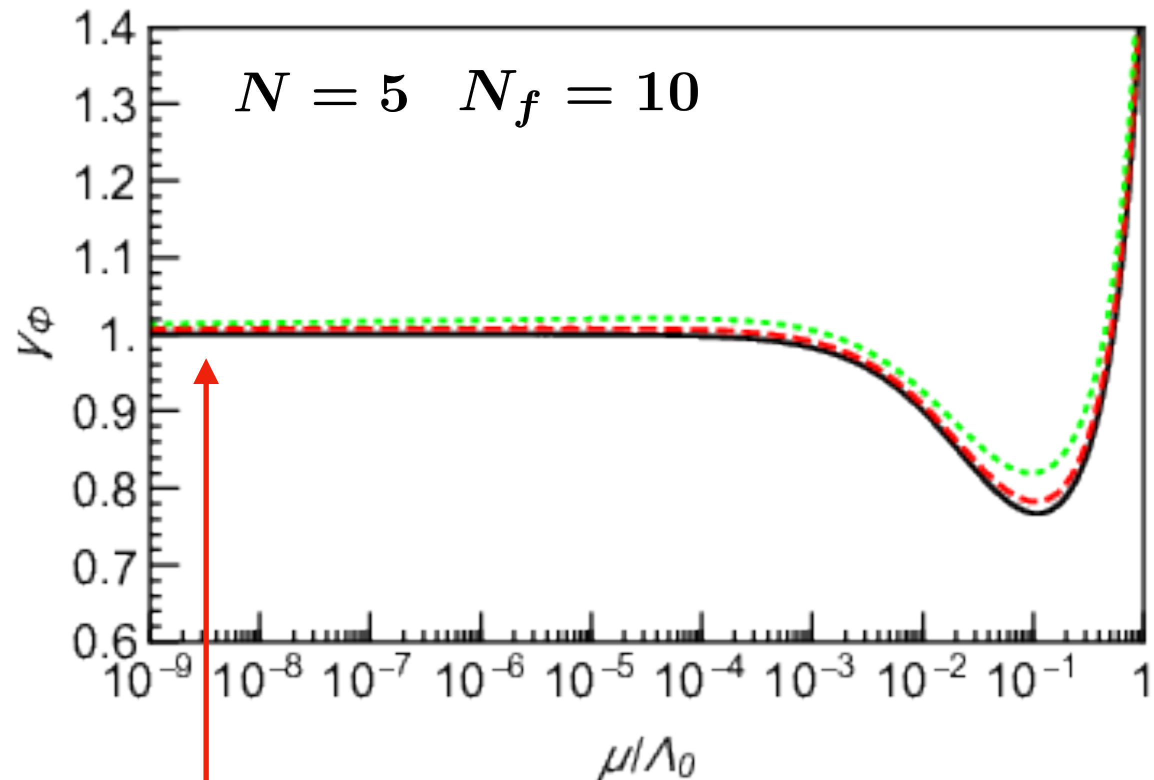
<u>Both couplings flow into a non-trivial IR fixed point.</u>

The IR fixed Point

Include the effect of the SU(3)c gauge coupling.

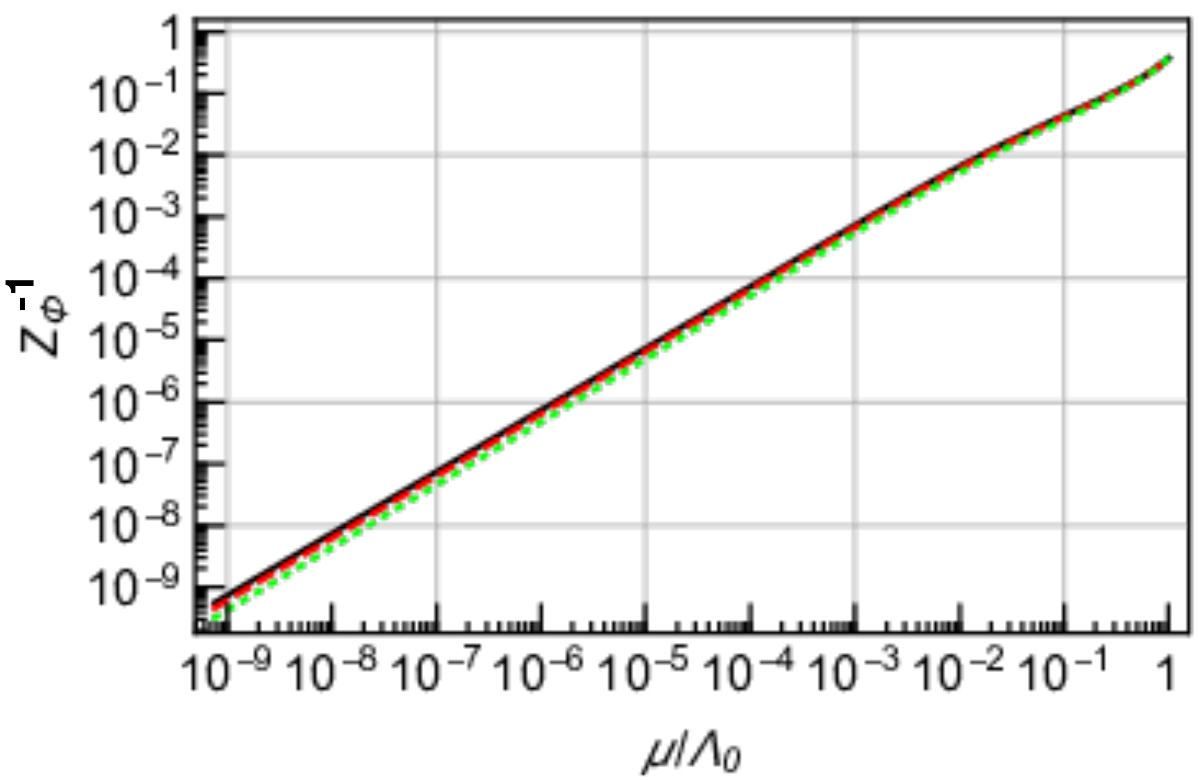
$$g = \lambda = \bar{\lambda} = 2 \qquad g_c = 0, 1, 2 \text{ at } \Lambda_0$$

Anomalous dimension at 2-loop



The value without the QCD effect

Wave function renormalization factor



The smallness enables to solve the axion quality problem.

Summary

- **Superconformal dynamics** can address the axion quality problem.
- PQ breaking fields <u>marginally couple to new quarks</u> charged under the $SU(3)_C$ and <u>a new SU(N)</u>.
- <u>A large anomalous dimension</u> of PQ breaking fields leads to a strong suppression of explicit $U(1)_{PQ}$-violating operators.
- <u>PQ breaking drives conformal breaking</u> and integrating out the new heavy quarks generates <u>the desired axion coupling to gluons</u>.

Thank you.

Backup Material

PQ Breaking

PQ breaking : $W'_X = \kappa' X(2\Phi\bar{\Phi} - f'^2)$

Canonical normalization : $\Phi = \left(\frac{M_c}{\Lambda}\right)^{\gamma_\Phi/2} \hat{\Phi}$

$$\Rightarrow \quad W_X = \kappa \left(\frac{M_c}{\Lambda}\right)^{\gamma_\Phi} X(2\hat{\Phi}\hat{\bar{\Phi}} - f^2)$$

$$\kappa \sim \kappa' \qquad \boxed{f \sim \left(\frac{M_c}{\Lambda}\right)^{-\gamma_\Phi/2} f'}$$

PQ (and conformal) breaking scale $M_c \sim f$