# Spontaneous CP violation & Baryon Asymmetry

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K. Fujikura, Y. Nakai, R. Sato, M. Yamada,
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# Why $d_n \ll \mu_n$ ?

Interaction between neutron spin & electromagnetic field

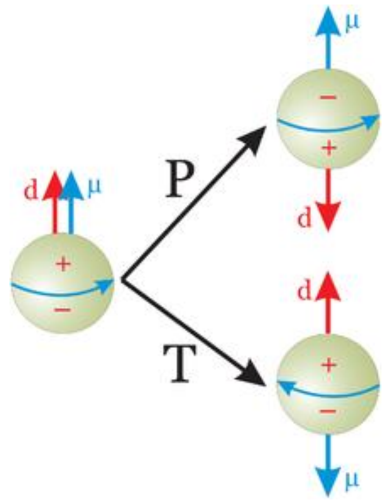
$$H = -d_n \frac{\vec{s}\cdot\vec{E}}{|s|} - \mu_n \frac{\vec{s}\cdot\vec{B}}{|s|}$$

Observed values :

$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$$ [nEDM collab. (2001.11966)]

$$\mu_n \simeq -2.0 \times 10^{-14}\ e\ \mathrm{cm}$$ [particle data group]

(c.f. $\hbar c/1\ \mathrm{GeV} \simeq 2 \times 10^{-14}\ \mathrm{cm}$)




[en.wikipedia.org]

EDM is T-odd observable. (MDM is T-even.)

T transf. : $\vec{s} \to -\vec{s}, \quad \vec{E} \to \vec{E}, \quad \vec{B} \to -\vec{B}$

Small EDM means good T symmetry ?

# T (CP) violation in the Standard Model

T symmetry $\overset{\text{CPT inv.}}{\Leftrightarrow}$ CP symmetry

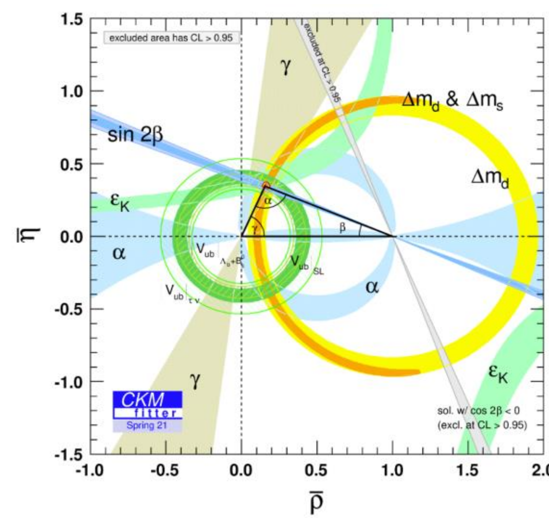
CP (T) viol. in SM
- CP phase in CKM matrix → $V_{\mathrm{CKM}} = U_u^\dagger U_d$
- $\theta$ term in QCD → $\bar{\theta} = \theta - \arg\det y_u y_d$

$$L \;=\; -y_{u,ij} q_{L,i} u_{R,j} \widetilde{H} \;-\; y_{d,ij} q_{L,i} d_{R,j} H \;+\; \frac{\theta g_s}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$U_u y_u V_u = \mathrm{diag}(m_u, m_c, m_t)/v$$
$$U_d y_d V_d = \mathrm{diag}(m_d, m_s, m_b)/v$$

$\delta_{\mathrm{CKM}} \sim O(1)$ e.g., $\sin 2\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = 0.691 \pm 0.017$

[Particle Data Group]




[CKM fitter]

$|\bar{\theta}| <\sim 10^{-10}$ $\qquad \frac{d_n}{e} \sim \bar{\theta} \times \frac{m_u}{m_n} \times \frac{1}{m_n}$

$< 10^{-26}$ cm $\qquad 10^{-3} \times 10^{-13}$ cm

Why $\underbrace{|\bar{\theta}|}_{<10^{-10}} \ll \underbrace{\delta_{\mathrm{CKM}}}_{\sim O(1)}$ ??

The strong CP problem

[Jackiw, Rebbi (1976)]
[Callan, Dashen, Gross (1976)]
[Peccei, Quinn (1977)]

# A solutions to strong CP problem

Spontaneous CP breaking [Nelson (1984)] [Barr (1984)]

- CP is good symmetry in UV Lagrangian $\rightarrow$ Suppress $|\bar{\theta}|$
- CP is spontaneously broken by VEV of some scalar field
- CKM phase is from this breaking

$\rightarrow \delta_{\text{CKM}} \neq 0$

But, we have to avoid generation of $\bar{\theta}$ after CP breaking. How?

0. Strong CP problem

1. A brief review on Nelson-Barr Mechanism

2. Nelson-Barr meets Affleck-Dine Baryogenesis

# A minimal model [Bento, Branco, Parada, (1992)]

- CP symmetry is good symmetry in UV → $y_u,\ y_d,\ y_D,\ M_D$ are real
- CKM phase from spontaneous breaking of CP → $\langle\eta_a\rangle$ are complex

| | SM-like quarks | | | Vector-like quarks | | CP breaking field |
|---|---|---|---|---|---|---|
| | $q_{L,i}$ | $u^c_{R,i}$ | $d^c_{R,i}$ | $D_L$ | $D^c_R$ | $\eta_a$ |
| SM gauge group | $(3,2)_{\frac{1}{6}}$ | $(\bar{3},1)_{-\frac{2}{3}}$ | $(\bar{3},1)_{\frac{1}{3}}$ | $(3,1)_{-\frac{1}{3}}$ | $(\bar{3},1)_{\frac{1}{3}}$ | $(1,1)_0$ |
| $Z_N$ | $0$ | $0$ | $0$ | $+1$ | $-1$ | $-1$ |

$$L = y_{u,ij} q_{L,i} u^c_{R,j} \widetilde{H}$$

$$+\ y_{d,ij} q_{L,i} d^c_{R,j} H + y_{D,ai} \eta_a D_L d^c_{R,i} + M_D D_L D^c_R$$

$Z_n$ breaking terms

$\cancel{q_L D^c_R H}$

$\cancel{\eta_a D_L D^c_R}$

$\cancel{D_L d^c_R}$

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$$m = yv, \quad B_i = \sum_a \kappa_{ai}\langle\eta_a\rangle$$

$$-L_{mass} = \begin{pmatrix} u^c_{R,1} & u^c_{R,2} & u^c_{R,3} \end{pmatrix} \begin{pmatrix} m_{u,11} & m_{u,12} & m_{u,13} \\ m_{u,21} & m_{u,22} & m_{u,23} \\ m_{u,31} & m_{u,32} & m_{u,33} \end{pmatrix} \begin{pmatrix} u_{L,1} \\ u_{L,2} \\ u_{L,3} \end{pmatrix}$$
$$+ \begin{pmatrix} d^c_{R,1} & d^c_{R,2} & d^c_{R,3} & D^c_R \end{pmatrix} \underbrace{\begin{pmatrix} m_{d,11} & m_{d,12} & m_{d,13} & B_1 \\ m_{d,21} & m_{d,22} & m_{d,23} & B_2 \\ m_{d,31} & m_{d,32} & m_{d,33} & B_3 \\ 0 & 0 & 0 & M_D \end{pmatrix}}_{M_D^{(4\times4)}} \begin{pmatrix} d_{L,1} \\ d_{L,2} \\ d_{L,3} \\ D_L \end{pmatrix}$$

$$\arg\det M_D^{(4\times4)} = 0 \quad \rightarrow \quad \bar{\theta} = 0$$

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$D_L$ and $\frac{1}{\sqrt{M_{CP}}}(B_1 d^c_{R,1} + B_2 d^c_{R,2} + B_3 d^c_{R.3} + M_D D^c_R)$ forms heavy mass eigenstate.

$d^c_R$'s and $D^c_R$ have O(1) mixing with complex phase!

