Direct baryogenesis after electroweak symmetry breaking

Hiroyuki Ishida (KEK)

@PASCOS2019, U. of Manchester, 01/07/19

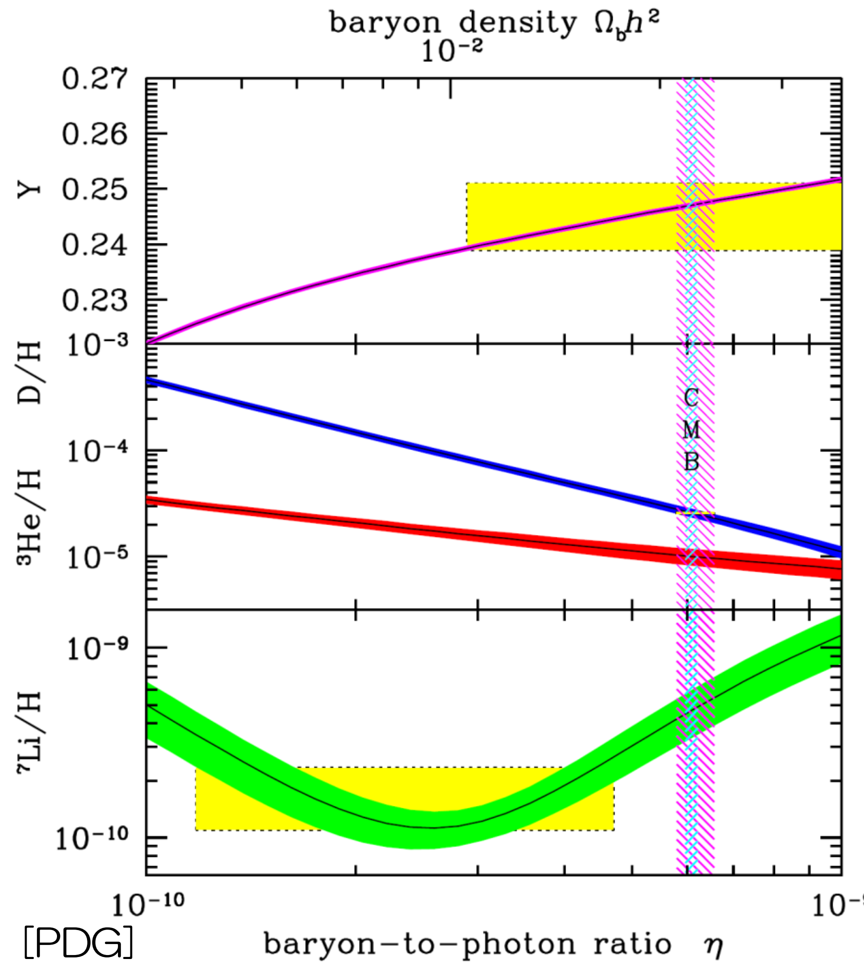
Collaborators: Takehiko Asaka (Niigata U.)
Wen Yin (KAIST)

Reference: 1907.*****

Introduction

Baryon asymmetry of the universe (BAU)

Inflationary cosmology starts baryon symmetric universe



[PDG]

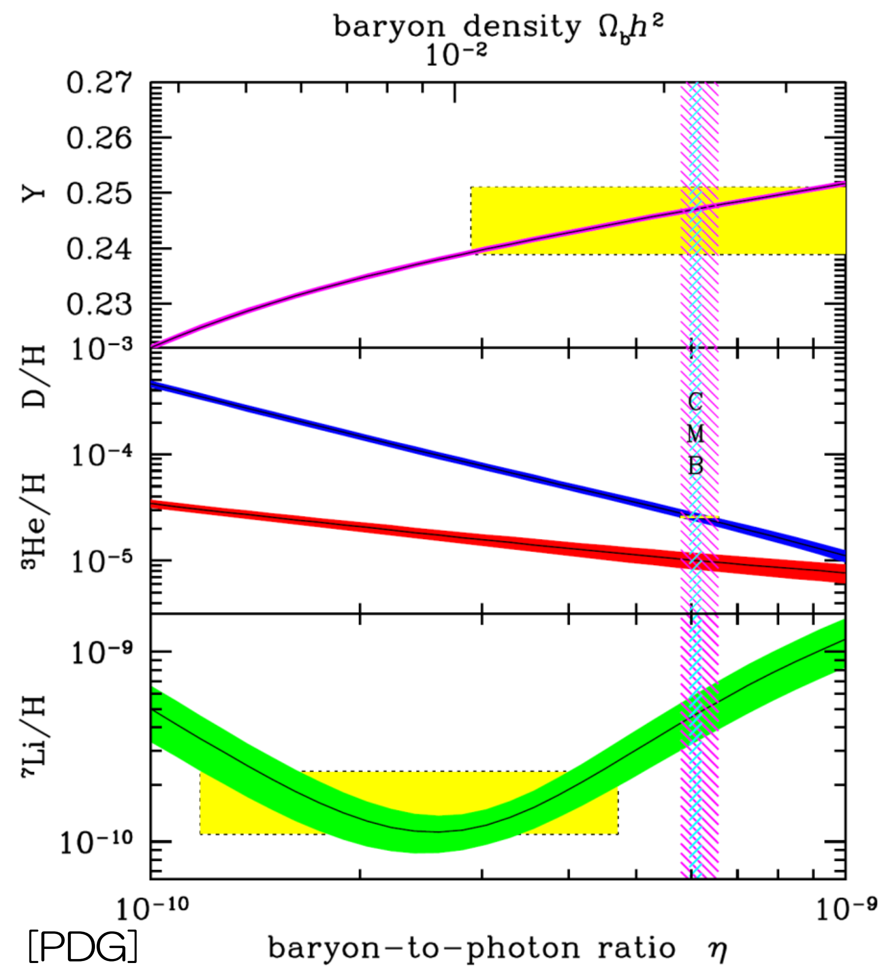
Introduction

Baryon asymmetry of the universe (BAU)

Inflationary cosmology starts baryon symmetric universe

⇩

How to generate BAU?



