Moduli-induced Baryogenesis

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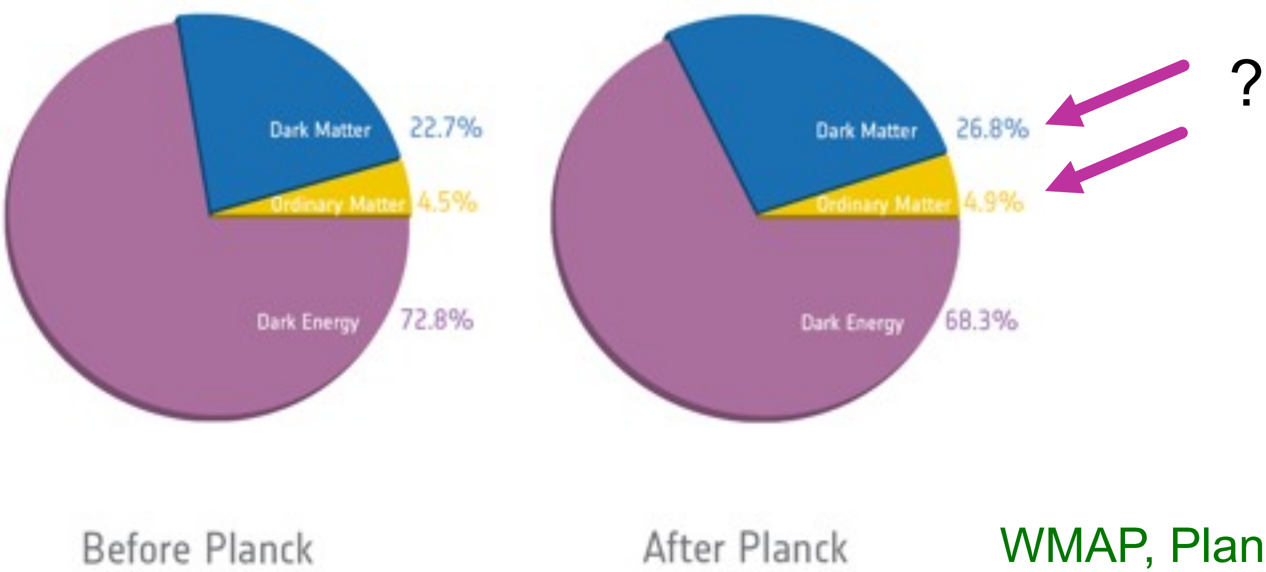
1. Introduction

The energy density of matter in the universe is precisely measured by WMAP and Planck satellites

matter
- dark matter
- baryon

However, standard model (SM) can't explain the matter density



WMAP, Planck '13

What we know about thermal history of the universe

10^{18} GeV ? Birth of the universe

?? GeV Inflation

$\approx$

MeV Big bang nucleosynthesis (BBN)

Present

What we know about thermal history of the universe

10^{18} GeV ? Birth of the universe

?? GeV Inflation

Matter should be produced during this period in beyond SM (BSM)

MeV Big bang nucleosynthesis (BBN)

Present

Supersymmetry (SUSY) is a good candidate for BSM

Pros:

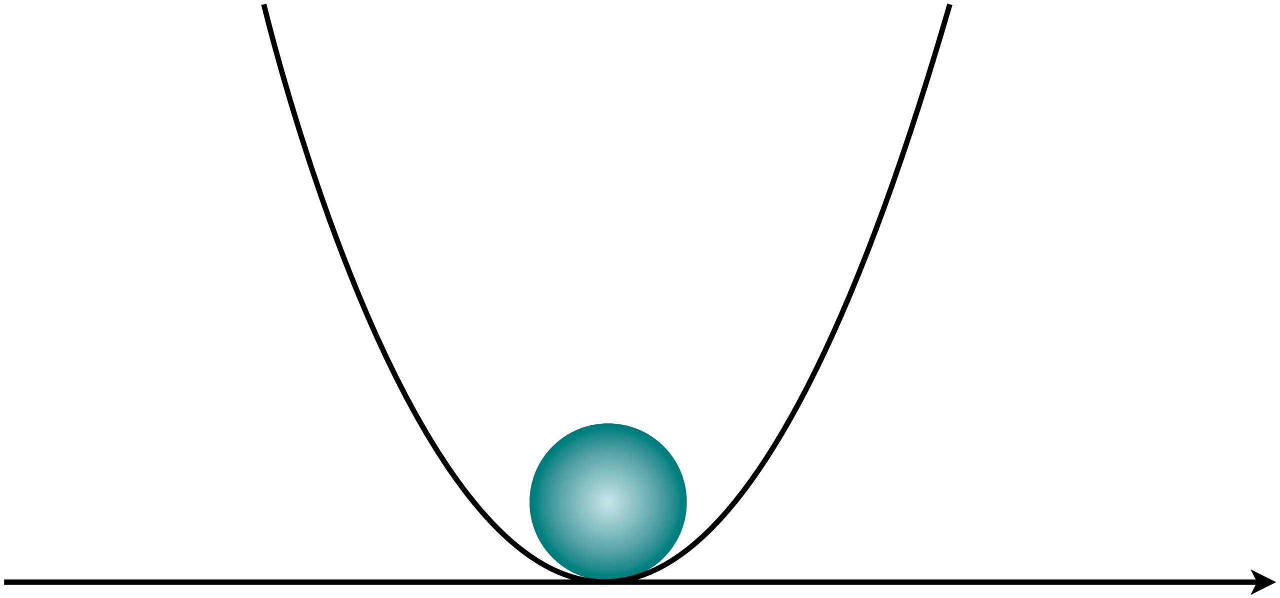
- (still) a solution to the hierarchy problem
- dark matter (DM) candidate
- UV completed theory (supergravity, superstring)