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$$\arg\det M_D^{(4\times4)} = 0 \quad \rightarrow \quad \bar{\theta} = 0$$

$$m'^{\dagger}_d m'_d = m_d^T m_d - \frac{m_d^T B\, B^\dagger m_d}{M_D^2 + B^\dagger B} = V_{\rm CKM} m_{d,\rm diag} V^\dagger_{\rm CKM}$$


$M_D \sim B$ $\rightarrow$ O(1) CKM phase

# Dangerous corrections

[See, Dine and Draper (2015) for review]

- Relative phase between $\eta$'s are physical $\rightarrow$ (# of $\eta$) $\geq 2$
- $\eta$'s should have same quantum number

$\eta_1\eta_2^*$
- Charge neutral
- Complex VEV

e.g.,

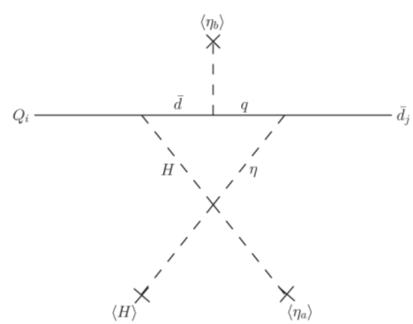
$$L_{\text{eff}} = \frac{1}{\Lambda}\eta_a\eta_b^* D_L D_R^c$$

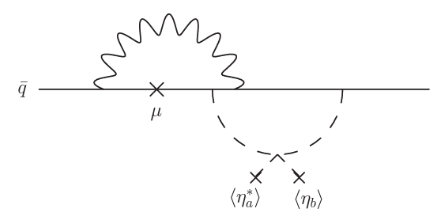
$$L_{\text{CPV}} = (\lambda_{ab}\eta_a\eta_b + h.c.)|H|^2 + \lambda'_{abcd}\eta_a\eta_b\eta_c^*\eta_d^*$$

$$\delta\bar{\theta} \sim \frac{\langle\eta\rangle^2}{\Lambda M_D} \sim \frac{M_{CP}}{\Lambda}$$

$$\delta\bar{\theta} \sim \frac{y_D^2\lambda}{16\pi^2}\frac{\langle\eta\rangle^2}{m_{CP}^2}$$

$$\delta\bar{\theta} \sim \frac{g_s^2 y_D^2\lambda'}{(16\pi^2)^2}\frac{\langle\eta\rangle^2}{m_{CP}^2}$$




($\langle\eta\rangle \sim m_{CP}$ is natural)

$\delta\theta < 10^{-10}$ requires

- Small $M_{CP}$
- Unnaturally small couplings

# Nelson-Barr meets supersymmetry

Dangerous terms can be suppressed by Supersymmetry !!

- Higher dim. Operators $\leftarrow$ Holomorphy
- radiative corrections $\leftarrow$ non-renormalization theorem

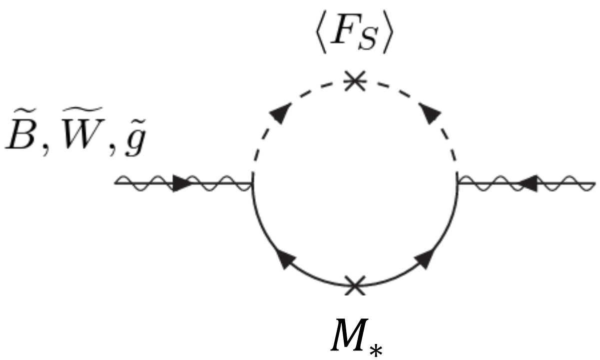
[Hiller, Schmaltz (2001, 2002)]

Gluino phase is dangerous in SUSY models

$$\bar{\theta} = \theta - \arg\det m_u m_d - 3\arg m_{\tilde{g}}$$

Gauge mediation (GMSB) is nice [Dine, Leigh, Kagan (1993)] [Hiller, Schmaltz (2002)]

$$W = M_* \Phi\bar{\Phi} + S\Phi\bar{\Phi} \quad \rightarrow \quad m_{\tilde{g}} = \frac{\alpha_s}{4\pi}\frac{F_S}{M_*}$$




Anomaly mediation (AMSB) contribution

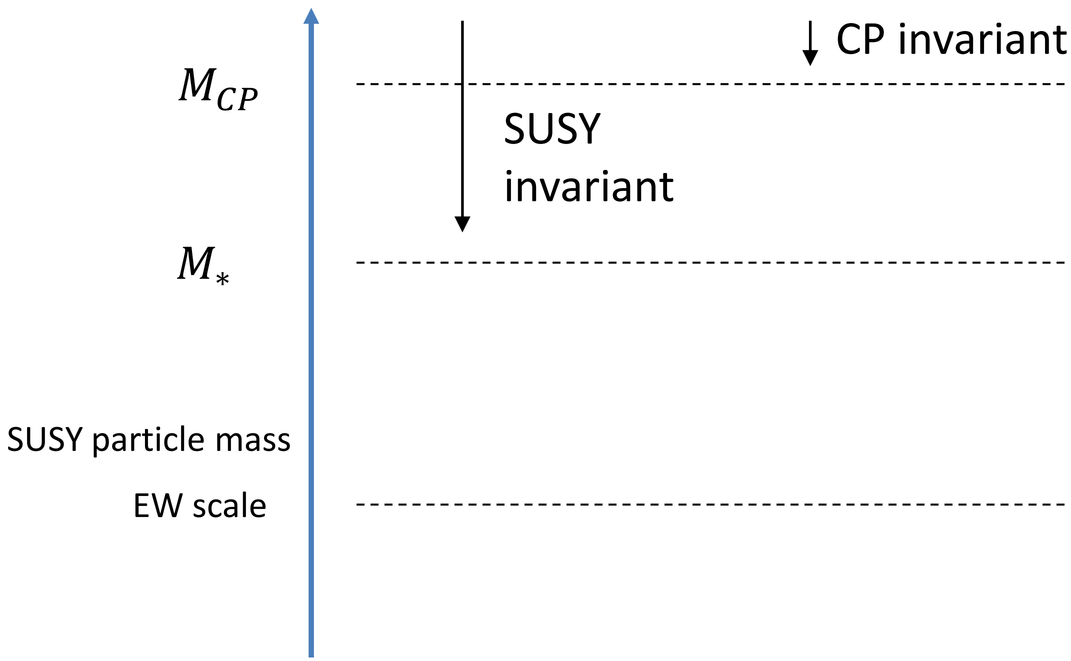
$$\frac{m_{\mathrm{AMSB}}}{m_{\mathrm{GMSB}}} \sim \frac{\alpha_s}{4\pi}\frac{m_{3/2}}{m_{\tilde{g}}} < 10^{-10} \quad \rightarrow \quad m_{3/2} <\sim 100\,\mathrm{keV} \times \left(\frac{m_{\tilde{g}}}{10\,\mathrm{TeV}}\right)$$

# Radiative correction on $\bar{\theta}$

[Fujikura, Nakai, Sato, Yamada (2022)]

Let us estimate $\delta\bar{\theta}$ in SUSY Nelson-Barr w/ GMSB.