[PDG]

Introduction

Baryon asymmetry of the universe (BAU)

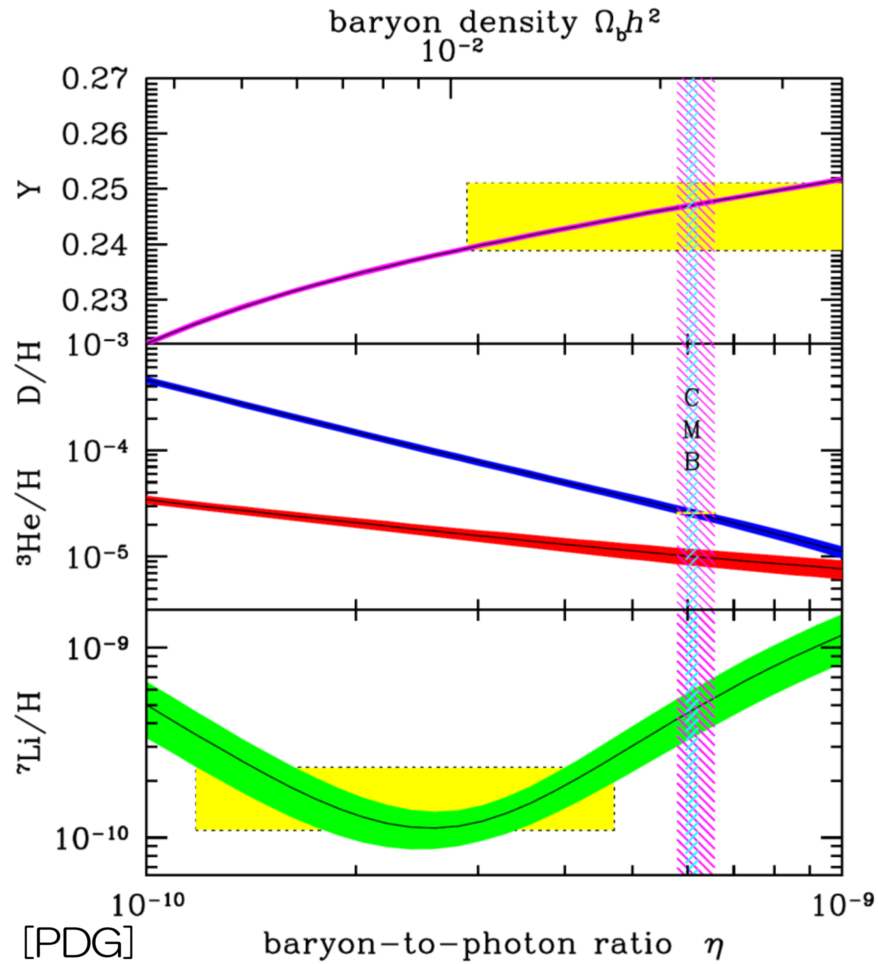
Inflationary cosmology starts baryon symmetric universe

How to generate BAU?

Sakharov's criteria

[Sakharov (1967)]

- B# violation
- C&CP violation
- Thermal decoupling



[PDG]

Introduction

Baryon asymmetry of the universe (BAU)

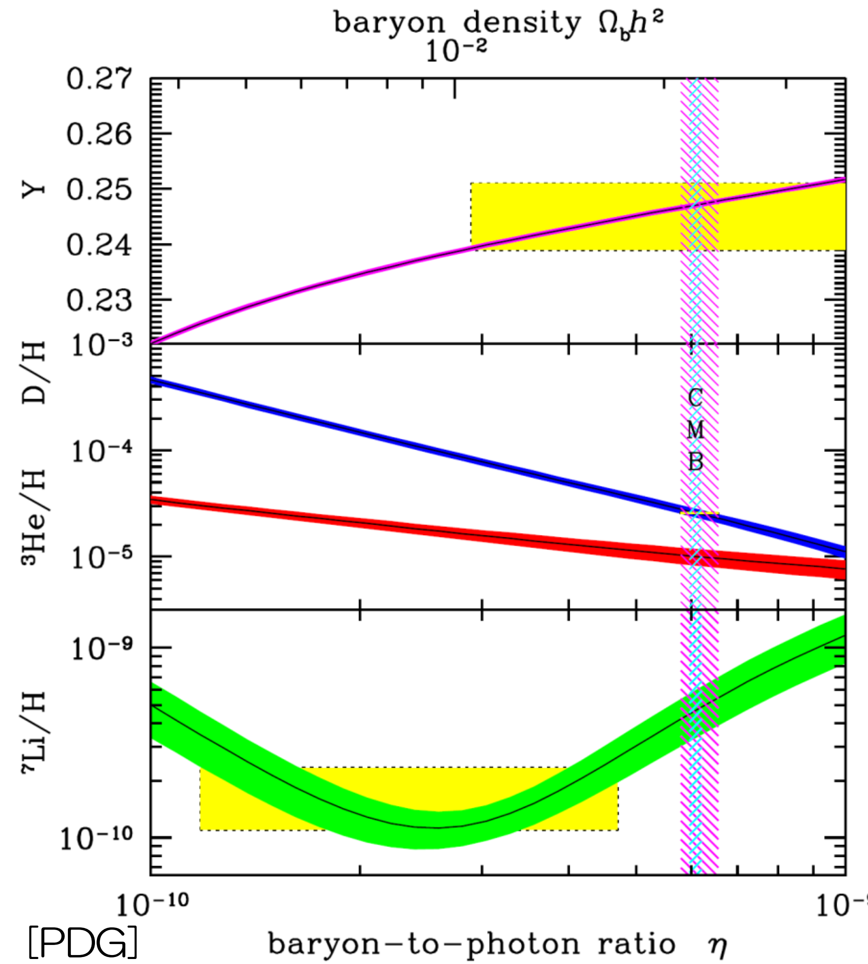
Inflationary cosmology starts baryon symmetric universe