Cons:

- gravitino problem — Weinberg '82
- moduli problem — Coughlan,Fischler,Kolb,Raby,Ross '83

Moduli:

- scalar field predicted in string theory
- it must be stabilized to compactify extra dimensions

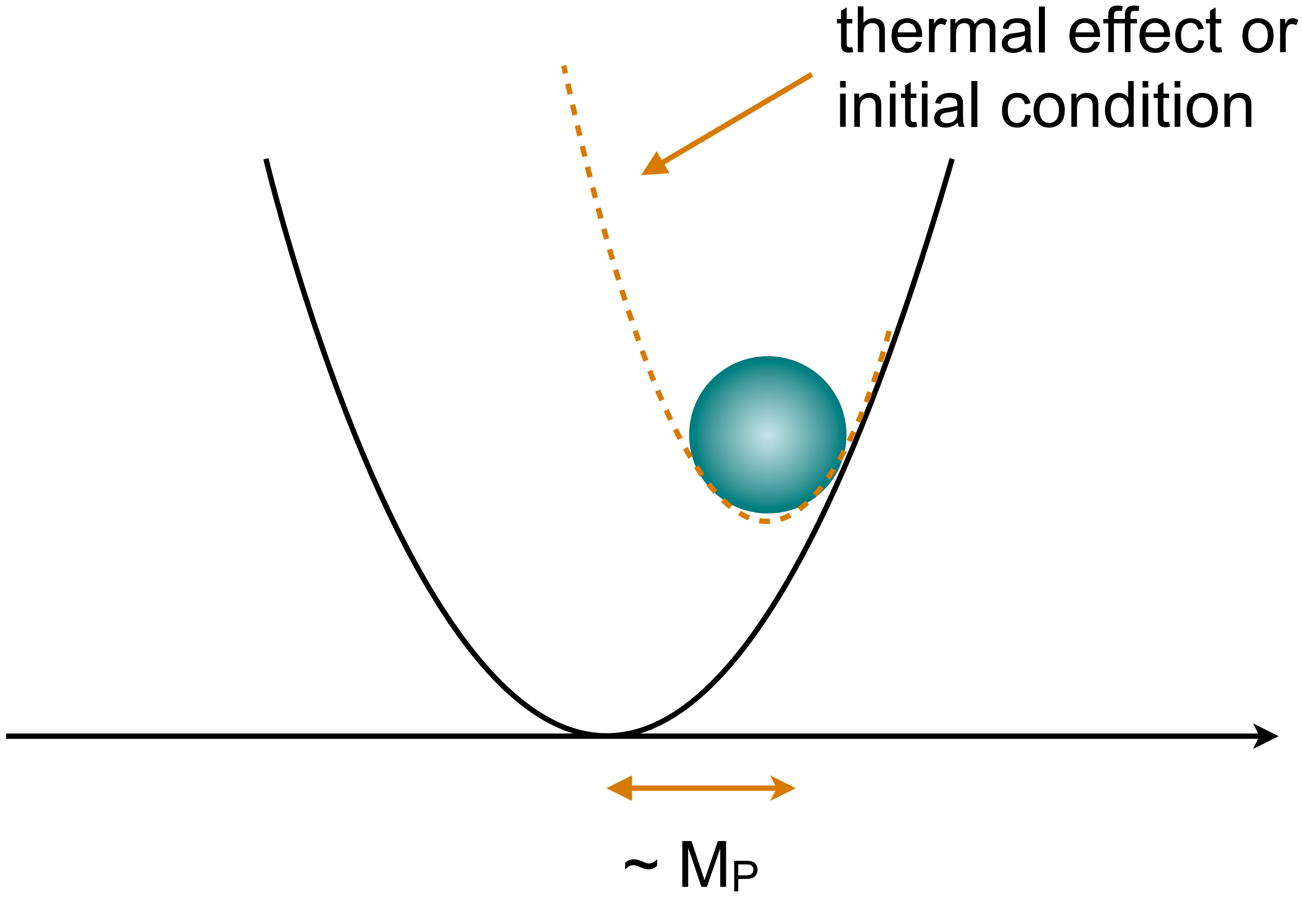


$\sim M_P$

M_P : Planck scale

In the early universe,

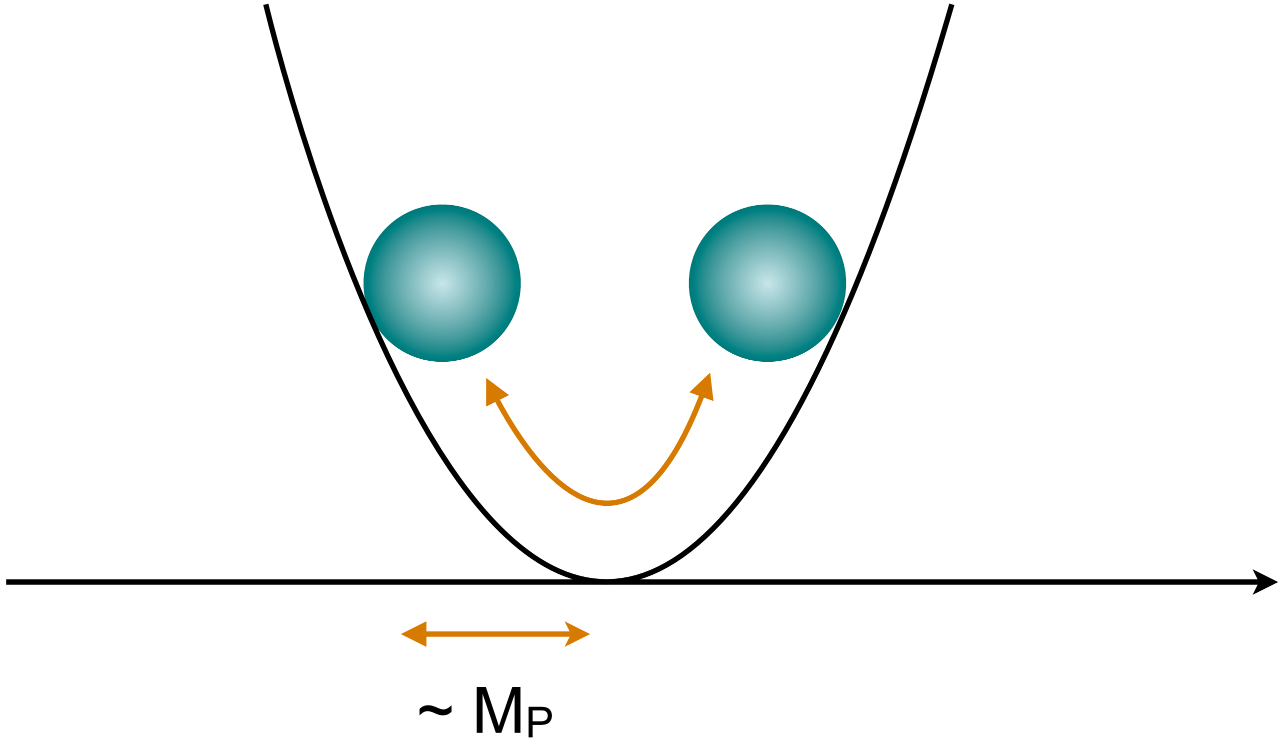
1) it can be displaced from its true minimum during inflation



