Affleck-Dine baryogenesis with R-parity violation

Ken'ichi Saikawa
Tokyo Institute of Technology (Titech)

Collaborate with Tetsutaro Higaki (KEK), Kazunori Nakayama (U. Tokyo),
Tomo Takahashi (Saga U.), and Masahide Yamaguchi (Titech)

based on
T. Higaki, K. Nakayama, KS, T. Takahashi, M. Yamaguchi, hep-ph/1404.5796. (accepted in PRD)

Abstract

- Investigate the Affleck-Dine baryogenesis scenario in the framework of

Minimal Supersymmetric Standard Model (MSSM)
+
R-parity violating interactions

- Discuss the parameter region for the successful baryogenesis by considering various conditions:
  - Constraint on R-parity violating couplings
  - Wash out effects
  - Dynamics of non-topological solitons (Q-balls)

R-parity (violation)

$$R_p = (-1)^{2S+3B+L}$$

S : spin
B : baryon number
L : lepton number

Farrar, Fayet, Phys. Lett. B76, 575 (1978)

$R_p = +1$ for SM particles

$R_p = -1$ for superpartners

- R-parity conserving superpotential in the MSSM

$$W_{\mathrm{MSSM}} = \mu H_u H_d + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j$$

$i, j, k = 1, 2, 3$: family indices

- R-parity violating superpotential

$$W_{\not{R}_p} = \underbrace{\mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k}_{\Delta L = 1} + \underbrace{\frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k}_{\Delta B = 1}$$

also violates baryon number and lepton number

Why R-parity (violation) ?

- R-parity conservation (PRC)
  - Prohibits proton decay
  - LSP becomes stable → dark matter
- R-parity violation (RPV)
  - R-parity can be largely violated in general
  - It relaxes stringent limits on SUSY particles at LHC
  - It introduces B/L violating interactions
    → relevant to the scenario for baryogenesis

Cosmological constraints on RPV

- Two relevant constraints

1. Light element bound
2. Sphaleron erasure

→ bounds on (trilinear) RPV couplings

$$\lambda \equiv \lambda_{ijk},\ \lambda'_{ijk},\ \text{or}\ \lambda''_{ijk}$$

- Light element bound

Decay of LSP via RPV couplings → dissociate light elements created during Big Bang Nucleosynthesis

Lifetime of LSP

$$\tau_{\rm LSP} \simeq 10^{-4}{\rm sec}\left(\frac{\lambda}{10^{-6}}\right)^{-2}\left(\frac{m_{\rm LSP}}{20{\rm GeV}}\right)^{-5}\left(\frac{m_{\tilde f}}{200{\rm GeV}}\right)^{4}$$

$m_{\rm LSP}$: mass of the LSP

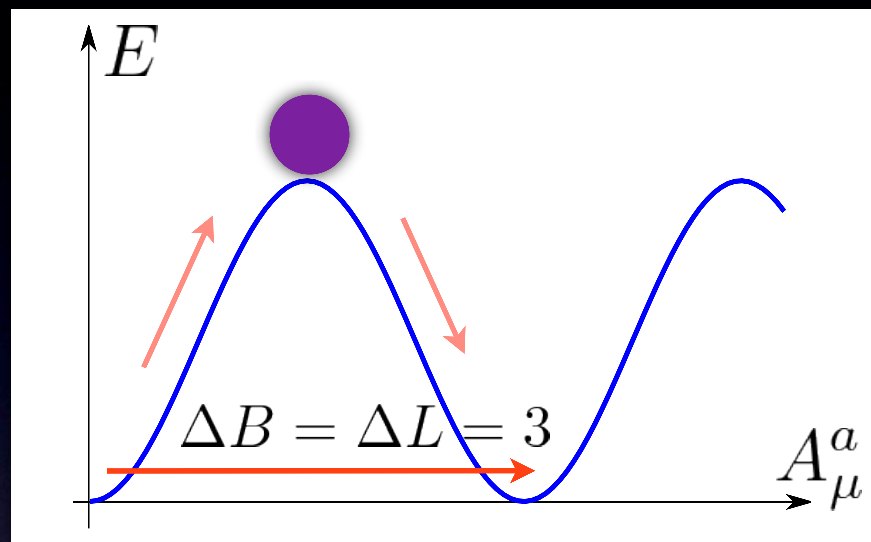
$m_{\tilde f}$: mass of the intermediate state sfermion

Requiring that $\tau_{\rm LSP} \lesssim 1{\rm sec}$

$$\lambda > 4\times 10^{-9}\left(\frac{m_{\rm LSP}}{100{\rm GeV}}\right)^{-5/2}\left(\frac{m_{\tilde f}}{1{\rm TeV}}\right)^{2}$$

Sphaleron erasure

- Sphaleron process Kuzmin, Rubakov, Shaposhnikov, Phys. Lett. B155, 36 (1985)



equilibrium for $T \gtrsim \mathcal{O}(100)\mathrm{GeV}$

erases (B+L) but conserves (B-L)

- 2 → 1 process via RPV coupling

example:

Campbell, Davidson, Ellis, Olive, Astropart. Phys. 1, 77 (1992)
Dreiner, Ross, Nucl. Phys. B410, 188 (1993)

$$\Gamma \sim \lambda^2 m_{\tilde{f}}^2 / T$$

sphaleron + RPV process → completely erases B and L

To avoid the erasure effect, $\Gamma < H$ for $T \gtrsim m_{\tilde{f}}$

$$\lambda < 4 \times 10^{-7} \left(\frac{m_{\tilde{f}}}{1\mathrm{TeV}} \right)^{1/2}$$

H : Hubble expansion rate

Affleck-Dine baryogenesis with RPV

- Affleck-Dine (AD) mechanism Affleck, Dine, Nucl. Phys. B249, 361 (1985)

Scalar potential of MSSM $\supset$ Flat directions ϕ (AD field)

Flat in the absence of SUSY breaking effect and lifting terms (see below)

Dynamics of AD field (non-equilibrium, CP violation) via B/L violating operator ⇒ Generate B/L number

- Lifting the potential (B/L violation)
  - Usual case: non-renormalizable operator $W = \phi^{n+3}/M^n, \ (n \geq 1)$
  - This scenario: renormalizable RPV operator $W_{\not{R}_p} = \lambda \phi^3 / 3$

Dynamics of the Affleck-Dine field

- Potential for the AD field $W_{\not R_p} = \frac{1}{3}\lambda\phi^3$

Assuming gravity (or anomaly) mediated SUSY breaking

$$V(\phi) = (m_\phi^2 - cH^2)|\phi|^2 + \left(\frac{\lambda}{3}a_m m_{3/2}\phi^3 + \mathrm{h.c.}\right) + \lambda^2|\phi|^4$$

m_ϕ : soft SUSY breaking mass

$m_{3/2}$: gravitino mass

$c,\ a_m$: dimensionless coefficients

- During inflation

$$H \gg m_\phi,\ m_{3/2}$$

$$V(\phi) \simeq -cH^2|\phi|^2 + \lambda^2|\phi|^4$$

$$\Rightarrow \quad \phi = \phi_{\rm inf} \equiv \frac{\sqrt{c}H_{\rm inf}}{\sqrt{2}\lambda}$$