How to generate BAU?

Sakharov's criteria

[Sakharov (1967)]

- B# violation
- C&CP violation
- Thermal decoupling



[PDG]

Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

  Leptogenesis [Fukugita, Yanagida (1986)]

Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

  Leptogenesis [Fukugita, Yanagida (1986)]

  Super heavy RH**ν**

  Decay ↓

  Lepton asymmetry

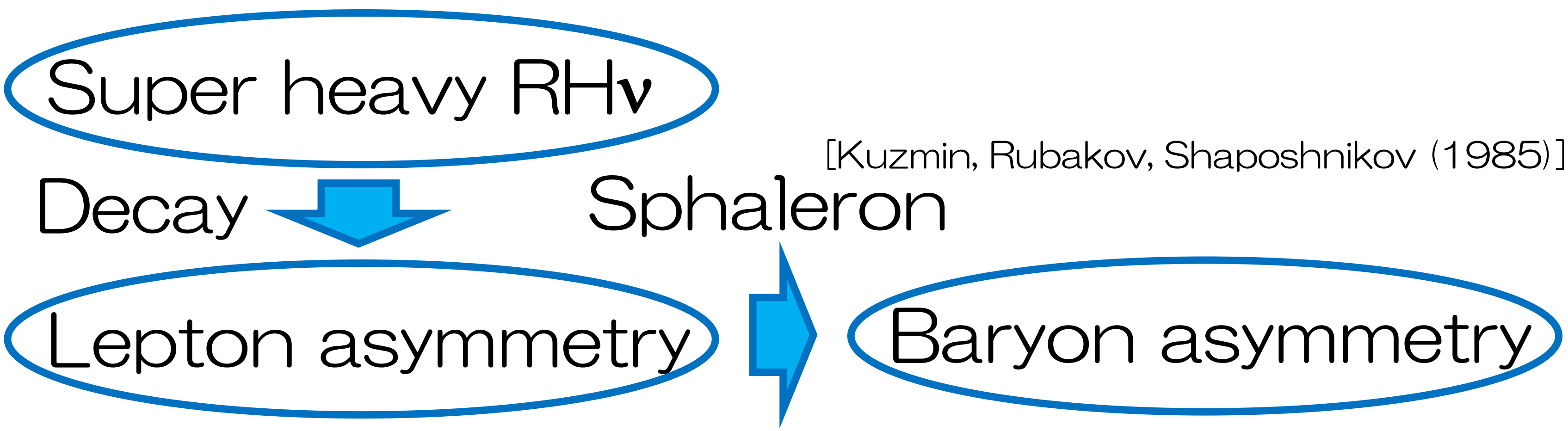
Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

Leptogenesis [Fukugita, Yanagida (1986)]



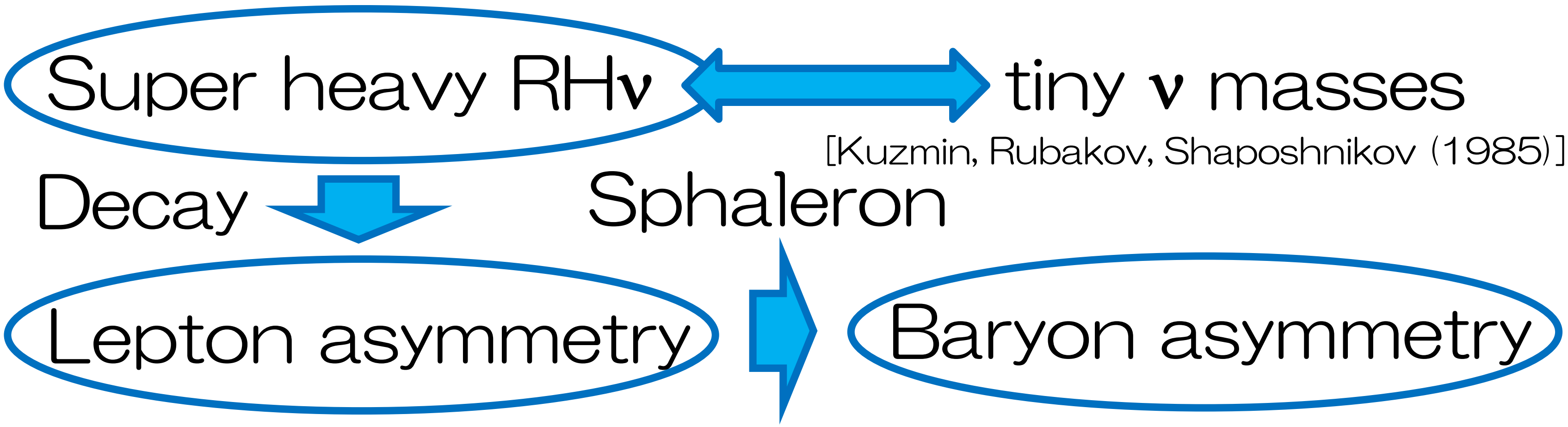
Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