In the early universe,

1) it can be displaced from its true minimum during inflation

2) after inflation it starts to oscillate around the minimum



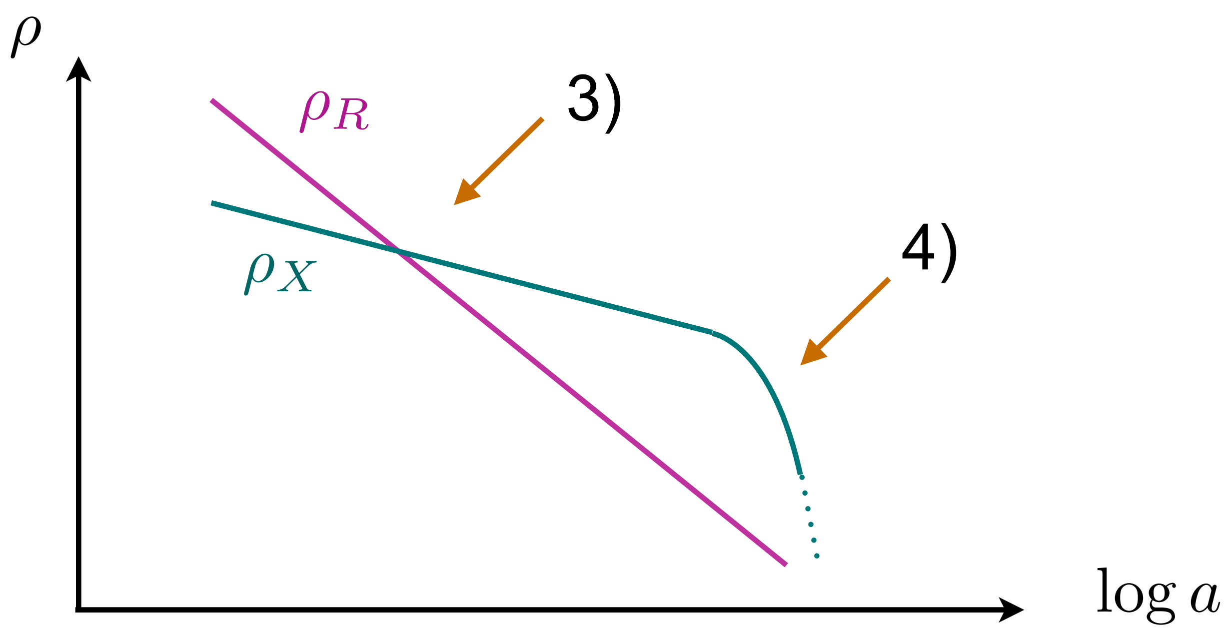
In the early universe,

1) it can be displaced from its true minimum during inflation

2) after inflation it starts to oscillate around the minimum

3) the coherent oscillation soon dominates the universe

4) finally it decays to produce huge entropy



Large amount of entropy by moduli decay

- may destroy successful BBN
- dilutes primordial relics, like baryon or DM

"Moduli problem"

However, moduli problem can be a solution

"Moduli-induced baryogenesis"

e.g.,

- gravitino-dominated universe — Cline,Raby '90
- saxion-dominated universe — Mollerach,Roulet '91

We study baryogenesis induced by moduli decay and discuss

- moduli stabilization scenario for baryogenesis
- scale of moduli mass, SUSY particle mass
- experimental consequences

Outline

1. Introduction
2. Baryogenesis induced by moduli
3. Results
4. Conclusion

2. Baryogenesis induced by moduli

Setup - *ingredients for baryogenesis -*

Sakharov '67

- C and CP violation
- Baryon number violation
- Departure from thermal equilibrium

C and CP violation

We consider KKLT-type moduli stabilization

Kachru,Kallosh,Linde,Trivedi '03

In KKLT, SUSY breaking is modulus-anomaly mediation:

$$A_{ijk},\ M_a \sim \underbrace{\left\langle \frac{F^X}{X+X^*} \right\rangle}_{\text{moduli}} + \underbrace{\mathcal{O}\left(\frac{1}{16\pi^2}\right) m_{3/2}^*}_{\text{anomaly}}$$

→ CP phase: $\arg(A_{ijk}M_a^*) \sim \arg(\langle F^X \rangle m_{3/2})$

A_{ijk} : coefficient of A-term

M_a : gaugino mass

X : moduli

$m_{3/2}$: gravitino mass

In the original KKLT scenario, CP phase is zero

$$W = \underset{\substack{\uparrow \\ \text{real}}}{w_0} + \underset{\substack{\uparrow \\ \text{real}}}{A} e^{-aX}$$

Non-zero CP phase, which can be $\mathcal{O}(0.1)$, arises from *additional* non-perturbative term(s):

$$W = \underset{\substack{\uparrow \\ \text{real}}}{w_0} + \underset{\substack{\uparrow \\ \text{real}}}{A} e^{-aX} + \underset{\substack{\uparrow \\ \cancel{\text{real}}}}{B} e^{-bX}$$

$$\longrightarrow \quad \langle F^X \rangle \propto m_{3/2}^* \times e^{i\delta}$$

$$\longrightarrow \quad \arg(A_{ijk} M_a^*) \sim \arg(\langle F^X \rangle m_{3/2}) \neq 0$$

Baryon number violation

We consider R-parity violation (RPV)

$$W_{\not R_p} = \frac{1}{2}\lambda_{ijk} U_i^c D_j^c D_k^c$$

$$\mathcal{L}_{\not R_p,\mathrm{soft}} = \frac{1}{2}(A_{ijk}\lambda_{ijk}\tilde{u}_i^c \tilde{d}_j^c \tilde{d}_k^c + A_{ijk}^* \lambda_{ijk}^* \tilde{u}_i^{c*} \tilde{d}_j^{c*} \tilde{d}_k^{c*})$$

Note LSP can decay to SM particles via RPV

→ no moduli-induced gravitino problem

Setup - *ingredients for baryogenesis -*

Sakharov ’67

- C and CP violation
- Baryon number violation
- Departure from thermal equilibrium

Departure from thermal equilibrium

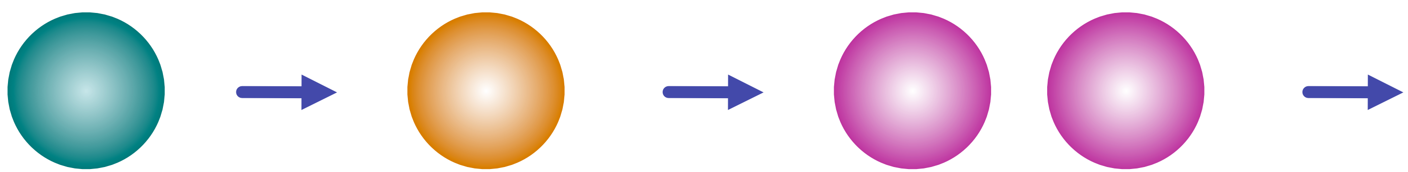
Moduli-dominated universe ends when moduli decays