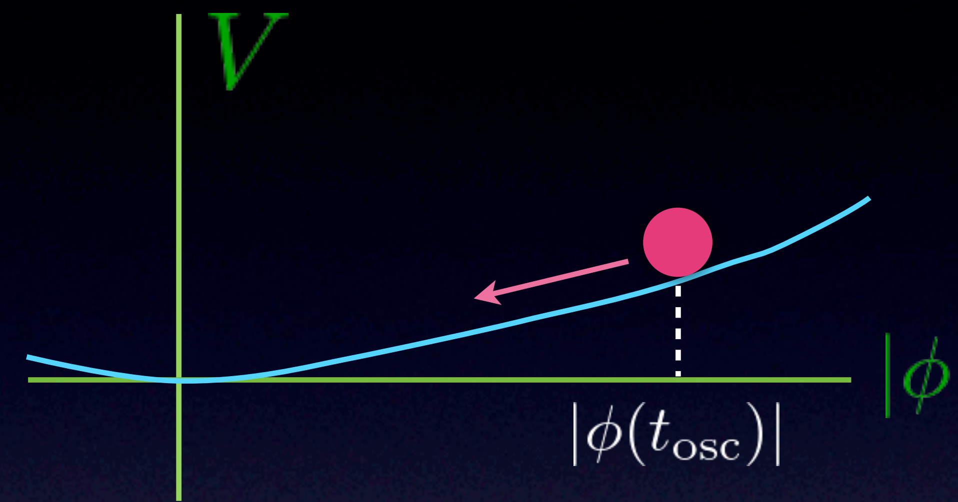
$H_{\rm inf}$: Hubble parameter during inflation

$$V(\phi) = (m_\phi^2 - cH^2)|\phi|^2 + \left(\frac{\lambda}{3} a_m m_{3/2} \phi^3 + \text{h.c.}\right)$$

A-term

- After inflation

$$H > m_\phi \quad H \propto R^{-3/2}$$



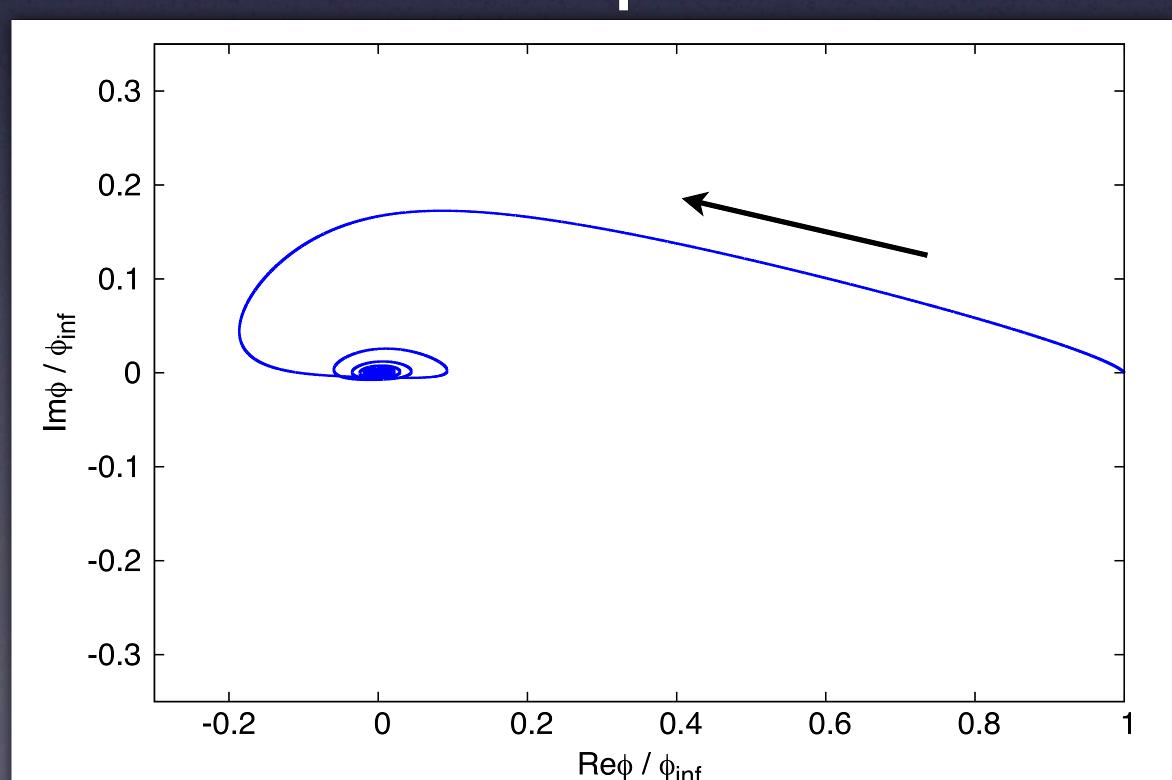
- $H \sim m_\phi$

  → AD field starts to oscillate

  from $$|\phi(t_{\mathrm{osc}})| \simeq \frac{\sqrt{c} H_{\mathrm{osc}}}{\sqrt{2}\lambda}$$

H_{osc} : Hubble parameter at the beginning of the oscillation

- A-term kicks in phase direction



$$n_B \propto i(\dot{\phi}^* \phi - \phi^* \dot{\phi}) \propto \dot{\theta} |\phi|^2$$

$$\phi = |\phi| e^{i\theta}$$

$$\frac{n_B}{s} \simeq 2 \times 10^{-9} \gamma \left(\frac{10^{-10}}{\lambda}\right)^2 \left(\frac{T_{\rm RH}}{10^5 \rm GeV}\right) \left(\frac{m_{3/2}}{10 \rm TeV}\right)$$

$$\gamma = \begin{cases} \frac{1}{3} \cdot \frac{8}{23} & \text{for} \quad L_i L_j E_k^c \quad \text{or} \quad L_i Q_j D_k^c \\ \frac{1}{3} & \text{for} \quad U_i^c D_j^c D_k^c \end{cases}$$

- Baryon asymmetry depends on three parameters: $\lambda,\ T_{\rm RH},\ \text{and}\ m_{3/2}$
- Cosmological constraints

1. Light element bound

$$\lambda > 4 \times 10^{-9} \left(\frac{m_{\rm LSP}}{100 \rm GeV}\right)^{-5/2} \left(\frac{m_{\tilde{f}}}{1 \rm TeV}\right)^2$$

2. Avoiding sphaleron erasure

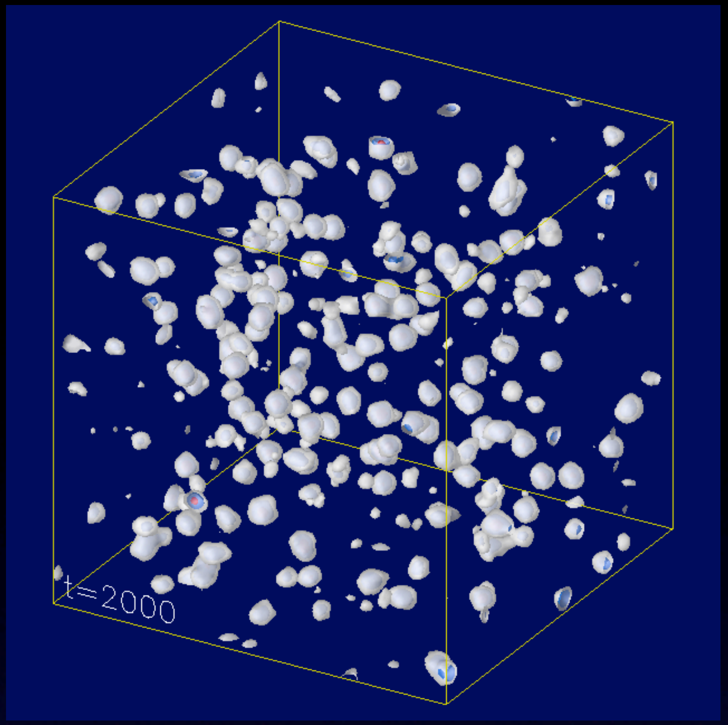
$$\lambda < 4 \times 10^{-7} \left(\frac{m_{\tilde{f}}}{1 \rm TeV}\right)^{1/2}$$