  Leptogenesis [Fukugita, Yanagida (1986)]



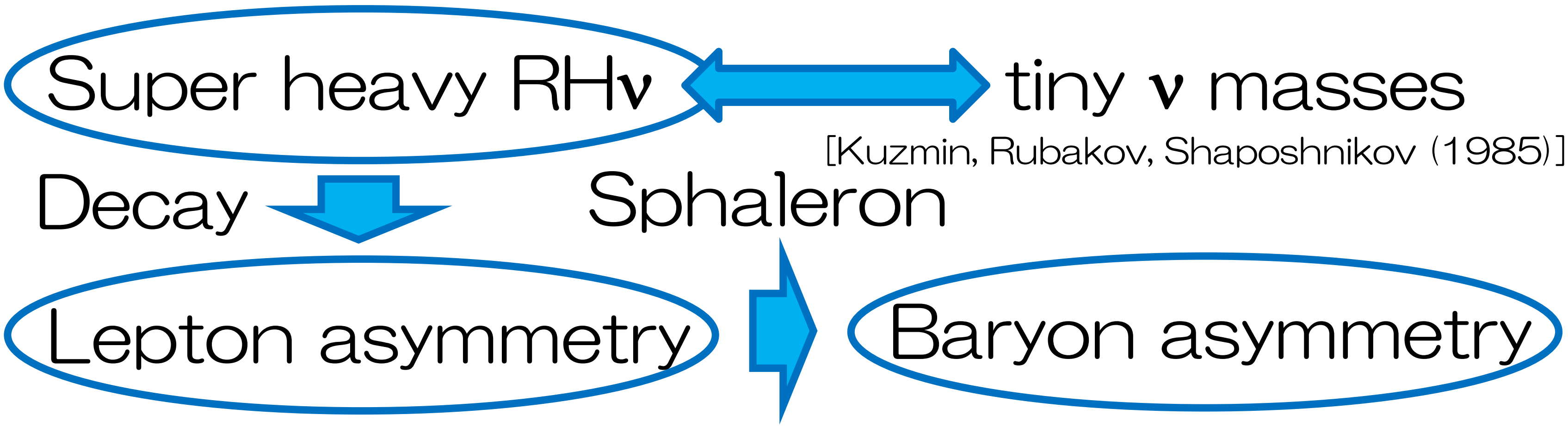
Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

  Leptogenesis [Fukugita, Yanagida (1986)]



- After EWSB; $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

  Sphaleron is frozen-out

Introduction

When is the seed of BAU created?

Reheating temperature: T_R

- Before EWSB; $T_R > 100\ \mathrm{GeV}$

  Leptogenesis [Fukugita, Yanagida (1986)]

  Super heavy RHν ⟺ tiny ν masses

  Decay ⇓

  Lepton asymmetry ⇒ Baryon asymmetry

  Sphaleron [Kuzmin, Rubakov, Shaposhnikov (1985)]

- After EWSB; $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

  Sphaleron is frozen-out ⇒ B# violation

Introduction

Difficulties of low scale baryogenesis

B# violation

Once $\Delta B = 1$ operator is introduced, proton decay has to be generated no matter how suppressed it is

Introduction

Difficulties of low scale baryogenesis

B# violation

Once $\Delta B = 1$ operator is introduced,
proton decay has to be generated
no matter how suppressed it is

⤷ Super stringent constraint is hard to avoid

Introduction

Difficulties of low scale baryogenesis

B# violation

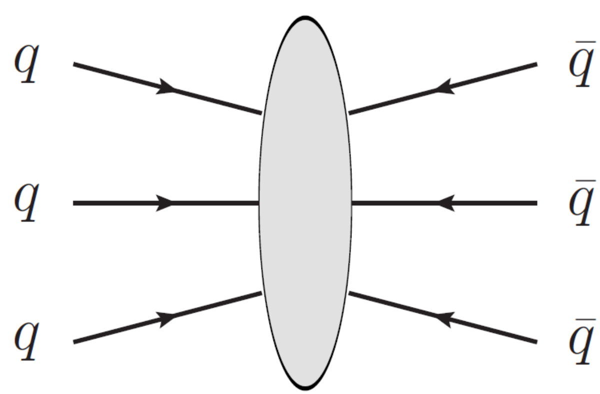
Once $\Delta B = 1$ operator is introduced,
proton decay has to be generated
no matter how suppressed it is

Super stringent constraint is hard to avoid

$\Delta B = 2$ process $\mathcal{L} \supset \kappa_1 Q^4 (d^c)^2 + \kappa_2 u^2 d^4 + \kappa_3 (Q^c)^2 d^3 u + h.c.$

Dim. 9 operator

n-$\bar{n}$ oscillation



c.f.
[Aitken, McKeen, Neder, Nelson (2017)]

Mechanism (summary)

Sakharov's criteria

B# violation

$\Delta B = 2$ process

C&CP violation

Thermal decoupling

Mechanism (summary)

Sakharov's criteria

B# violation

$\Delta B = 2$ process ⇒ proton stabilization

C&CP violation

Thermal decoupling

Mechanism (summary)

Sakharov's criteria

B# violation

$\Delta B = 2$ process → proton stabilization

C&CP violation

Difference of mass bases between Yukawa coupling and dim.9 op.