Let us assume $M_* < M_{CP}$



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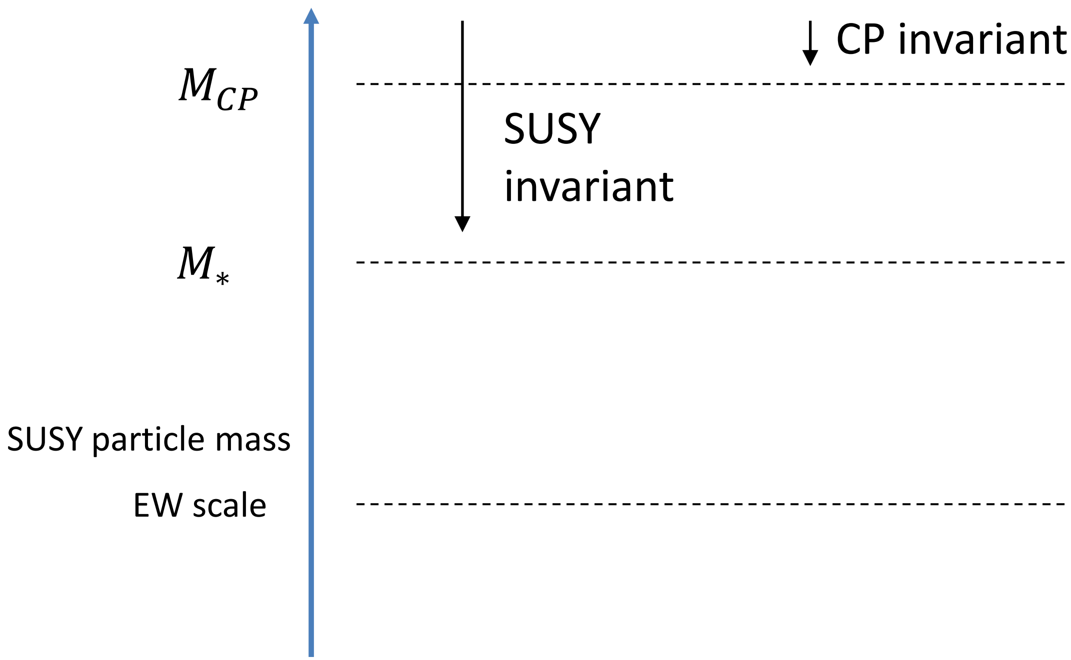
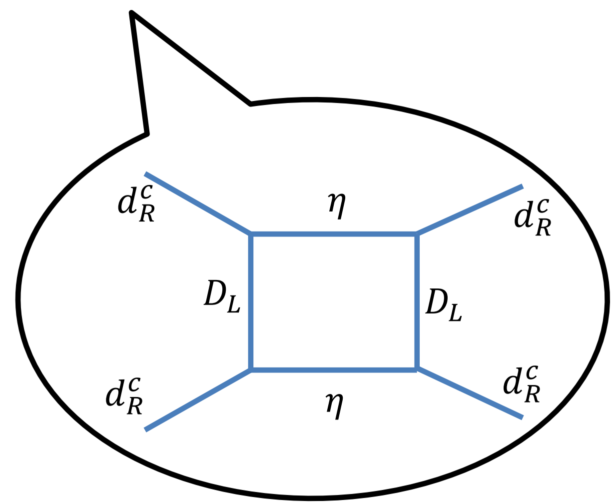



$$\Delta K_{\text{eff}} \sim \frac{y_D^4}{16\pi^2} d_{R,i}^{c*} d_{R,j}^{c} d_{R,k}^{c*} d_{R,m}^{c}$$



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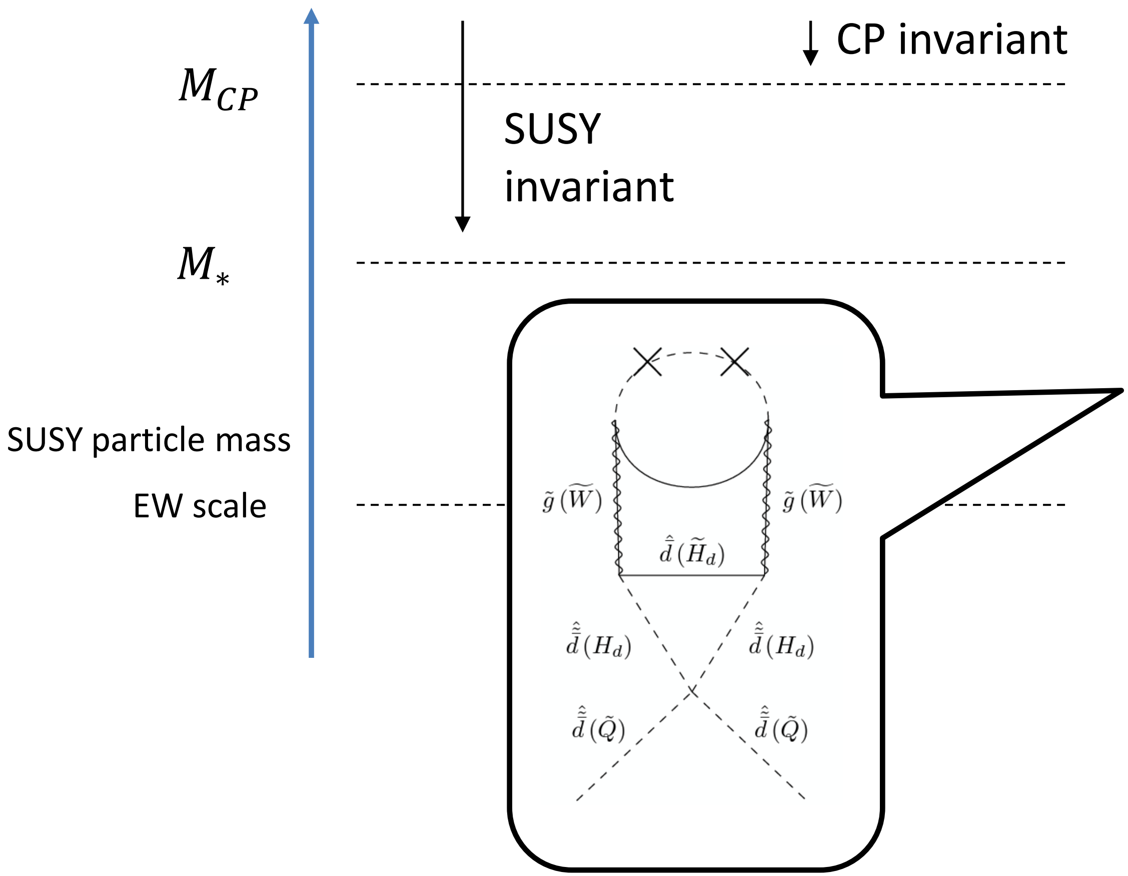


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$$\delta m_{\tilde{d}_R^c}^2 \sim \left(\frac{y_D^2}{16\pi^2}\right)^2 \frac{M_*^2}{M_{CP}^2} m_{\text{GMSB}}^2$$

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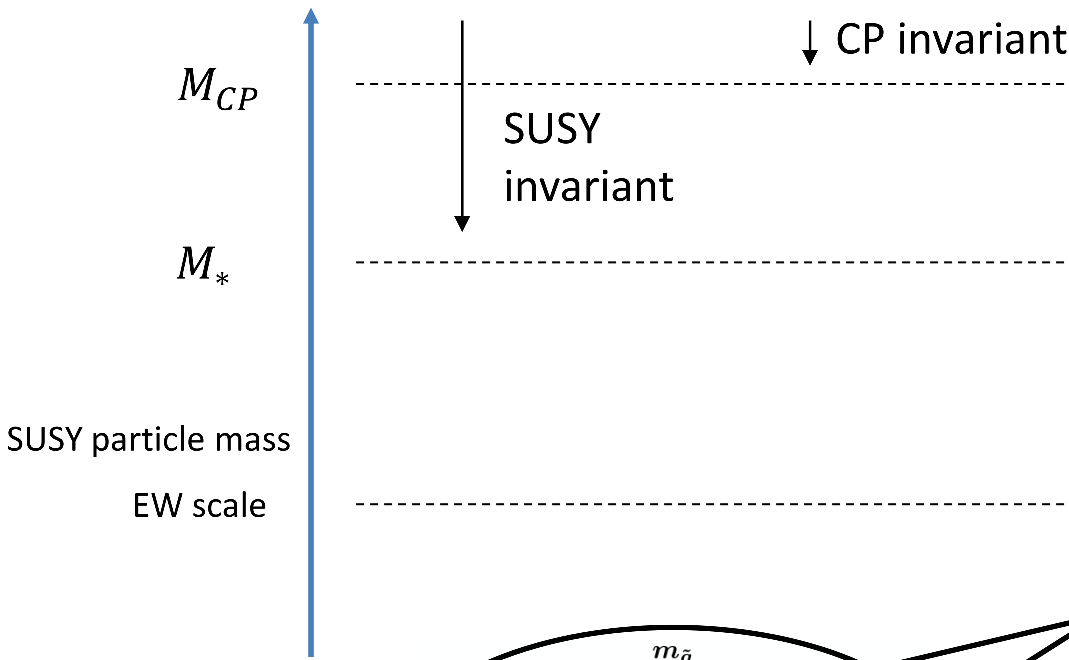