Two steps for baryogenesis:

step 1). moduli decays to visible sector particles

step 2). produced gluino decays

→ generates baryon asymmetry



baryon

moduli X

gluino $\tilde{g}$

quark, squark q $\tilde{q}$

step 1). Moduli decay

Moduli interacts with visible sector via gauge kinetic term:

$$\mathcal{L} = \int d^2\theta k_a X W^a W^a$$

W^a: gauge multiplet

$a : SU(3)_C, SU(2)_L, U(1)_Y$

Moduli decays to gauge boson/gaugino pair

$$X \to gg, \ \tilde{g}\tilde{g}, \ \cdots$$

Moduli decay reheats the universe

$$\boxed{\Gamma_X \simeq \frac{1}{4\pi}\frac{m_X^3}{M_P^2}}$$

- reheating temperature: $T_X \sim \sqrt{\Gamma_X M_P}$

$$\sim 0.2\ \mathrm{GeV}\left(\frac{m_X}{10^6\ \mathrm{GeV}}\right)^{3/2}$$

→ $T_X < m_{\mathrm{soft}}$ guarantees out-of-equilibrium gluino and squark decay

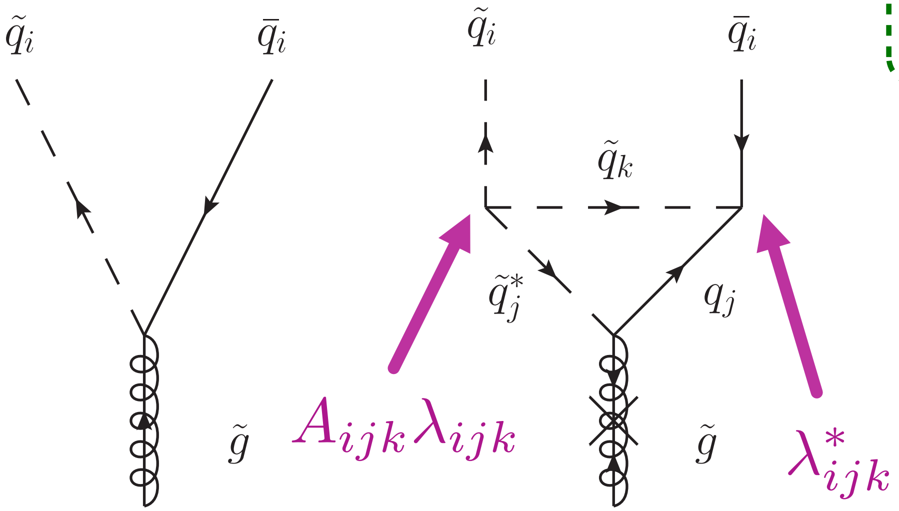
- branching ratio for gluino pair: $\mathrm{Br}(X \to \tilde{g}\tilde{g}) \simeq \dfrac{1}{3}$

→ many gluinos are produced

step 2). Gluino decay

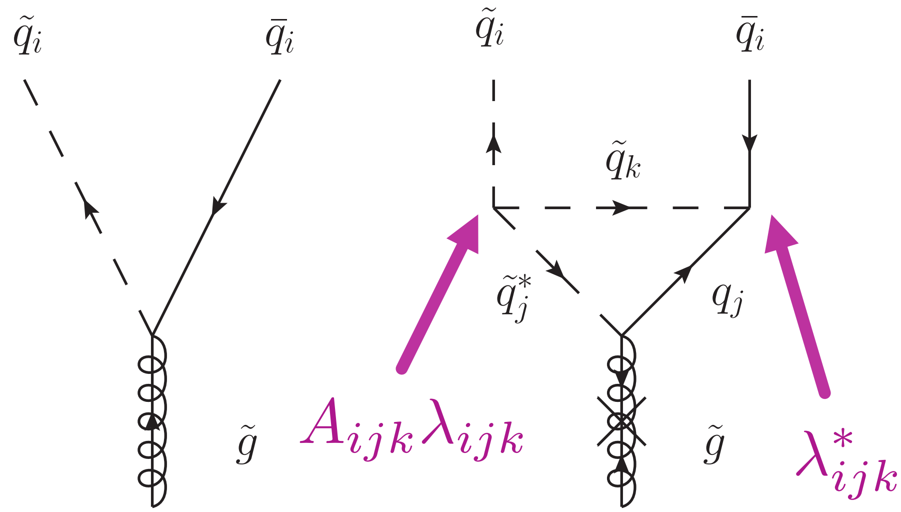
$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}U_i^c D_j^c D_k^c$$

$$\mathcal{L}_{\not{R}_p,\mathrm{soft}} = \frac{1}{2}(A_{ijk}\lambda_{ijk}\tilde{u}_i^c \tilde{d}_j^c \tilde{d}_k^c + \mathrm{h.c.})$$