Thermal decoupling

Mechanism (summary)

Sakharov's criteria

B# violation

$\Delta B = 2$ process ⇒ proton stabilization

C&CP violation

Difference of mass bases between Yukawa coupling and dim.9 op.

Thermal decoupling

Energy loss processes of initial quarks via scattering with ambient plasma

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$$(m_\phi \gg m_t)$$

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$(m_\phi \gg m_t)$ $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

→ Thermal plasma @preheating

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$(m_\phi \gg m_t)$ $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

Thermal plasma @preheating

Energetic q-$\bar{q}$ pair (focus on top quark)

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$(m_\phi \gg m_t)$ $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

Thermal plasma @preheating

Energetic q-$\bar{q}$ pair (focus on top quark)

$$|U_\phi\rangle|_{t=t_R} = V_u^P|u\rangle + V_c^P|c\rangle + V_t^P|t\rangle \ \left(V_i^P \equiv \langle i|U_\phi\rangle\right)$$

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$(m_\phi \gg m_t)$ $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

Thermal plasma @preheating

Energetic q-$\bar{q}$ pair (focus on top quark)

$$|U_\phi\rangle|_{t=t_R} = V_u^P|u\rangle + V_c^P|c\rangle + V_t^P|t\rangle \;\; (V_i^P \equiv \langle i|U_\phi\rangle)$$

$$|U_\phi\rangle|_{t=t_R+\Delta t} = V_u^P \exp\left(i\frac{m_u^2}{m_\phi}\Delta t\right)|u\rangle + V_c^P \exp\left(i\frac{m_c^2}{m_\phi}\Delta t\right)|c\rangle + V_t^P \exp\left(i\frac{m_t^2}{m_\phi}\Delta t\right)|t\rangle$$

Mechanism

Dynamics

a scalar ϕ (inflaton) dominate Universe

$(m_\phi \gg m_t)$ $\quad 1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

Thermal plasma @preheating

Energetic q-$\bar{q}$ pair (focus on top quark)

$$|U_\phi\rangle|_{t=t_R} = V_u^P|u\rangle + V_c^P|c\rangle + V_t^P|t\rangle \quad (V_i^P \equiv \langle i|U_\phi\rangle)$$

$\Delta t \equiv 1/\Gamma_{\rm th}$

$$|U_\phi\rangle|_{t=t_R+\Delta t} = V_u^P \exp\left(i\frac{m_u^2}{m_\phi}\Delta t\right)|u\rangle + V_c^P \exp\left(i\frac{m_c^2}{m_\phi}\Delta t\right)|c\rangle + V_t^P \exp\left(i\frac{m_t^2}{m_\phi}\Delta t\right)|t\rangle$$

Thermal plasma

lose energy, thermalized and stop osc.

Mechanism

Estimation of thermalization time $\Delta t \equiv 1/\Gamma_{\rm th}$

Mechanism

Estimation of thermalization time $\Delta t \equiv 1/\Gamma_{\mathrm{th}}$

Energy loss

Mechanism

Estimation of thermalization time $\Delta t \equiv 1/\Gamma_{\rm th}$

Energy loss

- Landau-Pomeranchuk-Migdal (LPM) effects

[Landau, Pomeranchuk (1953);Migdal (1956)]

$$\Gamma_{\rm LPM} \simeq C' \alpha_3^2 T_R \sqrt{\frac{2T_R}{m_\phi}}$$

- 2→4 Scattering

$$\Gamma_{\rm BV} \simeq \frac{C(\kappa_1, \kappa_2, \kappa_3) N_c^2}{4\pi \cdot (16\pi^2)^2} \frac{E_{\rm cm}^8}{\Lambda^{10}} \times \frac{N_c \zeta(3) T_R^3}{4\pi^2} \qquad \left(E_{\rm cm} \sim \sqrt{T_R M_{\rm pl}}\right)$$

$$\Gamma_{\rm th} \simeq \max\left(\Gamma_{\rm LPM}, \Gamma_{\rm BV}\right)$$

Mechanism

CP violation

once a state is observed as $|R\rangle$ by dim. 9 op.

$$P_{U_\phi \to R} - P_{\bar{U}_\phi \to \bar{R}} \simeq 4 \sum_{j \geq k} \Im[V_j d_j^* d_k V_k^*] \sin\left(\frac{m_k^2 - m_j^2}{m_\phi} \Delta t\right) \qquad (d_j^* \equiv \langle j | R \rangle)$$

Mechanism

CP violation

once a state is observed as $|R\rangle$ by dim. 9 op.

$$P_{U_\phi \to R} - P_{\bar{U}_\phi \to \bar{R}} \simeq 4 \sum_{j \geq k} \Im[V_j d_j^* d_k V_k^*] \sin\left(\frac{m_k^2 - m_j^2}{m_\phi} \Delta t\right) \qquad (d_j^* \equiv \langle j | R \rangle)$$

analogy to ordinary neutrino oscillation!

Mechanism

CP violation

once a state is observed as $|R\rangle$ by dim. 9 op.

$$P_{U_\phi \to R} - P_{\bar{U}_\phi \to \bar{R}} \simeq 4 \sum_{j \geq k} \Im[V_j d_j^* d_k V_k^*] \sin\left(\frac{m_k^2 - m_j^2}{m_\phi} \Delta t\right) \qquad (d_j^* \equiv \langle j | R \rangle)$$

analogy to ordinary neutrino oscillation!