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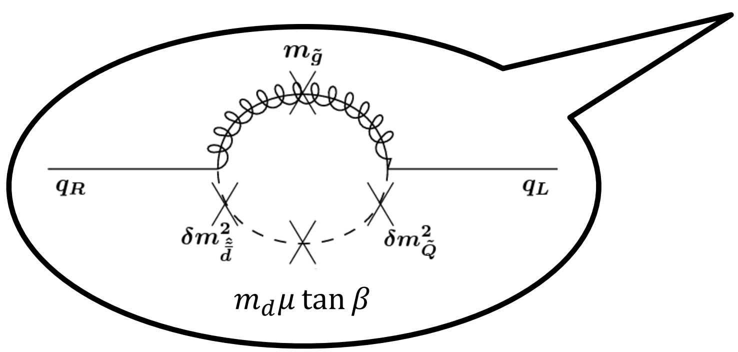
$$\delta m^2_{\tilde{d}_R^c} \sim \left(\frac{y_D^2}{16\pi^2}\right)^2 \frac{M_*^2}{M_{CP}^2} m^2_{\text{GMSB}}$$

$$\delta\theta \sim \frac{\alpha_s}{4\pi} \frac{\mu \tan\beta}{m^5_{\text{GMSB}}} \text{Im Tr}\left[y_d^{-1} \delta m^2_{\tilde{d}_R^c}\, y_d \delta m^2_{\tilde{q}_L}\right]$$

$$\sim 10^{-7} \times y_D^4 \frac{M_*^2}{M_{CP}^2} \tan\beta$$



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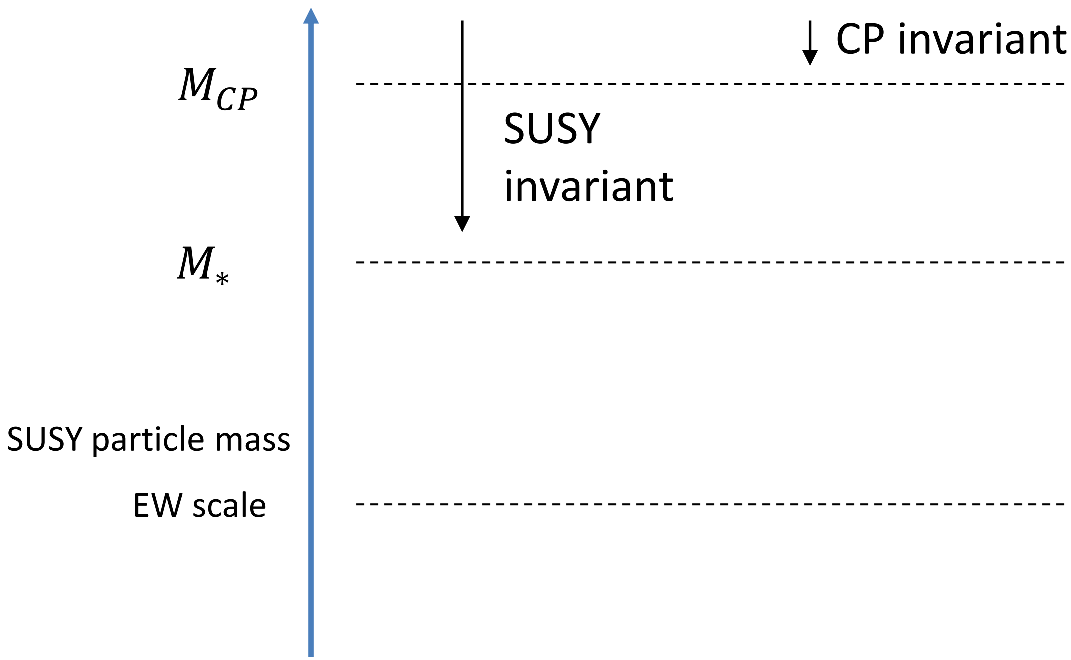


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$$\sim 10^{-7} \times y_D^4 \frac{M_*^2}{M_{CP}^2} \tan\beta$$

Safely small. Mildly prefer small $M_*/M_{CP}$

$$y_D^4 \tan\beta \times \frac{M_*^2}{M_{CP}^2} <\sim 10^{-3}$$

# Summary so far

Nelson-Barr models

→ $\bar{\theta} = 0$ @ tree-level up to dim 4 interaction.

SUSY Nelson-Barr models

→ Holomorphy & non-renormalization theorem helps to $\bar{\theta} = 0$

SUSY Nelson-Barr models w/ GMSB

→ Phase of gluino mass can be controlled.
Radiative correction on $\bar{\theta}$ is small enough.

Nelson-Barr + Supersymmetry + gauge mediation
is nice!

0. Strong CP problem

1. A brief review on Nelson-Barr Mechanism

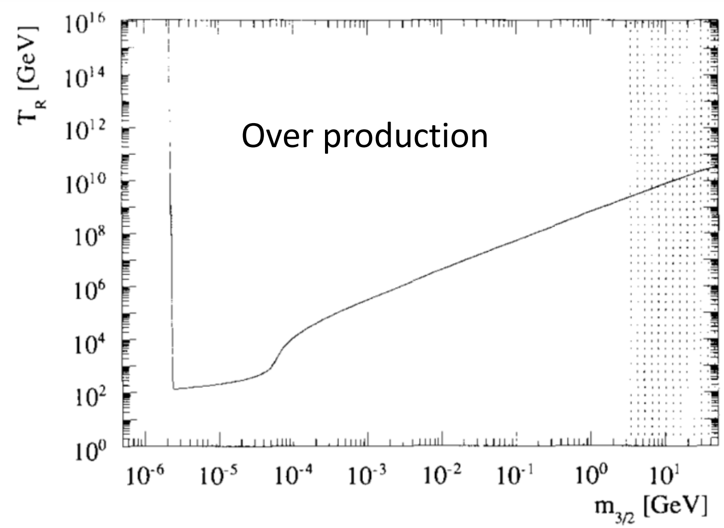
2. Nelson-Barr meets Affleck-Dine Baryogenesis

# Cosmology

SUSY Nelson-Barr w/ GMSB motivates low reheating temperature $T_{RH}$

1. Gravitino problem

   Stable gravitino + large $T_{RH}$ could cause over-closure




[Moroi, Murayama, Yamaguchi (1993)]

2. Domain wall from spontaneous CP breaking

   CP can be regarded discrete $Z_2$.
   Large $T_{RH}$ is dangerous

Affleck-Dine Baryogenesis is an interesting direction

# Affleck Dine Baryogenesis

[Affleck, Dine(1985)]
[Murayama, Yanagida (1993)]
[Dine, Randall, Thomas (1996)]

Scalar potential in SUSY models

$$V = \sum_i |F_i|^2 + \frac{1}{2}\sum g^2 |D|^2$$

[Buccela, Derendinger, Ferrara, Savoy (1982)]
[Affleck, Dine, Seiberg, (1984, 1985)]
[Gherghetta, Kolda, Martin (1996)]

Non-trivial solution of $F = D = 0 \;\rightarrow\;$ flat direction

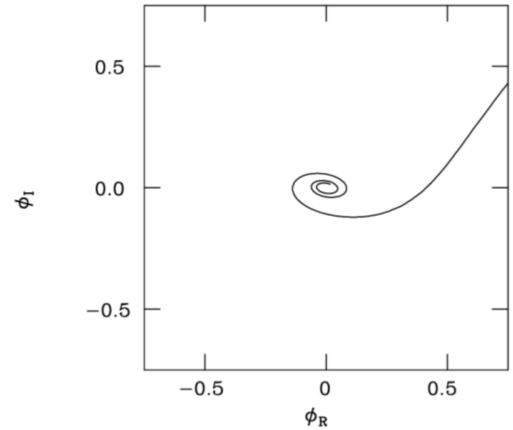
Gauge invariant combination of chiral superfields

Recipe of B-L asymmetry :

1. Large VEV in flat direction
2. Scalar field starts to roll
3. Get phase rotation from B-L breaking terms

$$j_\mu = i\phi\partial_\mu\phi^* - i\phi^*\partial_\mu\phi$$
$$\phi = \frac{1}{\sqrt{2}}\varphi\, e^{i\theta}$$

$$\Rightarrow \quad j_0 = \rho = \varphi^2\dot{\theta}$$




[taken from Dine, Randall, Thomas (1995)]

# “Flat” direction with vector-like quark

A “flat” direction involving heavy VLQ:

$$\phi = q_L \overline{D}_R^c \ell_L \qquad q_L \approx \begin{pmatrix} \phi \\ 0 \end{pmatrix}, \quad \ell_L \approx \begin{pmatrix} 0 \\ \phi \end{pmatrix}, \quad D_R^c \approx \phi$$