(it can be also avoided if Q-balls are long-lived)

3. Q-balls survive or not

Q-ball formation

Q-ball:
Non-topological soliton in scalar field theory with global U(1) symmetry



Hiramatsu, Kawasaki, Takahashi, JCAP 1006(2010)008

Oscillation of AD field
(B number generation)

↓

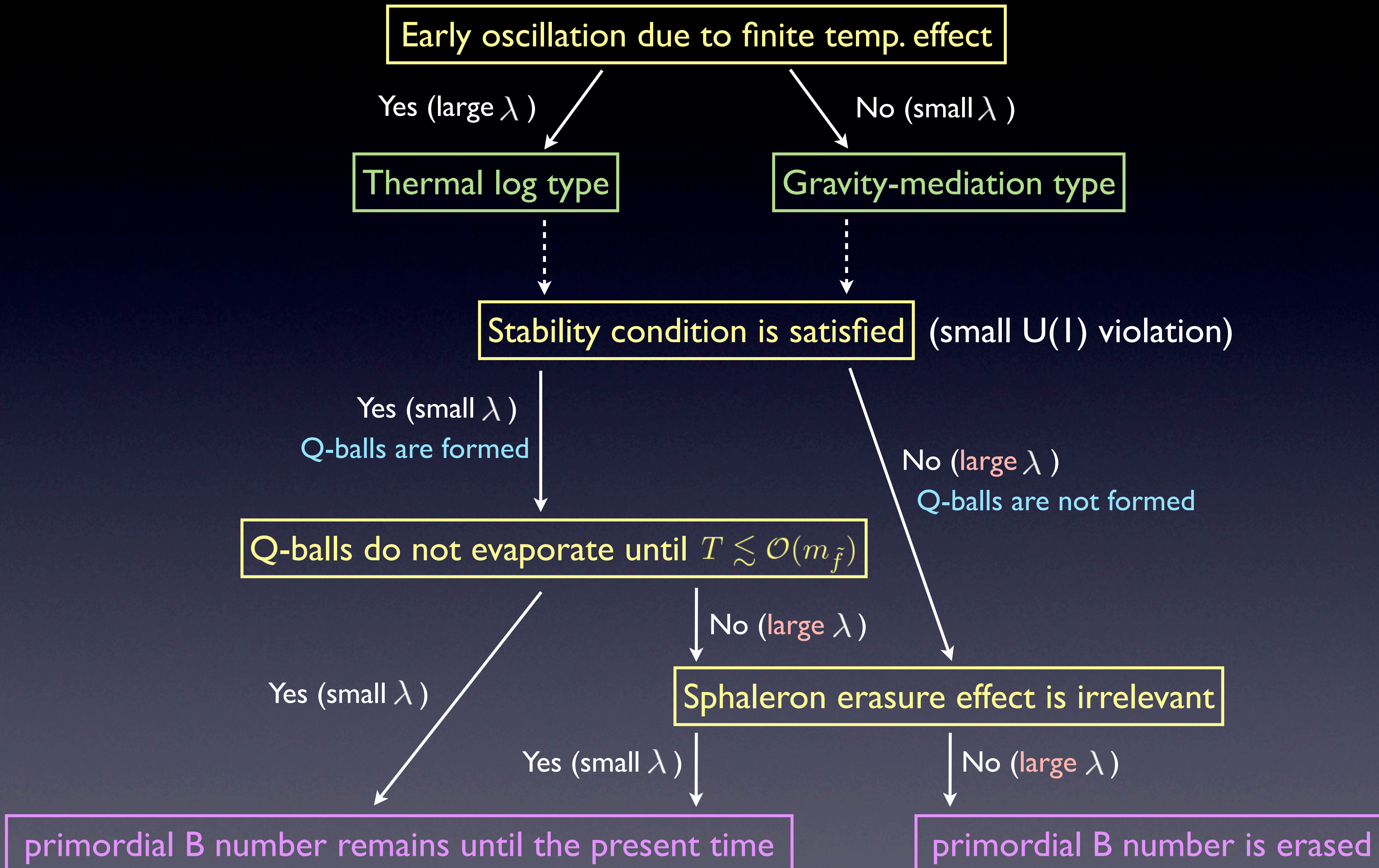
Q-ball formation

↓ ↓

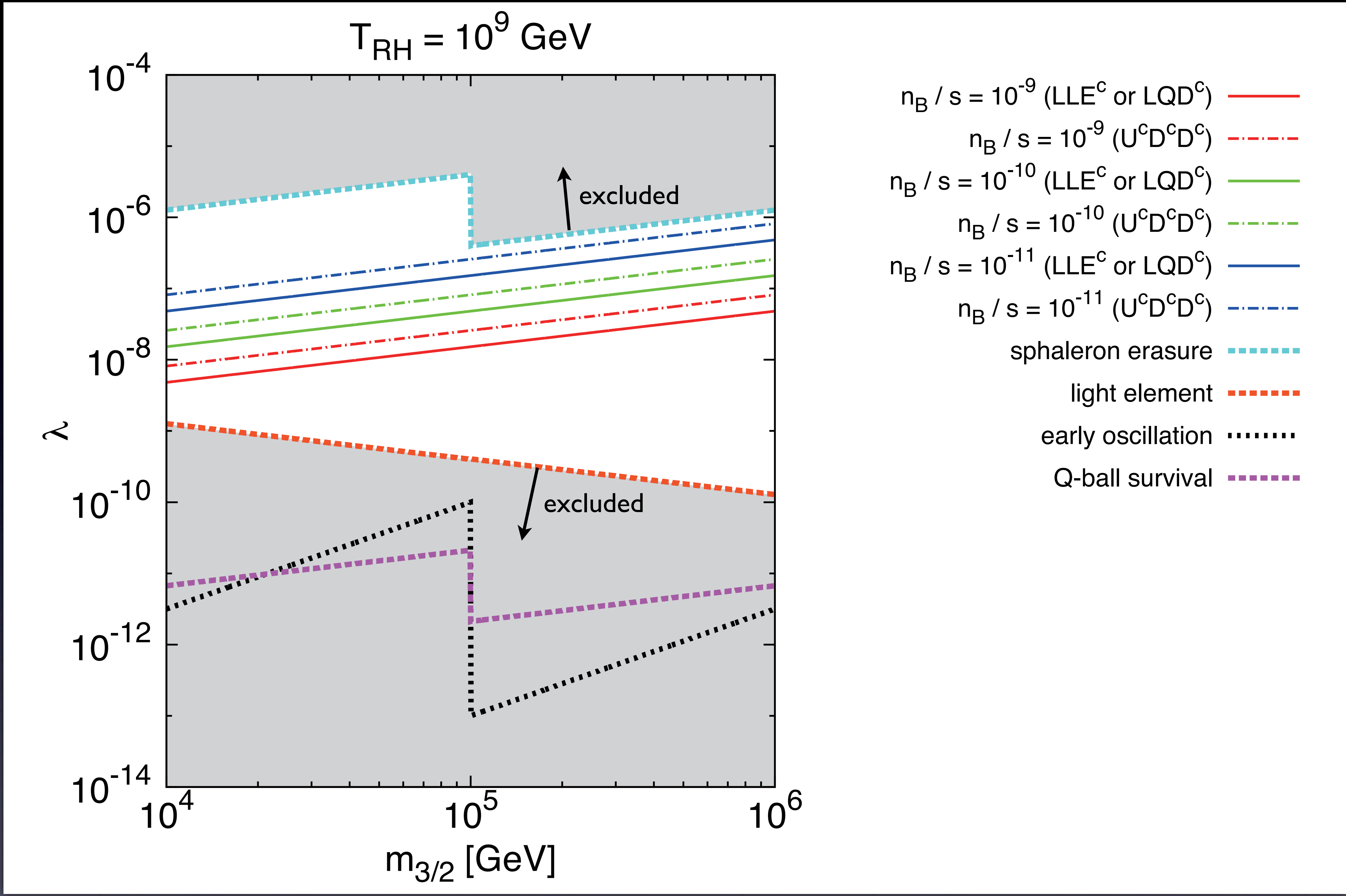
Stable, long-lived Q-ball → Release B number if it decays below $T < \mathcal{O}(m_{\tilde{f}})$ (large λ scenario)