Key: no universal diagonal basis

Only if $V_i = \delta_{ia}$ or $d_j = \delta_{ja}$,

namely, aligned to quark mass basis

CPV vanishes

Mechanism

Amount of BAU

B# violating process in thermalization process

↳ Γ_{BV}

Mechanism

Amount of BAU

B# violating process in thermalization process

⤷ $\Gamma_{\rm BV}$ ⇒ B# creation rate: $\sim \dfrac{\Gamma_{\rm BV}}{\Gamma_{\rm th}}$

Mechanism

Amount of BAU

B# violating process in thermalization process

$\Gamma_{\rm BV}$ ⇒ B# creation rate: $\sim \dfrac{\Gamma_{\rm BV}}{\Gamma_{\rm th}}$

Created asymmetry

$$\frac{\Delta_B}{s} \simeq \frac{3T_R}{4m_\phi} B \times (P_{U_\phi \to R} - P_{\bar{U}_\phi \to \bar{R}}) \times \frac{\Gamma_{\rm BV}}{\Gamma_{\rm th}}$$

$$\sim 10^{-10} B \xi_{CP} |C| C'^{-2} \times \left(\frac{E_{\rm cm}}{4\Lambda}\right)^6 \left(\frac{T_R}{90\ {\rm GeV}}\right)^2 \left(\frac{200\ {\rm TeV}}{\Lambda}\right)^4$$

$$\xi_{CP} \equiv \sum_{k=c,u} \Im [V_t d_t^* d_k V_k^*]$$

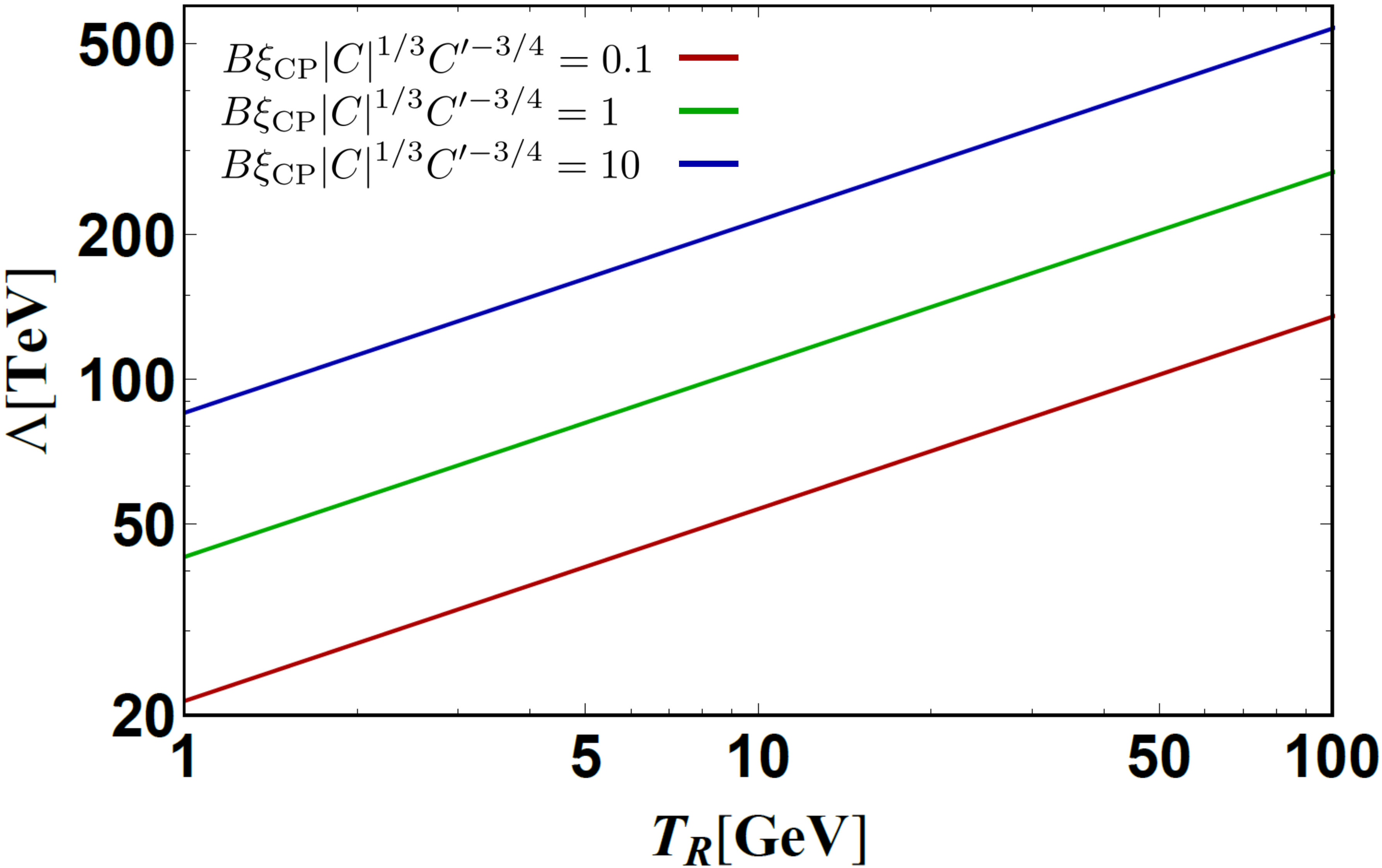
Results

Numerical check (analytic expression)

Upper bound on Λ

Results

Numerical check (analytic expression)