VLQ destabilizes Q-ball :

- Non-topological soliton w/ large charge
- In MSSM Q-ball case, Pauli blocking on the surface suppresses decay of Q-ball
- VL squark can decay into MSSM squarks (no Pauli blocking)

# Potential of “flat” direction

We take the following Kahler potential:

$$K_H = -\frac{c_H}{M_{pl}^2} I^* I \phi^* \phi + \frac{c_K}{M_{pl}^6} I^* I (q_L^* D_R^{c*} \ell_L^*)(q_L D_R^c \ell_L)$$

Destabilize origin

stabilize potential

$$K_A = -\frac{c_A}{(N!)^3 M_{pl}^{3N}} I^* I (q_L D_R^c \ell_L)^N + h.c.$$

B-L breaking (kick for rotation)

$I$ : inflaton

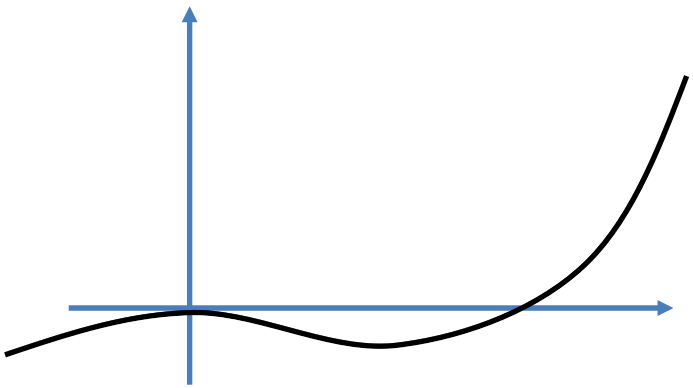
$c_A$ term breaks B-L symmetry!

The scalar potential for $\phi$ direction:

$$V = m_\phi^2 |\phi|^2 - c_H H^2(t) |\phi|^2 + \frac{c_K H^2(t)}{M_{pl}^4} |\phi|^6 - \left( \frac{c_A H^2(t)}{(N!)^3 M_{pl}^{3N-2}} \phi^{3N} + h.c. \right)$$

$$(m_\phi \sim M_D)$$

# Cosmological history



1. During inflation

$$c_H, c_K > 0 \quad \rightarrow \quad \langle\varphi\rangle \sim \left(\frac{4c_H}{3c_K}\right)^{\frac{1}{4}} M_{pl} \neq 0$$

$$\sqrt{c_H} H_{inf} > m_\phi \sim M_D$$

2. Oscillation of $\phi$ after inflation

AD field start to roll when $H \sim \frac{m_\phi}{\sqrt{c_H}}$

Phase rotation if $c_A \neq 0$

3. Reheating completes

$$\frac{n_{B-L}}{s} \sim 10^{-10} \times \left(\frac{T_{RH}}{10^3\ \mathrm{GeV}}\right) \times \left(\frac{m_\phi}{10^8\ \mathrm{GeV}}\right)^{-1}$$

# Parameters

Domain wall problem $$T_{\max} \sim \left(T_{RH}^2 H_{\inf} M_{\rm pl}\right)^{1/4} < \langle\eta\rangle \sim \frac{M_{CP}}{y^D}$$

Gravitino DM

$$T_{RH} \simeq 0.27\, T_{dec,3/2} \left(\frac{m_{3/2}}{100\ \mathrm{keV}}\right)^{1/5}$$

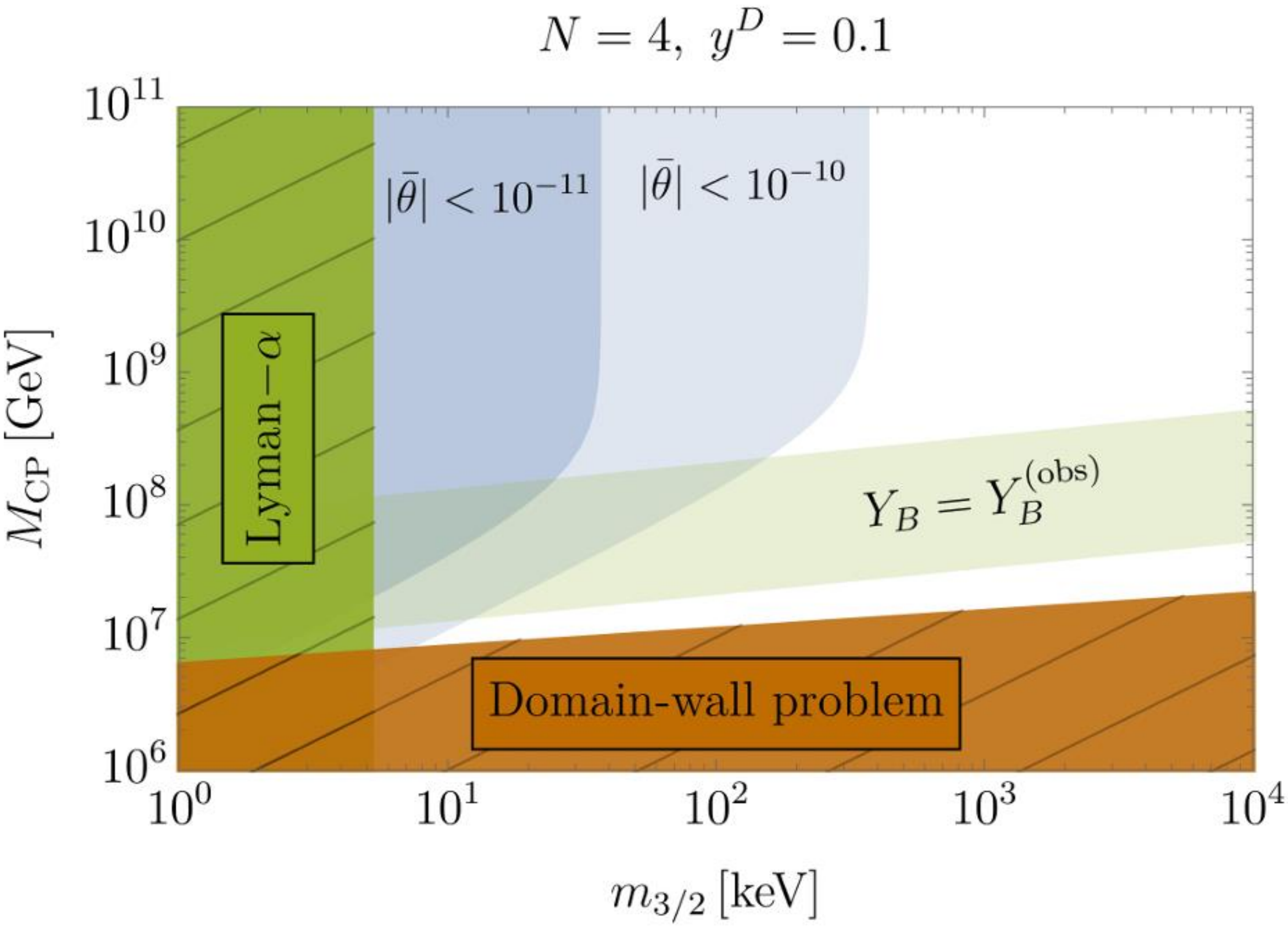
$m_{3/2} > \sim 5.3\ \mathrm{keV}$ [Irsic et al (2017)] (Lyman $\alpha$ constraint)

BAU $$\frac{n_{B-L}}{s} \sim 10^{-10} \times \left(\frac{T_{RH}}{10^3\ \mathrm{GeV}}\right) \times \left(\frac{m_\phi}{10^8\ \mathrm{GeV}}\right)^{-1}$$