Evaporation → B number remains until today if sphaleron erasure effect is irrelevant (small λ scenario)

Q-ball dynamics is complicated !

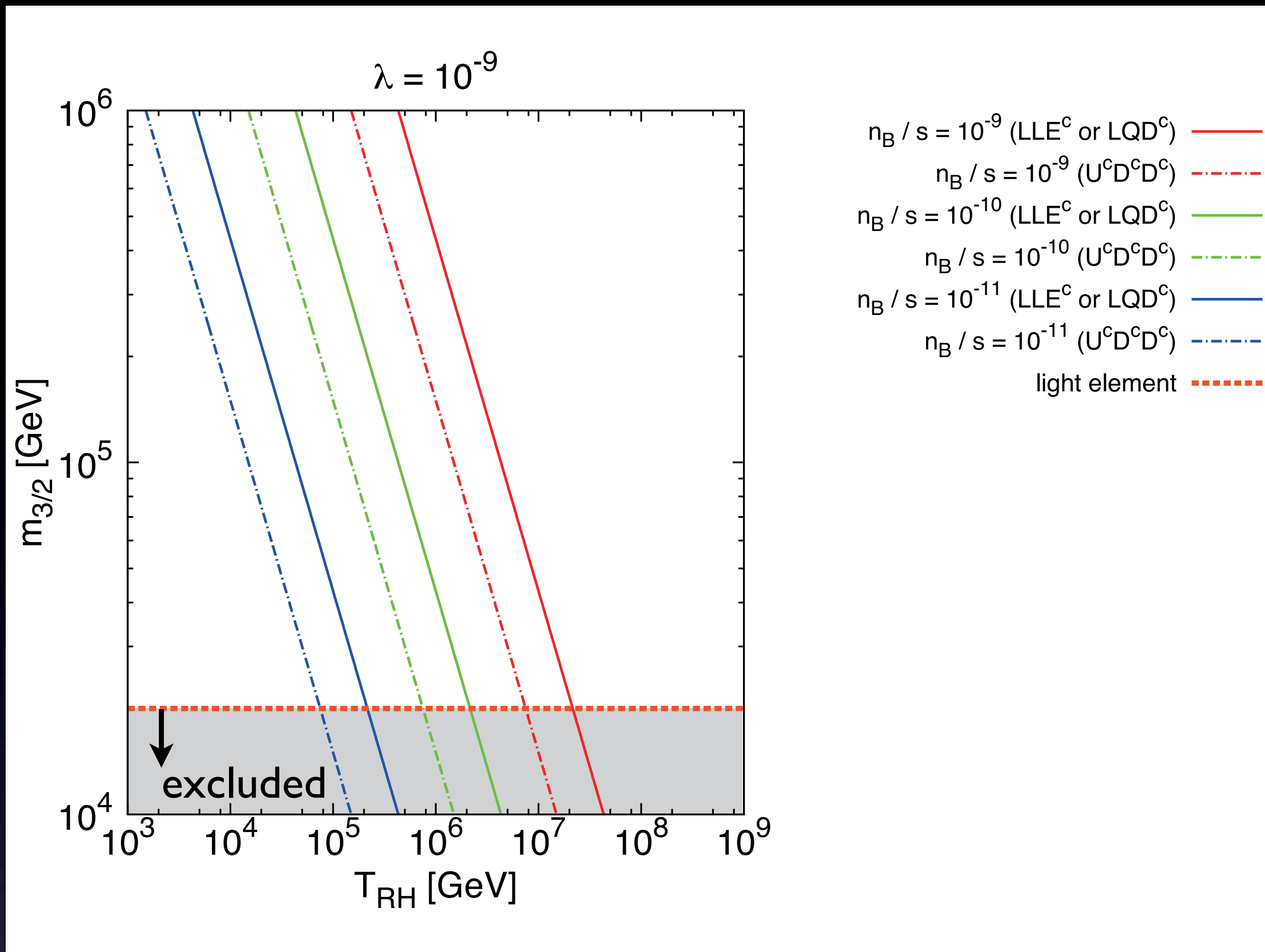


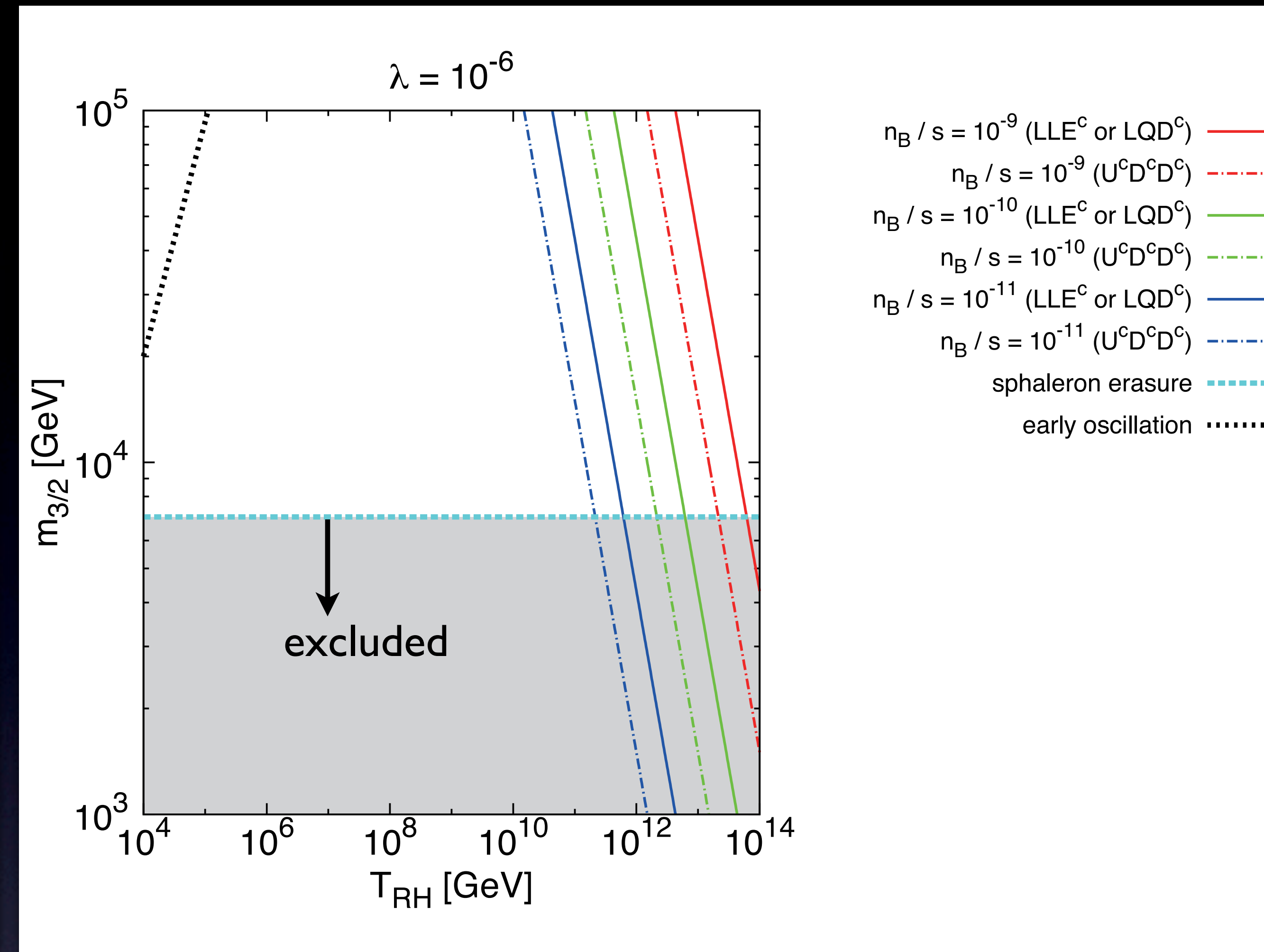
Destruction effect becomes relevant for larger value of λ



$m_{3/2} = m_\phi = m_{\tilde{f}} = 10 m_{\rm LSP} \quad \text{for} \quad m_{3/2} < 10^5\,\text{GeV}$ (gravity mediation)

$m_{3/2} = 100 m_\phi = 100 m_{\tilde{f}} = 400 m_{\rm LSP} \quad \text{for} \quad m_{3/2} > 10^5\,\text{GeV}$ (anomaly mediation)





- large λ
  → sphaleron erasure effect becomes relevant
- small λ
  → (unstable) LSP is long-lived → affects BBN
- typically $m_{3/2} \gtrsim \mathcal{O}(10^3 - 10^4)\mathrm{GeV}$ is required

Summary

- Affleck-Dine mechanism naturally works via a trilinear R-parity violating interaction
- Large λ scenario (preserve B/L number against the erasure effect) is impossible
  - Q-balls are likely to be destructed
- Small λ scenario is possible if
  - Magnitude of RPV coupling is marginally small

$$10^{-9} \lesssim \lambda \lesssim 10^{-6}$$

  - Gravitino mass as heavy as $m_{3/2} \gtrsim 10^4 \mathrm{GeV}$

Backup slides

Model

- PRV superpotential

$$W_{\not R_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

- All of the combinations $H_u L_i$, $L_i L_j E_k^c$, $L_i Q_j D_k^c$ and $U_i^c D_j^c D_k^c$ correspond to the flat directions if R-parity is conserved
  → lifted by the RPV superpotential

- Assume that a single trilinear term dominates

(Effect of the bilinear term $\mu_i H_u L_i$ is negligible:

$$\mu_i \lesssim \mathcal{O}(10^{-6})\mu \sim \mathcal{O}(10^{-6}) m_{\rm soft}$$