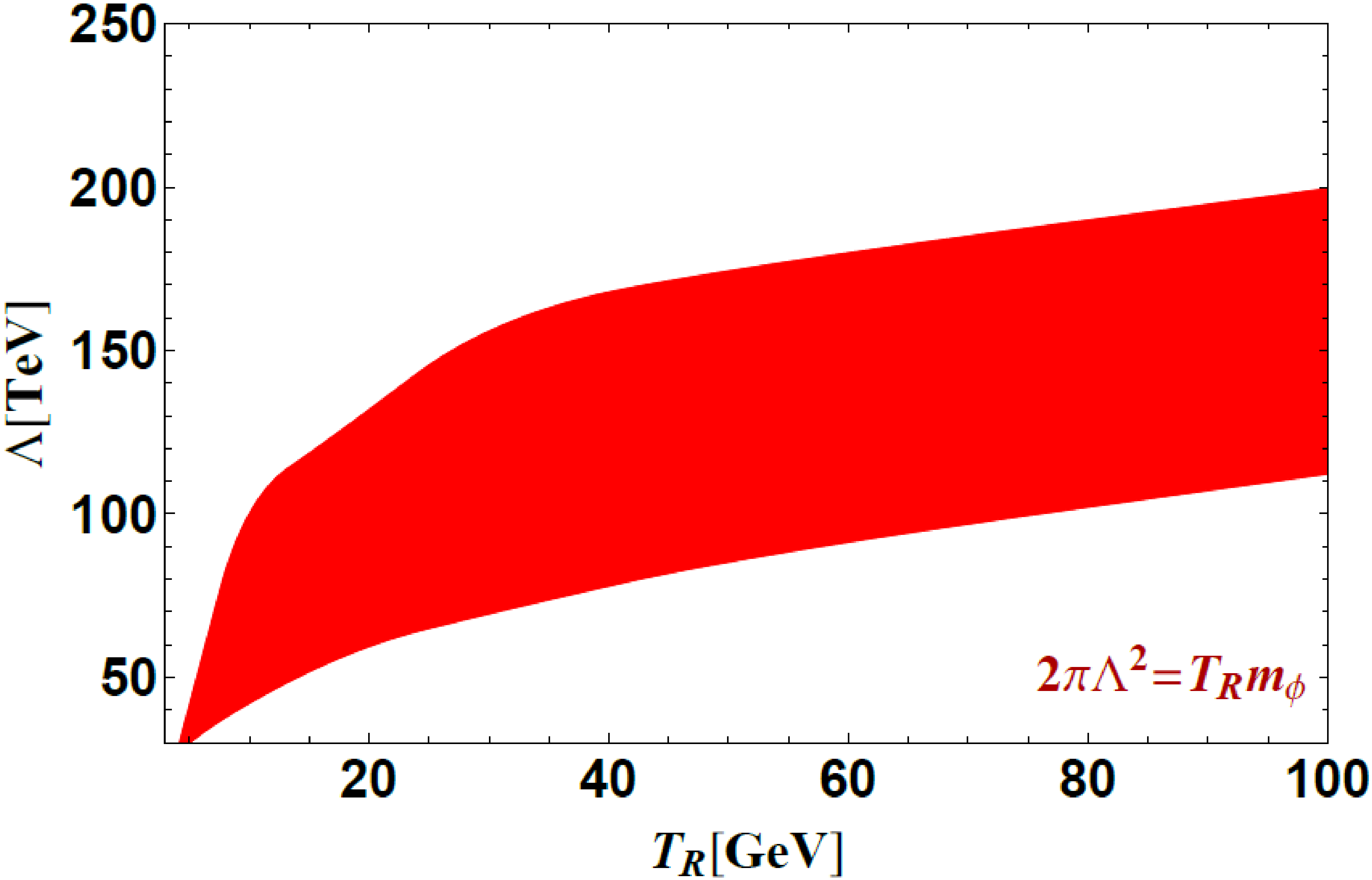


Results

Numerical check (by solving Boltzmann eq.)

Results

Numerical check (by solving Boltzmann eq.)