Strong CP $$\delta\bar{\theta} < \sim 10^{-10}$$

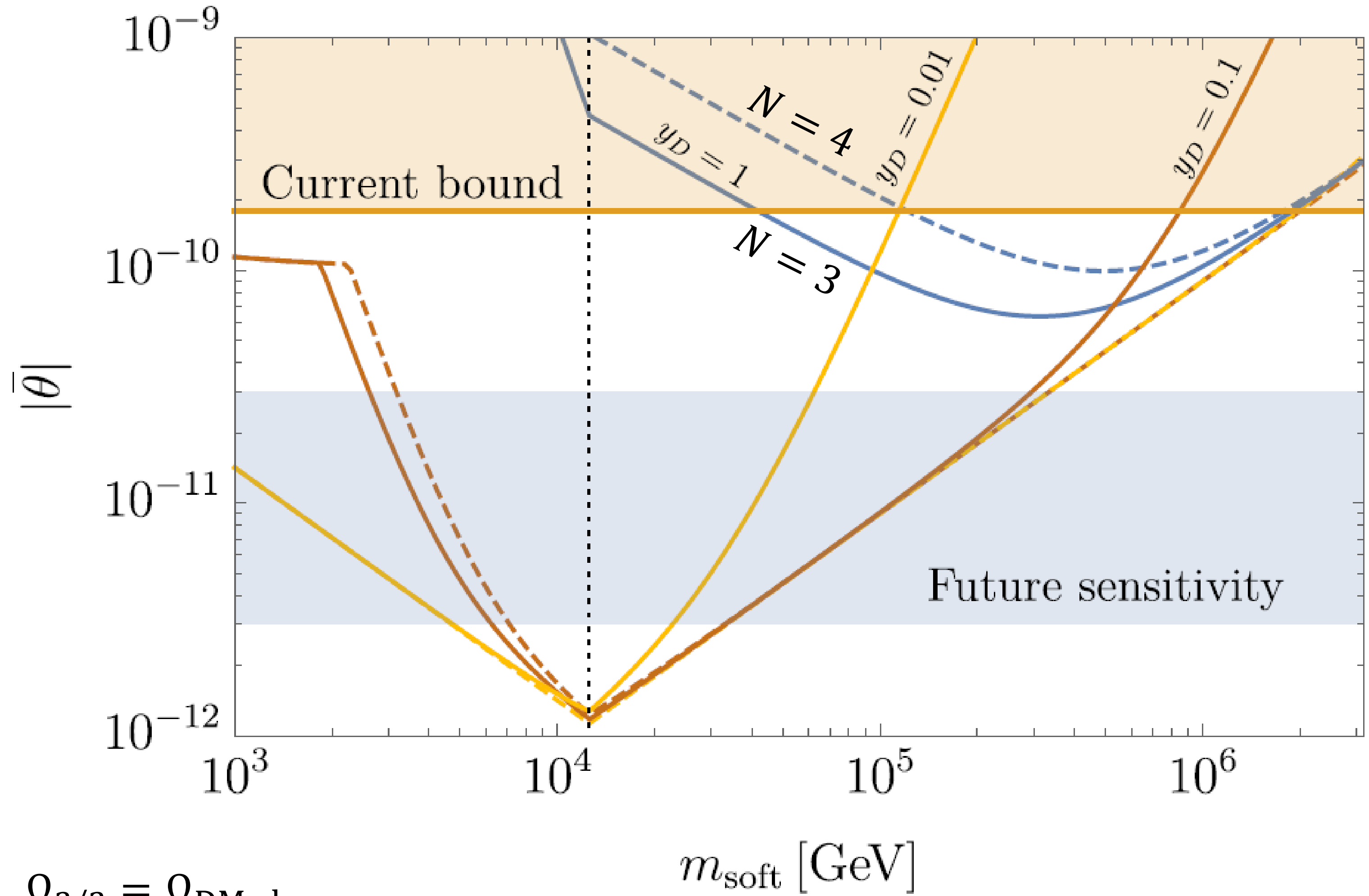
$$\left\{\begin{array}{l} \theta_{AMSB} \sim \dfrac{\alpha_s}{4\pi}\dfrac{m_{3/2}}{m_{\tilde{g}}} \\[2ex] \theta_{radcorr} \sim 10^{-7} y_D^4 \tan\beta \times \min\left[\dfrac{M_*^2}{M_{CP}^2}, 1\right] \\[2ex] \theta_{planck} \sim 10^{-2}\left(\dfrac{\mathrm{Re}\mu\tan\beta}{M_{pl}}\right)^{-1}\left(\dfrac{\langle\eta\rangle}{M_{pl}}\right)^N \end{array}\right.$$

# Result




- $T_{RH} \leftarrow \Omega_{3/2} = \Omega_{\mathrm{DM,obs}}$
- $M_* \leftarrow m_{\mathrm{soft}} = 10\ \mathrm{TeV}$

# Result

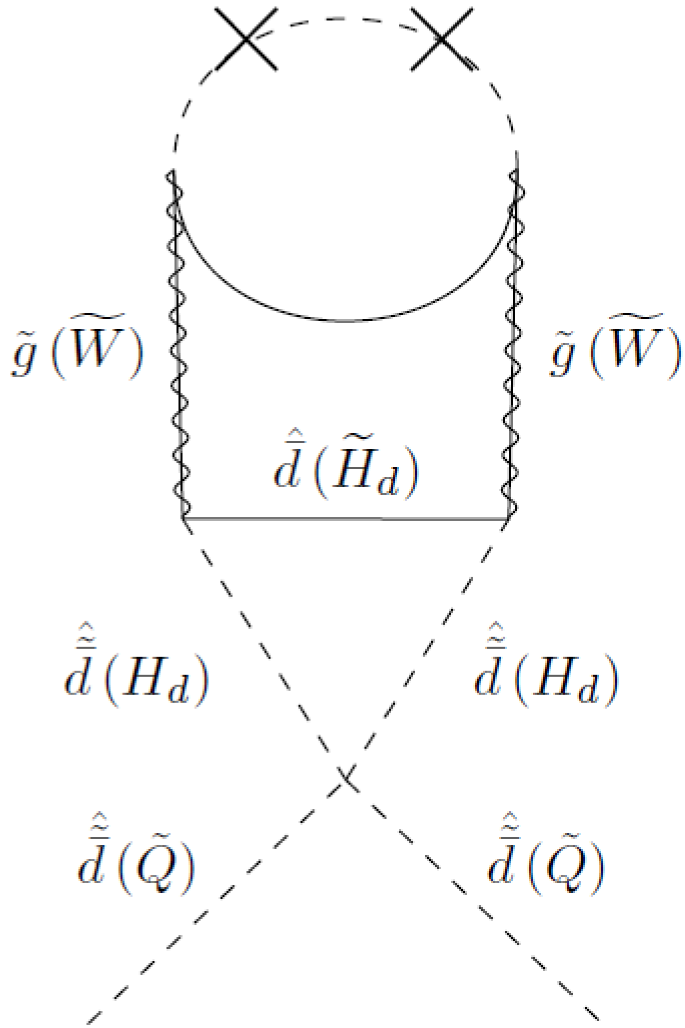


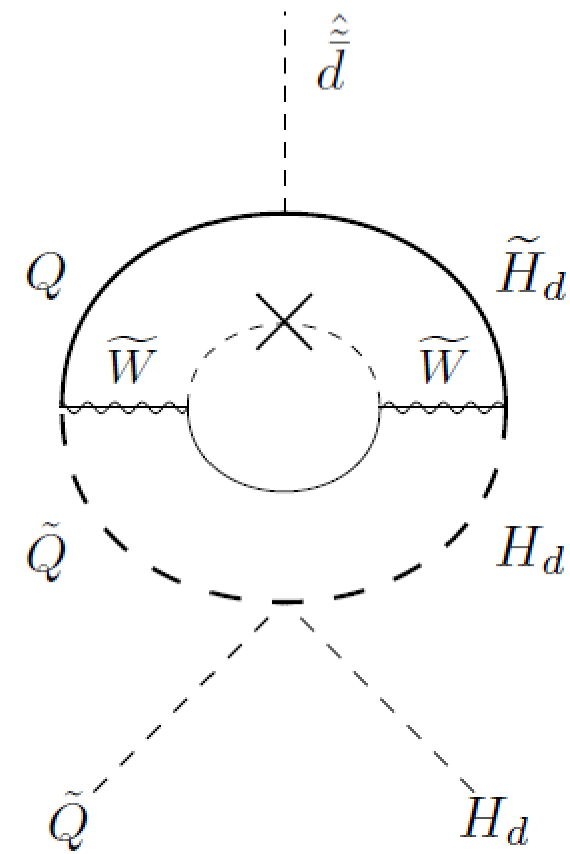

- $\Omega_{3/2} = \Omega_{\mathrm{DM,obs}}$
- $Y_B = Y_{B,\mathrm{obs}}$
- Smallest $m_{3/2}$ (smallest $\bar{\theta}$)