from upper bound of neutrino mass → reduces the efficiency of baryogenesis by a factor of $\mathcal{O}(10^{-6})$)

→ $$W_{\not R_p} = \frac{1}{3}\lambda\phi^3$$

$\lambda \equiv \lambda_{ijk},\ \lambda'_{ijk},\ \text{or}\ \lambda''_{ijk}$

ϕ : parameterizes LLE, LQD, or UDD direction

Baryon/Lepton number generation

- ϕ has a B / L number

Example: LLE direction

$$L_i = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\0\end{pmatrix}, \qquad L_j = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\\phi\end{pmatrix}, \qquad E_k^c = \frac{1}{\sqrt{3}}\phi$$

$$U(1)_L: \quad L_i \to e^{i\alpha}L_i, \quad E_k^c \to e^{-i\alpha}E_k^c$$

Noether current → baryon / lepton density

$$j_L^\mu = \frac{i}{3}[(\partial^\mu\phi^*)\phi - \phi^*(\partial^\mu\phi)] \Rightarrow n_L = \frac{1}{3}n$$ for $L_iL_jE_k^c$ or $L_iQ_jD_k^c$

$$j_B^\mu = -\frac{i}{3}[(\partial^\mu\phi^*)\phi - \phi^*(\partial^\mu\phi)] \Rightarrow n_B = -\frac{1}{3}n$$ for $U_i^cD_j^cD_k^c$

where $n = i(\dot{\phi}^*\phi - \phi^*\dot{\phi}) \propto \dot{\theta}|\phi|^2$ $\qquad \phi = |\phi|e^{i\theta}$

- A-term (RPV interaction) violates $U(1)_B$ or $U(1)_L$

$$V(\phi) = (m_\phi^2 - cH^2)|\phi|^2 + \left(\frac{\lambda}{3}a_m m_{3/2}\phi^3 + \text{h.c.}\right)$$

phase variation $\dot{\theta}$ → generate B / L number

Eq. of motion $$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial}{\partial \phi^*} V(\phi) = 0$$

$$\dot{n} = i(\ddot{\phi}^* \phi - \phi^* \ddot{\phi})$$

$$\Rightarrow \frac{d}{dt}(nR^3) = 2R^3 \mathrm{Im}\left(\frac{\partial V}{\partial \phi}\phi\right)$$