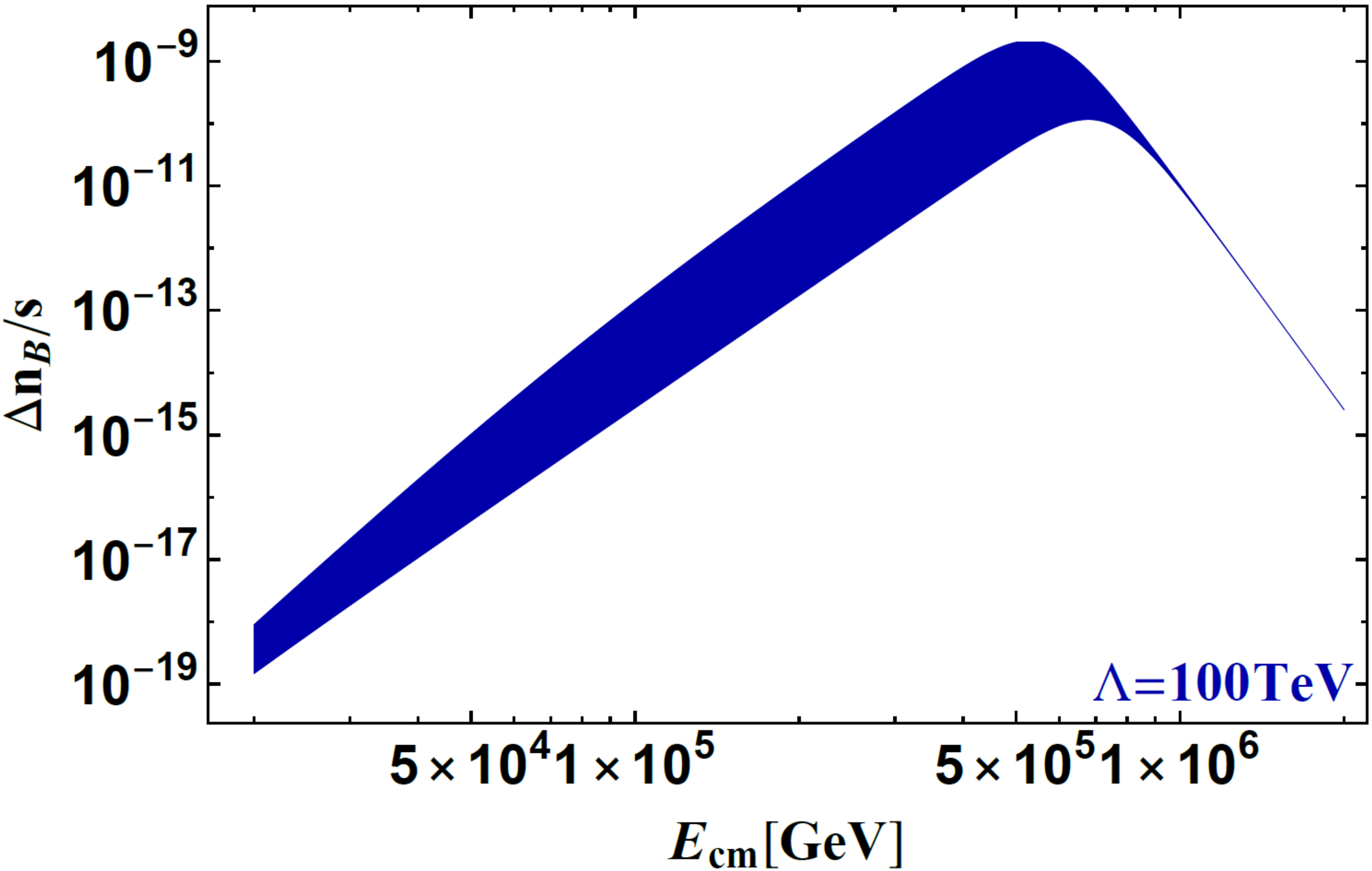


Results

Numerical check (baryon number)

Results

Numerical check (baryon number)



Conclusions

Direct baryogenesis @ $1\ \mathrm{GeV} < T_R < 100\ \mathrm{GeV}$

$\Delta B = 2$ ⇨ proton is completely stable

Sakharov's criteria

B# violation: $\Delta B = 2$ process

C&CP violation: Difference of mass bases

Thermal decoupling: Energy loss processes

Amount of BAU

$$\frac{\Delta_B}{s} \sim 10^{-10} B \xi_{CP} |C| C'^{-2} \times \left(\frac{E_{\rm cm}}{4\Lambda}\right)^6 \left(\frac{T_R}{90\ \mathrm{GeV}}\right)^2 \left(\frac{200\ \mathrm{TeV}}{\Lambda}\right)^4$$

Sufficient amount of BAU can be produced!

Hiroyuki Ishida (KEK)

Conclusions

Future works

$$\mathcal{L} \supset \kappa_1 Q^4 (d^c)^2 + \kappa_2 u^2 d^4 + \kappa_3 (Q^c)^2 d^3 u + h.c.$$

flavor dependence!

n-$\bar{n}$ oscillation

$$(\kappa_i)^{-1/5}_{111111} \lesssim 1000 \text{ TeV}$$

correlation with flavor observables!

constructing a concrete UV model

Thank you!

Backup slides

Cutoff of the model

Effective Lagrangian

$$\mathcal{L} \supset \kappa_1 Q^4 (d^c)^2 + \kappa_2 u^2 d^4 + \kappa_3 (Q^c)^2 d^3 u + h.c.$$

Wave function renormalization

$$\left(\frac{1}{16\pi^2}\right)^4 \left| \mathcal{O}\left(\kappa_{1,2,3}\right) \left(\Lambda_{\text{cutoff}}\right)^5 \right|^2 \lesssim 1$$

Four-Fermi like coupling $\left(\mathcal{L} \supset \tilde{G}_F QQud\right)$

$$\left(\frac{1}{16\pi^2}\right)^3 \left| \mathcal{O}\left(\kappa_{1,2,3}\right) \Lambda_{\text{cutoff}}^4 \right|^2 \lesssim \mathcal{O}\left(\tilde{G}_F\right)$$

Perturbativity of scattering cross section

$$E_{\text{cm}} \lesssim \Lambda_{\text{cutoff}} \simeq (4\pi)^{5/4} \mathcal{O}\left(\kappa_{1,2,3}^{-1/5}\right)$$

A simple UV model

By introducing two scalar quarks

$$\mathcal{L}^{\mathrm{UV}} \supset c_1 \Phi_1 Q Q + c_2 \Phi_2 d^c d^c + c_3 \Phi_1 u^c d^c + A \Phi_1^2 \Phi_2 + h.c.$$

Correspondence to low energy parameters

$$\kappa_1 \sim \frac{A^* c_1^2 c_2}{m_1^4 m_2^2}, \kappa_2 \sim \frac{A^* c_2 c_3^2}{m_1^4 m_2^2}, \kappa_3 \sim \frac{A^* c_1 c_2 c_3}{m_1^4 m_2^2}$$

$$\tilde{G}_F \simeq \frac{c_1 c_3^*}{m_1^2}$$