# Summary

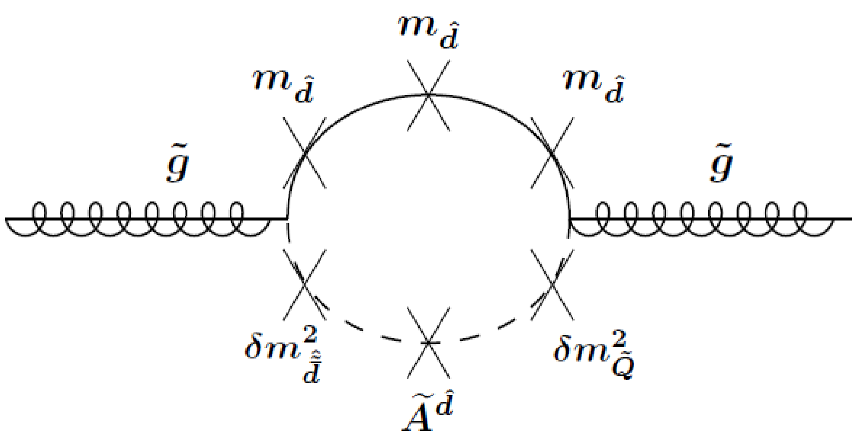
- SUSY + GMSB + Nelson-Barr is nice framework to solve strong CP problem
- It motivates Affleck-Dine Baryogenesis (gravitino problem, low $T_{RH}$, …)
- Q-ball in flat direction w/ heavy VLQ is destabilized
- Neutron EDM could be an interesting probe for this scenario

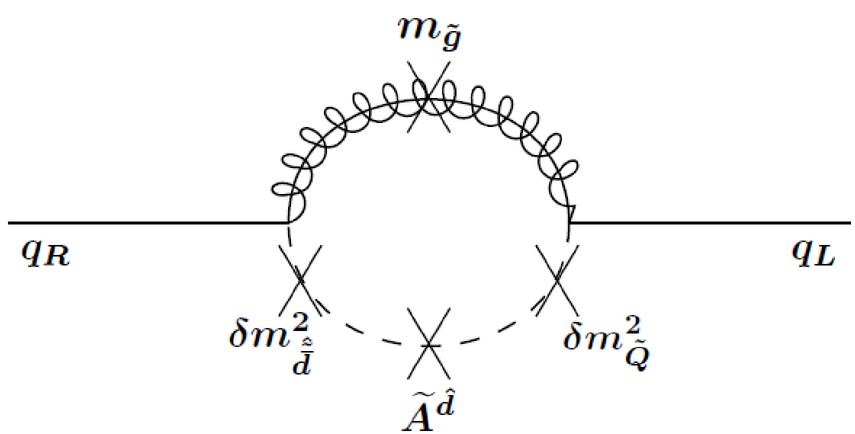
# Backup


$\tilde{g}\,(\widetilde{W})$
$\tilde{g}\,(\widetilde{W})$
$\hat{\tilde{d}}\,(\widetilde{H}_d)$
$\hat{\tilde{\tilde{d}}}\,(H_d)$
$\hat{\tilde{\tilde{d}}}\,(H_d)$
$\hat{\tilde{\tilde{d}}}\,(\tilde{Q})$
$\hat{\tilde{\tilde{d}}}\,(\tilde{Q})$


$\hat{\tilde{\tilde{d}}}$
$Q$
$\widetilde{H}_d$
$\widetilde{W}$
$\widetilde{W}$
$\tilde{Q}$
$H_d$
$\tilde{Q}$
$H_d$

[ 31 ]

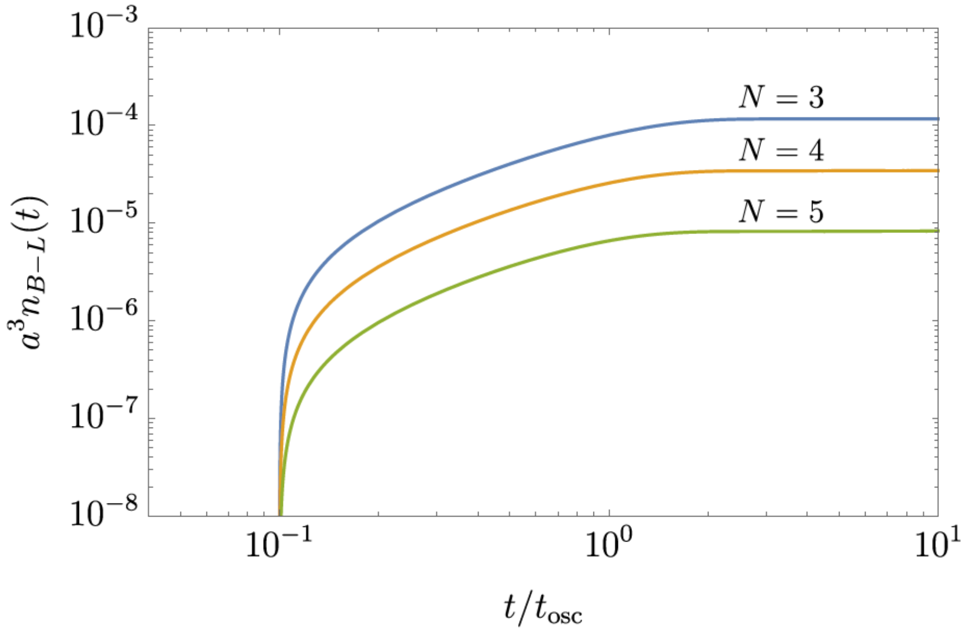

$m_{\hat{d}}$
$m_{\hat{d}}$
$m_{\hat{d}}$
$\tilde{g}$
$\tilde{g}$
$\delta m^2_{\tilde{\hat{\bar{d}}}}$
$\delta m^2_{\tilde{Q}}$
$\widetilde{A}^{\hat{d}}$


$m_{\tilde{g}}$
$q_R$
$q_L$
$\delta m^2_{\tilde{\hat{\bar{d}}}}$
$\delta m^2_{\tilde{Q}}$
$\widetilde{A}^{\hat{d}}$