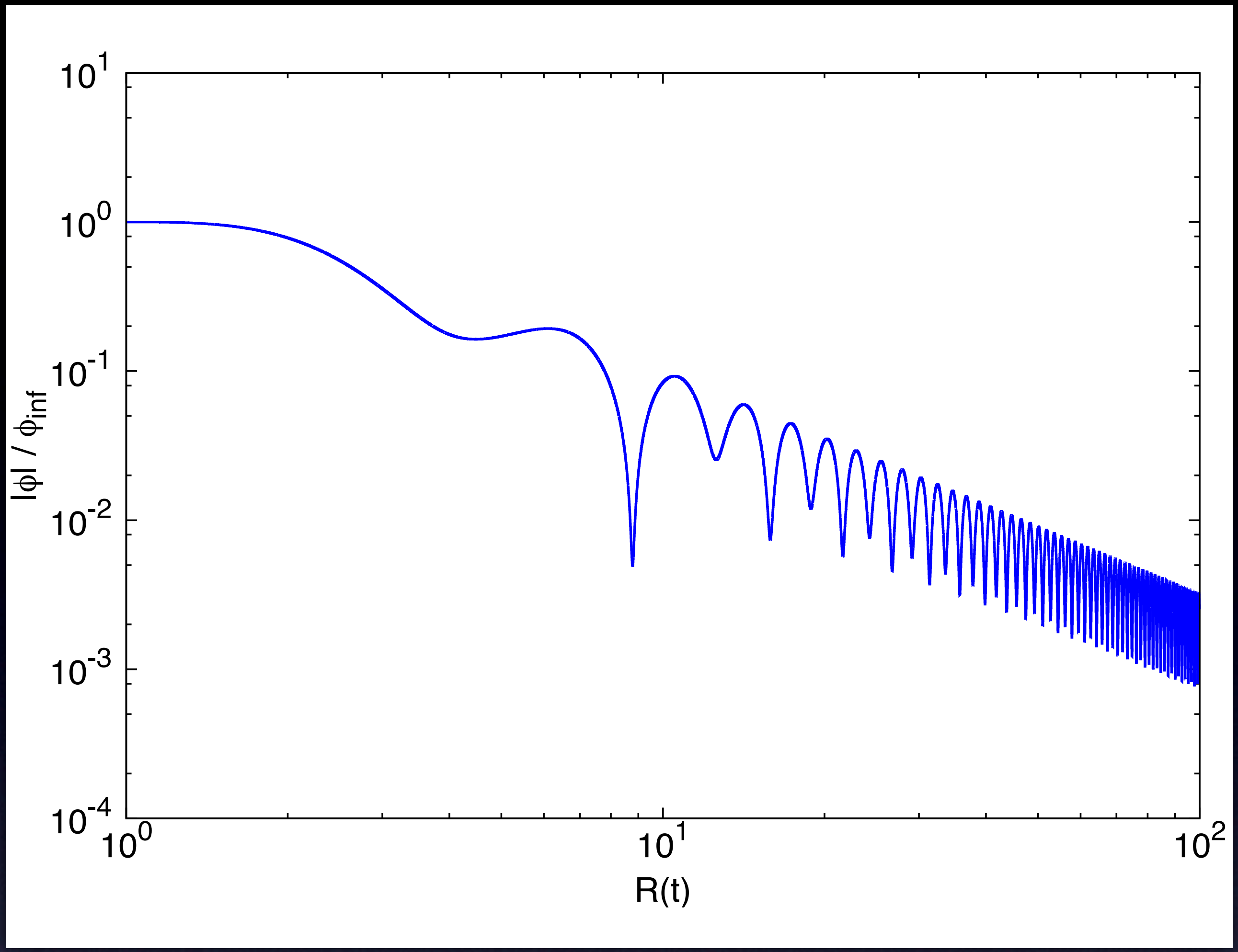
$$\Rightarrow R(t)^3 n(t) = 2\int_{t_{\rm inf}}^{t_{\rm osc}} dt R^3 (\lambda |a_m| m_{3/2} |\phi|^3 \delta_{\rm eff}) + 2\int_{t_{\rm osc}}^{t} dt R^3 (\lambda |a_m| m_{3/2} |\phi|^3 \delta_{\rm eff})$$

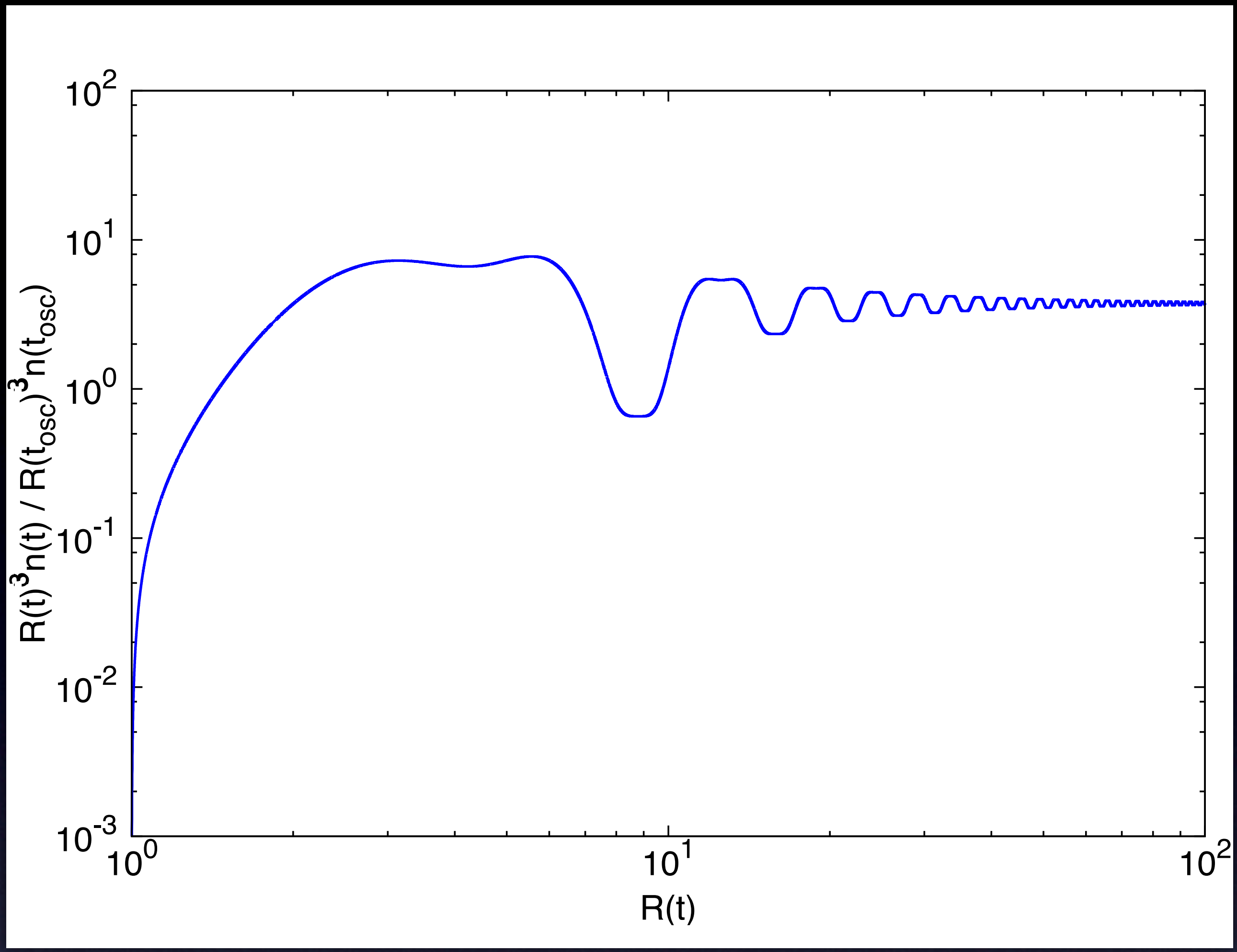
$t_{\rm inf}$: end of inflation $\delta_{\rm eff} \equiv \sin(\arg(a_m) + 3\arg(\phi))$

Matter (inflaton oscillation) dominated $R \propto t^{2/3}$

$t_{\rm inf} < t < t_{\rm osc}$	$\lvert\phi\rvert \simeq \frac{\sqrt{c}H}{\sqrt{2}\lambda} \propto t^{-1}$	$R^3 \lvert\phi\rvert^3 \propto t^{-1}$
$t_{\rm osc} < t$	$\lvert\phi\rvert \propto R^{-3/2} \propto t^{-1}$	$R^3 \lvert\phi\rvert^3 \propto t^{-1}$