→ RPV interaction gives asymmetry in gluino decay:

$$\Delta\Gamma(\tilde{g} \to \tilde{q}_i \bar{q}_i) = \Gamma(\tilde{g} \to \tilde{q}_i \bar{q}_i) - \Gamma(\tilde{g} \to \tilde{q}_i^* q_i) \neq 0$$



$$\frac{\Delta\Gamma(\tilde{g} \to \tilde{q}_i \bar{q}_i)}{\Gamma_{\tilde{g}}} \sim \frac{1}{12\pi} \frac{|\lambda_{ijk}|^2 \mathrm{Im}(A_{ijk} M_{\tilde{g}}^*)}{|M_{\tilde{g}}|^2}$$

CP phase

$$\sim 10^{-3} \left(\frac{|\lambda_{ijk}|^2 \, \mathrm{Im}(A_{ijk} M_{\tilde{g}}^*)/|M_{\tilde{g}}|^2}{0.1} \right)$$

magnitude of RPV

$M_{\tilde{g}}$: gluino mass

At this stage, net B number is zero

$$\tilde{g} \longrightarrow \tilde{q}_i \bar{q}_i \qquad\qquad (\Delta B = 0)$$

Following squark decay via RPV produces net B number

$$\tilde{q}_i \longrightarrow \bar{q}_j \bar{q}_k \qquad\qquad (\Delta B = 1)$$

$$\Rightarrow \quad \epsilon_B \sim \frac{\Delta\Gamma(\tilde{g} \rightarrow \tilde{q}_i \bar{q}_i)}{\Gamma_{\tilde{g}}} \times \mathrm{Br}^{\tilde{q}_i}$$

$$\mathrm{Br}^{\tilde{q}_i} \equiv \mathrm{Br}(\tilde{q}_i \rightarrow \bar{q}_j \bar{q}_k)$$

$\sim \mathcal{O}(1)$ when $\lambda_{ijk} \sim \mathcal{O}(1)$

Let's combine step 1) and 2)

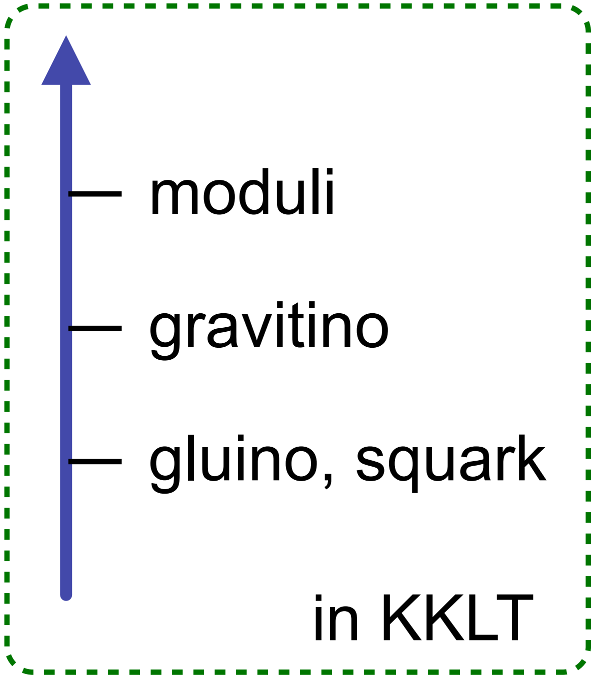
- $\rho_X \simeq \rho_R$
- $n_{\tilde{g}} = 2 n_X \mathrm{Br}(X \to \tilde{g}\tilde{g})$
- $n_B = n_{\tilde{g}} \epsilon_B$

$$\Rightarrow \quad \frac{n_B}{s} = \frac{3 T_X}{4 m_X} 2\mathrm{Br}(X \to \tilde{g}\tilde{g}) \epsilon_B$$

3. Results

Parameters:

- moduli mass: $m_X \simeq 2m_{3/2}\ln(M_P/m_{3/2})$
- soft mass scale: $m_{\rm soft} = \dfrac{m_{3/2}}{4\pi^2}$
- RPV: $\lambda_{332} \neq 0$, the others are zero



(i) $\tilde{t}$, $\tilde{b}$, $\tilde{s}$ are lighter than $\tilde{g}$

$$M_{\tilde{g}} = 3m_{\rm soft}\,, \quad m_{\tilde{t},\,\tilde{b},\,\tilde{s}} = m_{\rm soft}\,, \quad m_{\tilde{q}\neq\tilde{t},\,\tilde{b},\,\tilde{s}} = 6m_{\rm soft}$$