$$\phi = \frac{1}{\sqrt{2}} \varphi \, e^{i\theta}$$

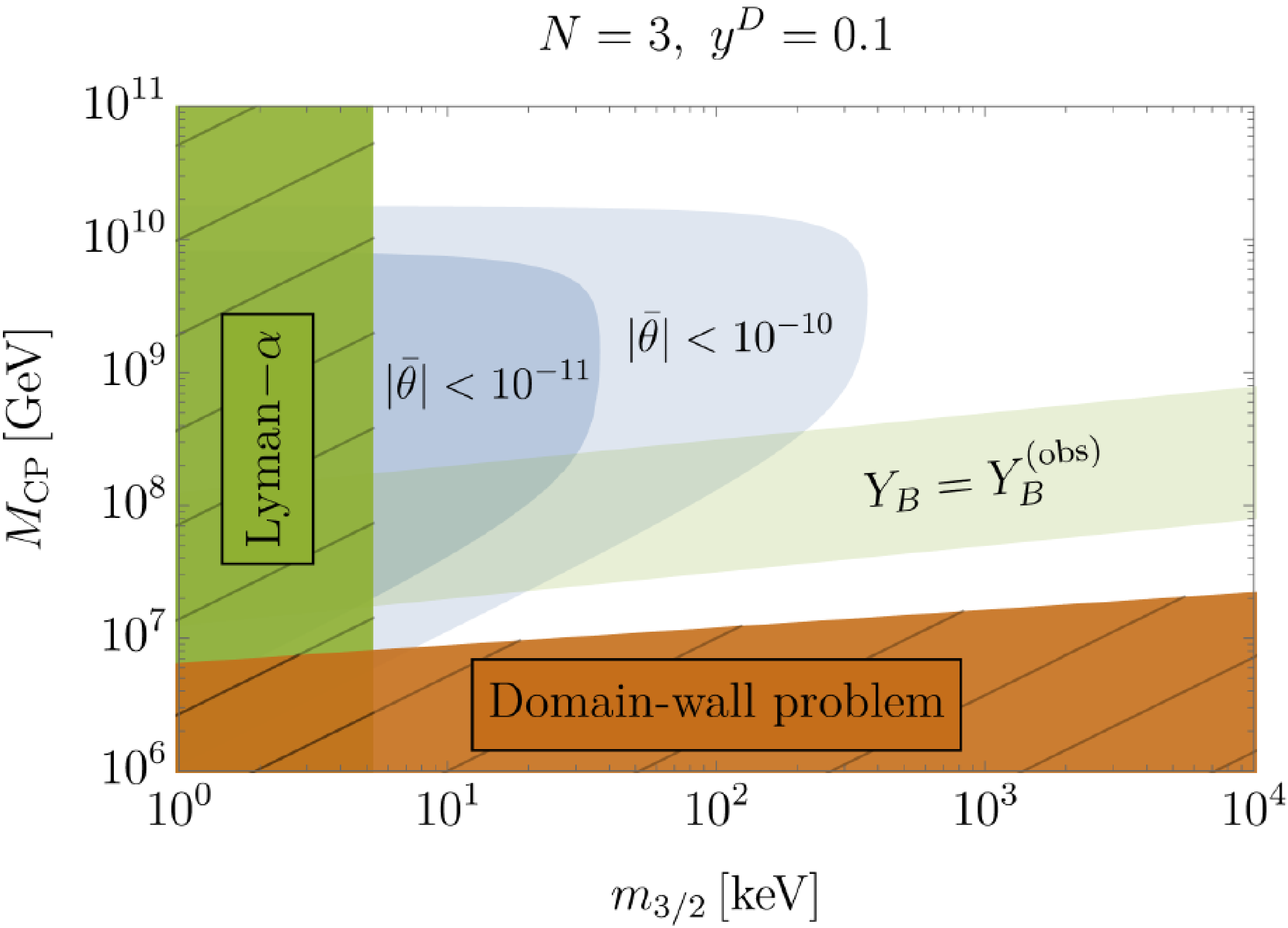
$$\ddot{\varphi} + 3H\dot{\varphi} - \dot{\theta}^2 \varphi + \frac{\partial V}{\partial \varphi} = 0$$

$$\ddot{\theta} + 3H\dot{\theta} + \frac{2\dot{\varphi}}{\varphi}\dot{\theta} + \frac{1}{\varphi^2}\frac{\partial V}{\partial \theta} = 0$$

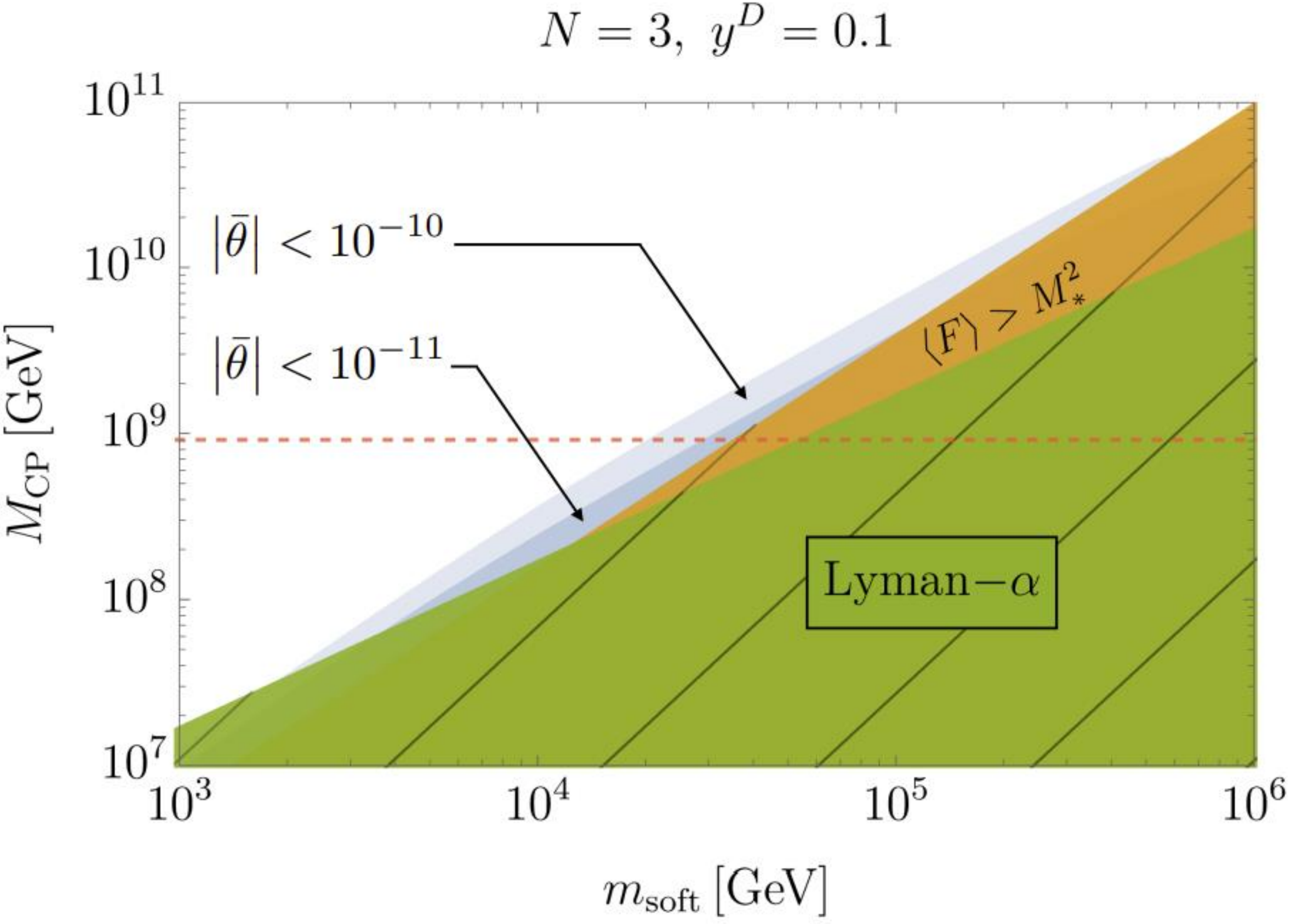



$$\varphi^2 \dot{\theta} a^3 \;\; \sim \;\; \frac{\partial V}{\partial \theta} \frac{a^3}{H_{osc}} \;\; \sim \;\; \frac{V_{osc} a_{osc}^3}{H_{osc}}$$

$$\frac{n_{B-L}}{s} \sim T_{RH}\frac{n_{B-L,RH}}{\rho_{RH}} \sim T_{RH}\frac{n_{B-L,osc}}{\rho_{osc}} \sim \frac{T_{RH}}{(N!)^3}\frac{M_{pl}^2 m_\phi}{H_{osc}^2 M_{pl}^2} \sim \frac{1}{(N!)^3}\frac{T_{RH}}{m_\phi}$$



$N = 3,\ y^D = 0.1$
$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$M_{\rm CP}$ [GeV]
Lyman$-\alpha$
$|\bar\theta| < 10^{-11}$
$|\bar\theta| < 10^{-10}$
$Y_B = Y_B^{(\rm obs)}$
Domain-wall problem
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$m_{3/2}$ [keV]



$N = 3,\ y^D = 0.1$
$|\bar{\theta}| < 10^{-10}$
$|\bar{\theta}| < 10^{-11}$
$\langle F \rangle > M_*^2$
Lyman$-\alpha$
$M_{\rm CP}$ [GeV]
$m_{\rm soft}$ [GeV]
$10^{7}$
$10^{8}$
$10^{9}$
$10^{10}$
$10^{11}$
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$

nEDM@SNS
LANL
TUCAN
PanEDM
PNPI-ILL-PTI
n2EDM

# Phase in AMSB contribution

AMSB contribution is inevitable:

SUGRA potential & gravitino mass :

$$V = \left|\frac{\partial W}{\partial \phi}\right|^2 - \frac{3|W|^2}{M_{\text{pl}}^2} + \cdots \qquad \langle W \rangle = m_{3/2} M_{\text{pl}}^2$$

Anomaly mediation

$$m_\lambda = \frac{g^2}{16\pi^2}\left(3N_c - N_f\right) m_{3/2}$$