$R^3|\phi|^3 \propto t^{-1}$ both for $t < t_{\rm osc}$ and $t > t_{\rm osc}$





Rapidly oscillating contribution for $t > t_{\rm osc}$ → insignificant

$$n(t_{\rm osc}) \simeq 2\lambda |a_m| m_{3/2} \delta_{\rm eff} \frac{2}{3H_{\rm osc}} |\phi(t_{\rm osc})|^3 \ln \frac{t_{\rm osc}}{t_{\rm inf}}$$

$$\simeq \frac{\sqrt{2c^3}}{3\lambda^2} |a_m| m_{3/2} \tilde{\delta}_{\rm eff} H_{\rm osc}^2 \ln \frac{t_{\rm osc}}{t_{\rm inf}}$$

$$|\phi(t_{\rm osc})| \simeq \frac{\sqrt{c} H_{\rm osc}}{\sqrt{2}\lambda}$$

$\tilde{\delta}_{\rm eff}$: uncertainty of $\mathcal{O}(1)$ (dependences on $t_{\rm osc}$, $\arg(a_m)$, and $H_{\rm inf}/m_\phi$)

$$\frac{n}{s} = \frac{1}{s(t_{\rm RH})}\left(\frac{R(t_{\rm osc})}{R(t_{\rm RH})}\right)^3 n(t_{\rm osc}) \simeq \frac{\sqrt{2c^3}|a_m|\tilde{\delta}_{\rm eff}}{12\lambda^2}\frac{m_{3/2}T_{\rm RH}}{M_{\rm Pl}^2}$$

$\ln(t_{\rm osc}/t_{\rm inf}) \simeq 1$

$s(t_{\rm RH})$: entropy density at reheating $t_{\rm RH}$

$T_{\rm RH}$: reheating temperature

Conversion effect $L \leftrightarrow B$ from sphaleron interactions ("leptogenesis")

$$\frac{n_B}{s} = -\frac{8}{23}\frac{n_L}{s}$$

Khlebnikov, Shaposhnikov, Nucl. Phys. B308, 885 (1988)
Harvey, Turner Phys. Rev. D42, 3344 (1990)

$$\frac{n_B}{s} = \gamma\frac{\sqrt{2c^3}|a_m|\tilde{\delta}_{\rm eff}}{12\lambda^2}\frac{m_{3/2}T_{\rm RH}}{M_{\rm Pl}^2}$$

with $\gamma = \begin{cases} \frac{1}{3}\cdot\frac{8}{23} & \text{for} \quad L_iL_jE^c_k \quad \text{or} \quad L_iQ_jD^c_k \\ \frac{1}{3} & \text{for} \quad U^c_iD^c_jD^c_k \end{cases}$

For simplicity $c = |a_m| = \tilde{\delta}_{\rm eff} = 1$

$$\frac{n_B}{s} \simeq 2\times 10^{-9}\gamma\left(\frac{10^{-10}}{\lambda}\right)^2\left(\frac{T_{\rm RH}}{10^5{\rm GeV}}\right)\left(\frac{m_{3/2}}{10{\rm TeV}}\right)$$

Large B asymmetry for small λ
(ϕ acquires large VEV during inflation)

Finite temperature effect

- Lifts the potential of the AD field
  → ϕ begins to oscillate at earlier time
- It does not affect the estimate for net baryon number

$$n \propto H_{\rm osc}^2 \ \rightarrow\ n/s \propto (R(t_{\rm osc})/R(t_{\rm RH}))^3 n \propto H_{\rm osc}^2 / H_{\rm osc}^2$$

- Q-ball configuration (its charge) becomes modified
  - Zero-temperature:

$$V(\phi) \supset m_\phi^2 |\phi|^2 \left[1 + K \ln\left(\frac{|\phi|^2}{M_*^2}\right)\right]$$

charge

$$Q \simeq \mathcal{O}(1) \times 10^9 \left(\frac{m_{3/2}}{m_\phi}\right)\left(\frac{|K|}{0.01}\right)^{1/2}\left(\frac{10^{-6}}{\lambda}\right)^2$$

"gravity-mediation type"

  - Finite temperature:

$$V(\phi, T) \supset \alpha_g^2 T^4 \ln\left(\frac{|\phi|^2}{T^2}\right)$$

$\alpha_g = g^2/4\pi$: coupling constant

charge

$$Q \simeq \mathcal{O}(1) \times 10^7 \left(\frac{\alpha_g}{0.1}\right)^2 \left(\frac{10^{-6}}{\lambda}\right)^2$$

"thermal log type"

Condition for the early oscillation

- If the thermal log term dominates, the oscillation of AD field occurs at

$$\alpha_g^2 T^4/|\phi|^2 \approx H^2$$

$$\Rightarrow \quad H_{\rm osc} \simeq \left(2\alpha_g^2 \lambda^2 T_{\rm RH}^2 M_{\rm Pl}\right)^{1/3}$$

- Condition for the early oscillation

$$m_\phi < \left(2\alpha_g^2 \lambda^2 T_{\rm RH}^2 M_{\rm Pl}\right)^{1/3}$$

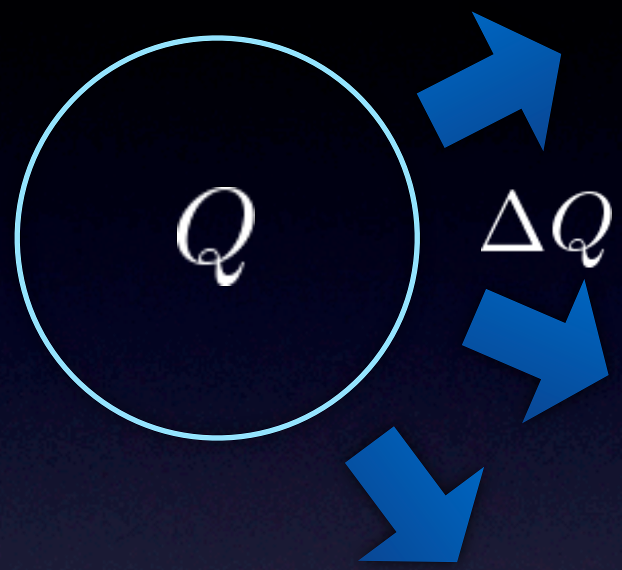
- This corresponds to the bound

$$\lambda > 10^{-9} \left(\frac{0.1}{\alpha_g}\right) \left(\frac{10^5 {\rm GeV}}{T_{\rm RH}}\right) \left(\frac{m_\phi}{1 {\rm TeV}}\right)^{3/2}$$

(if the initial value of ϕ is small [= large λ], thermal log term becomes responsible for the early oscillation)

Destruction of Q-balls

1. Evaporation into the surrounding plasma



Laine, Shaposhnikov, Nucl. Phys. B532, 376 (1998)
Banerjee, Jedamzik, Phys. Lett. B484, 278 (2000)