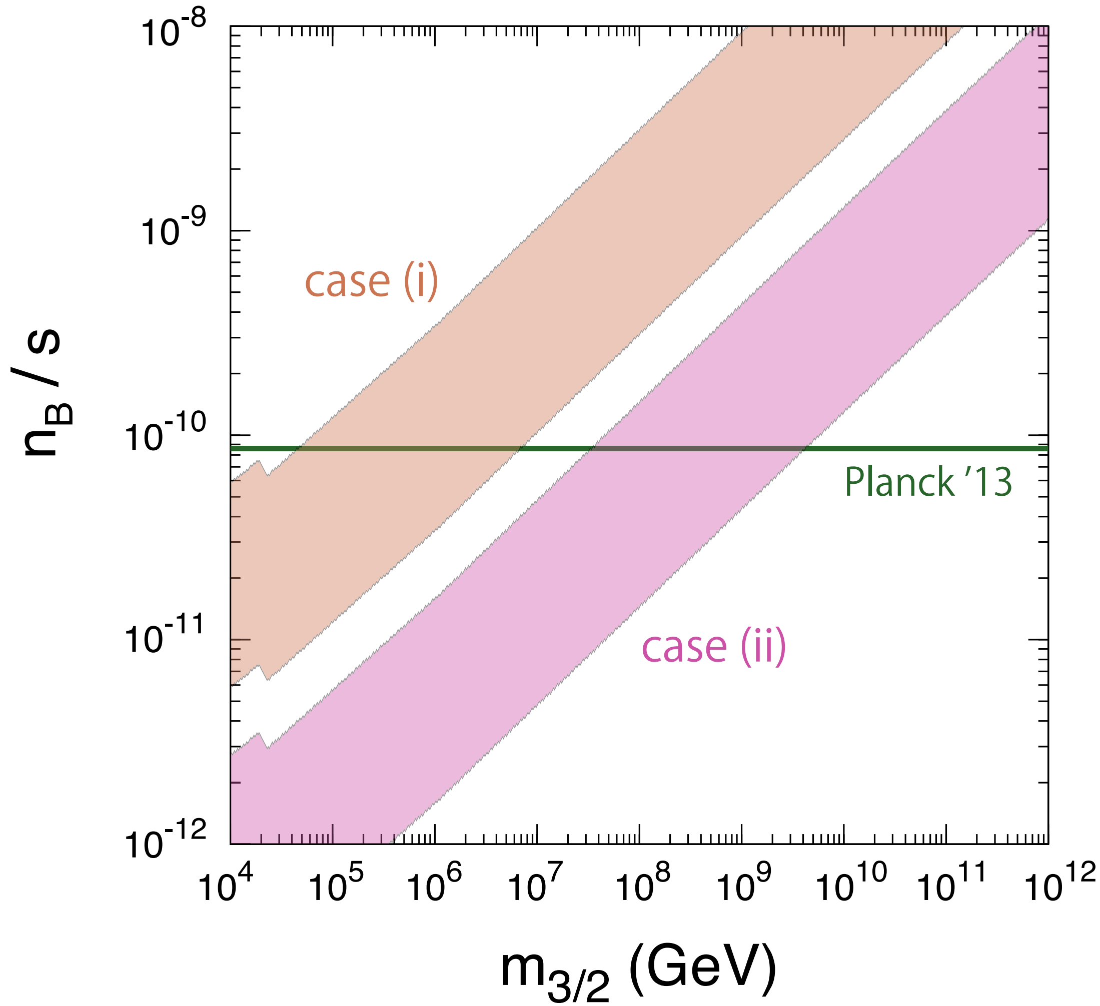
$$\mathrm{Br}^{\tilde{t},\,\tilde{b},\,\tilde{s}} = 0.5$$

(ii) $\tilde{t}$, $\tilde{b}$ are lighter than $\tilde{g}$

$$M_{\tilde{g}} = 3m_{\rm soft}\,, \quad m_{\tilde{t},\,\tilde{b}} = m_{\rm soft}\,, \quad m_{\tilde{q}\neq\tilde{t},\,\tilde{b}} = 6m_{\rm soft}$$

$$\mathrm{Br}^{\tilde{t},\,\tilde{b}} = 0.5$$

$$0.01 \ \leq \ -|\lambda_{332}|^2 \frac{\mathrm{Im}(A_{332} M_{\tilde{g}}^*)}{|M_{\tilde{g}}|^2} \ \leq \ 0.1$$



Successful baryogenesis when $m_{3/2} \gtrsim 100 \ \mathrm{TeV}$

Experimental consequences:

- electric dipole moments of electron and neutron

$$\longrightarrow \quad \mathrm{Im}(A_{ijk}M_{\tilde{g}}^{*})/|M_{\tilde{g}}|^2 \lesssim 0.1 \times \left(\frac{m_{\mathrm{soft}}}{1\ \mathrm{TeV}}\right)^2$$

- dinucleon decay $pp \to K^+K^+$

$$\longrightarrow \quad |\lambda_{332}| \lesssim \mathcal{O}(1) \left(\frac{m_{\mathrm{soft}}}{1\ \mathrm{TeV}}\right)^{5/2} \left(\frac{250\ \mathrm{MeV}}{\Lambda_{\mathrm{QCD}}}\right)^{5/2}$$