Condition for the survival of Q-balls:

$$Q > \Delta Q$$

$Q \propto \lambda^{-2}$

→ upper limit on λ

2. Instability due to the U(1) violating term (A-term)

Large λ

→ Approximate U(1) conservation is not valid

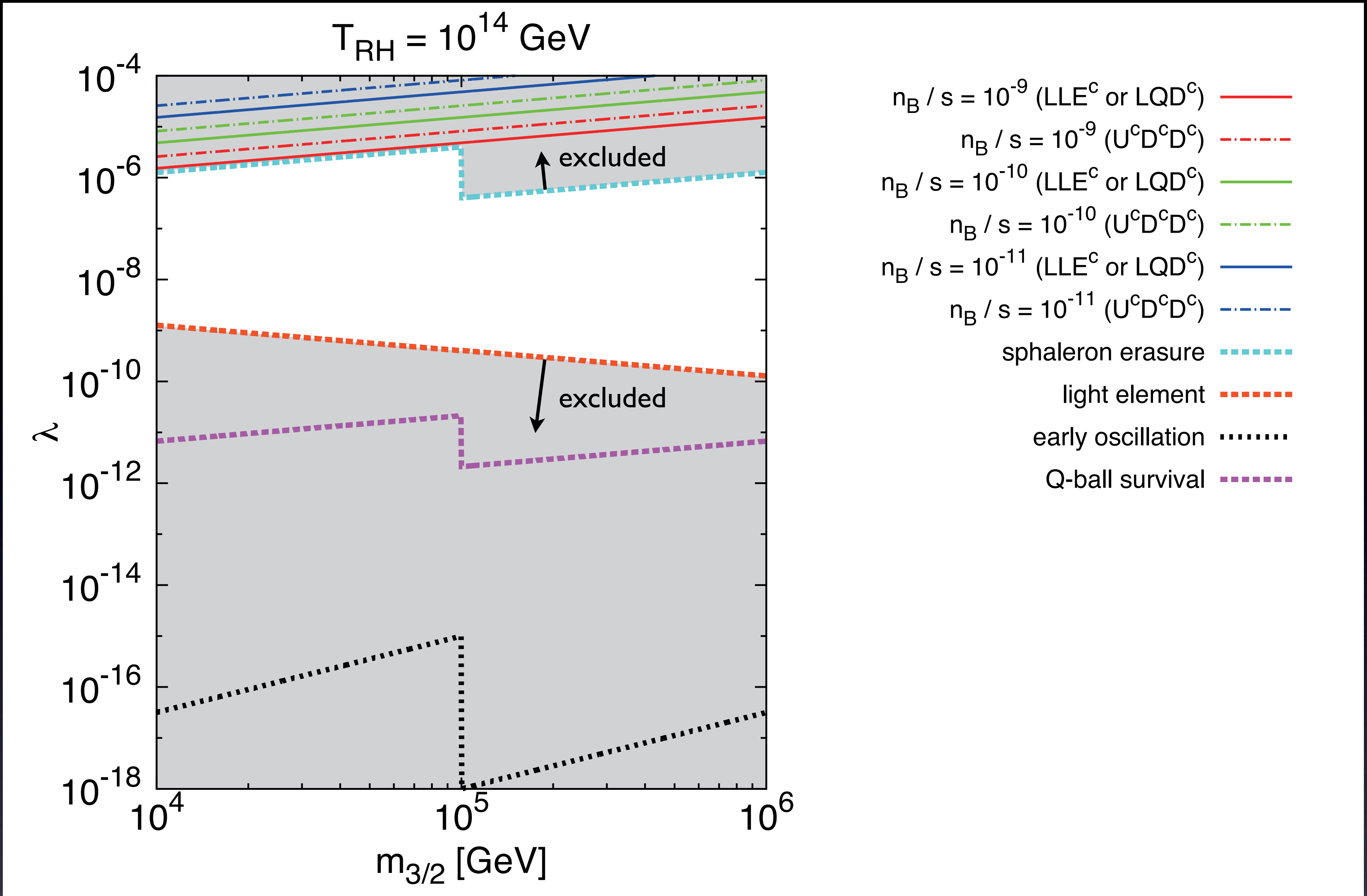
→ Destabilizes Q-ball   Kawasaki, Konya, Takahashi, Phys. Lett. B619, 233 (2005)

Condition for the stability of Q-balls:

$$\xi_Q \equiv \frac{(\mathrm{A\ term})}{(\mathrm{soft\ mass\ term})} = \frac{2}{3}\frac{\lambda |a_m| m_{3/2} \phi_c}{m_\phi^2} < 10^{-2}$$

ϕ_c : value at the center of Q-ball

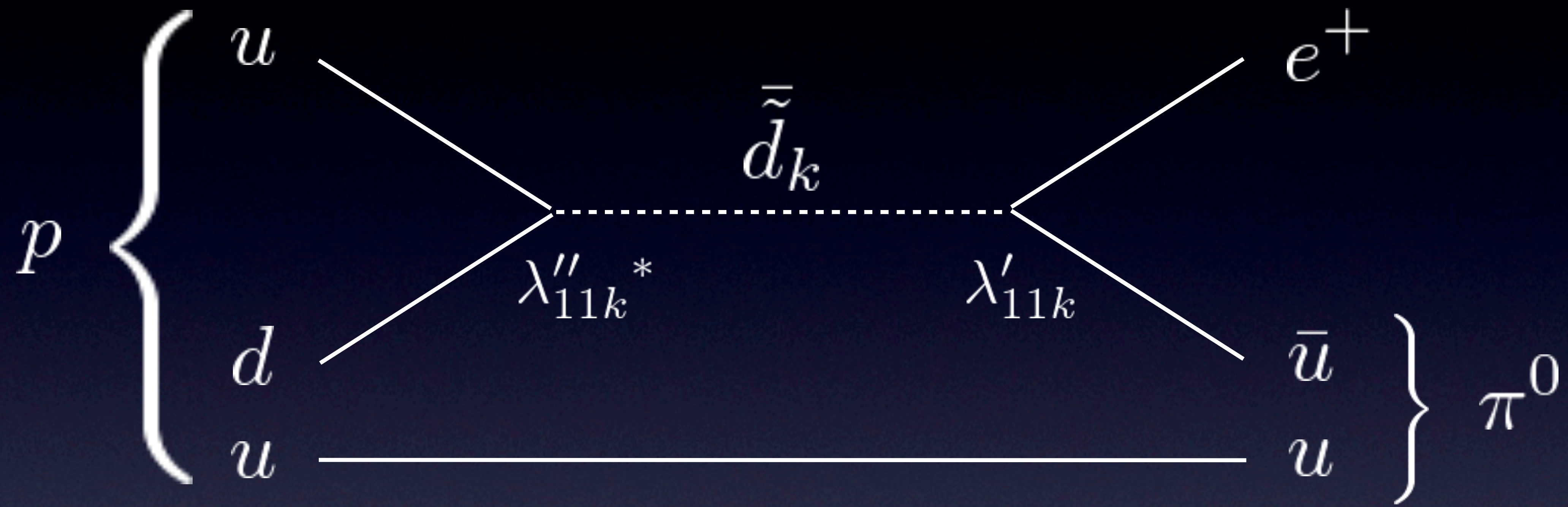
→ upper limit on λ



- For $T_{\rm RH} \gtrsim 10^{14}{\rm GeV}$
  an adequate amount of the primordial B asymmetry is generated above the erasure bound
- But Q-balls are unstable → excluded

Proton decay

$$p \to \pi^0 e^+$$



$$W_{\not R_p} \supset \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

$$|\lambda'_{imk}\lambda''^{*}_{11k}| < \mathcal{O} \times 10^{-27} \left(\frac{100\mathrm{GeV}}{m_{\tilde{d}}}\right)^2$$

$i, k = 1, 2, 3, \; m = 1, 2$

- Bounds on the product of two RPV couplings
- Can be avoided if one of them is extremely suppressed