Recall $m_{3/2} \gtrsim 100\ \mathrm{TeV}$ corresponds to $m_{\mathrm{soft}} \gtrsim \mathrm{TeV}$

The scenario may be probed in the future experiments

4. Conclusion

A huge entropy production due to late decaying moduli is unavoidable and problematic

We found the moduli decay can be a source of baryon

- KKLT scenario has built-in features for the baryogenesis *i.e.* $\mathcal{O}(0.1)$ CP phase, out-of equilibrium gluino/squark decay
- $m_{3/2} \gtrsim 100\ \mathrm{TeV}\ (m_{\mathrm{soft}} \gtrsim \mathrm{TeV})$ for successful baryogenesis
- such parameter region can be probed in the future experiments, *e.g.*, EDMs, dinucleon decay

Backup

Estimation

$$\frac{n_B}{s} = \frac{3T_X}{4m_X} 2\mathrm{Br}(X \to \tilde{g}\tilde{g})\epsilon_B$$

- $T_X \sim 0.2\ \mathrm{GeV} \left(\frac{m_X}{10^6\ \mathrm{GeV}}\right)^{3/2}$
- $\epsilon_B \sim 10^{-3} \left(\frac{|\lambda_{332}|^2\, \mathrm{Im}(A_{332} M_{\tilde{g}}^*)/|M_{\tilde{g}}|^2}{-0.1}\right) \left(\frac{\mathrm{Br}^{\tilde{q}}}{0.5}\right)$
- $\mathrm{Br}(X \to \tilde{g}\tilde{g}) \simeq \frac{1}{3}$

$$\longrightarrow \quad \frac{n_B}{s} \sim 9 \times 10^{-11} \left(\frac{m_X}{10^6\ \mathrm{GeV}}\right)^{1/2} \left(\frac{\epsilon_B}{10^{-3}}\right)$$

Experimental consequences:

- electric dipole moment

$$d_n \leq 2.9 \times 10^{-26}\ e\ \mathrm{cm} \quad (90\%\ \mathrm{C.L.})$$

$$d_e \leq 8.7 \times 10^{-29}\ e\ \mathrm{cm} \quad (90\%\ \mathrm{C.L.})$$

$$\longrightarrow \quad \mathrm{Im}(A_{ijk} M_{\tilde{g}}^{*})/|M_{\tilde{g}}|^2 \lesssim 0.1 \times \left(\frac{m_{\mathrm{soft}}}{1\ \mathrm{TeV}}\right)^2$$

- neutron-antineutron oscillation

$$\tau_{n\text{-}\bar{n}} \geq 2.4 \times 10^8 \text{ sec} \quad (90\% \text{ C.L.})$$

$$\longrightarrow \quad |\lambda_{112}| \lesssim 4.4 \times 10^{-3} \left(\frac{m_{\rm soft}}{1 \text{ TeV}}\right)^{5/6} \left(\frac{250 \text{ MeV}}{\tilde{\Lambda}}\right)$$

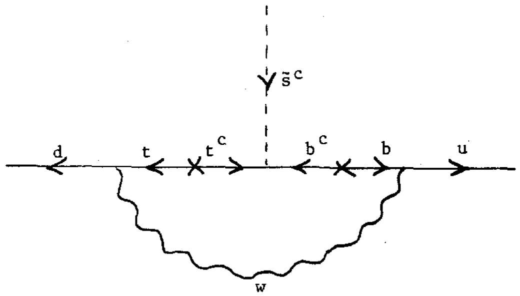
- dinucleon decay

$$\tau(pp \to K^+ K^+) \geq 1.7 \times 10^{32} \text{ yr} \quad (90\% \text{ C.L.}).$$

$$\longrightarrow \quad |\lambda_{112}| \lesssim 3.2 \times 10^{-7} \left(\frac{m_{\rm soft}}{1 \text{ TeV}}\right)^{5/2} \left(\frac{250 \text{ MeV}}{\tilde{\Lambda}}\right)^{5/2}$$

Loop diagram induces $ud\tilde{s}$ -type coupling from λ_{332}

Dimopoulos, Hall '87



$\lambda_{332} = 1$ → $ud\tilde{s}$ -type $\mathcal{O}(10^{-7})$

$$|\lambda_{112}| \lesssim 3.2 \times 10^{-7} \left(\frac{m_{\rm soft}}{1\ \mathrm{TeV}}\right)^{5/2} \left(\frac{250\ \mathrm{MeV}}{\tilde{\Lambda}}\right)^{5/2}$$

→ $$|\lambda_{332}| \lesssim \mathcal{O}(1) \left(\frac{m_{\rm soft}}{1\ \mathrm{TeV}}\right)^{5/2} \left(\frac{250\ \mathrm{MeV}}{\tilde{\Lambda}}\right)^{5/2}$$