Direct baryogenesis after electroweak symmetry breaking

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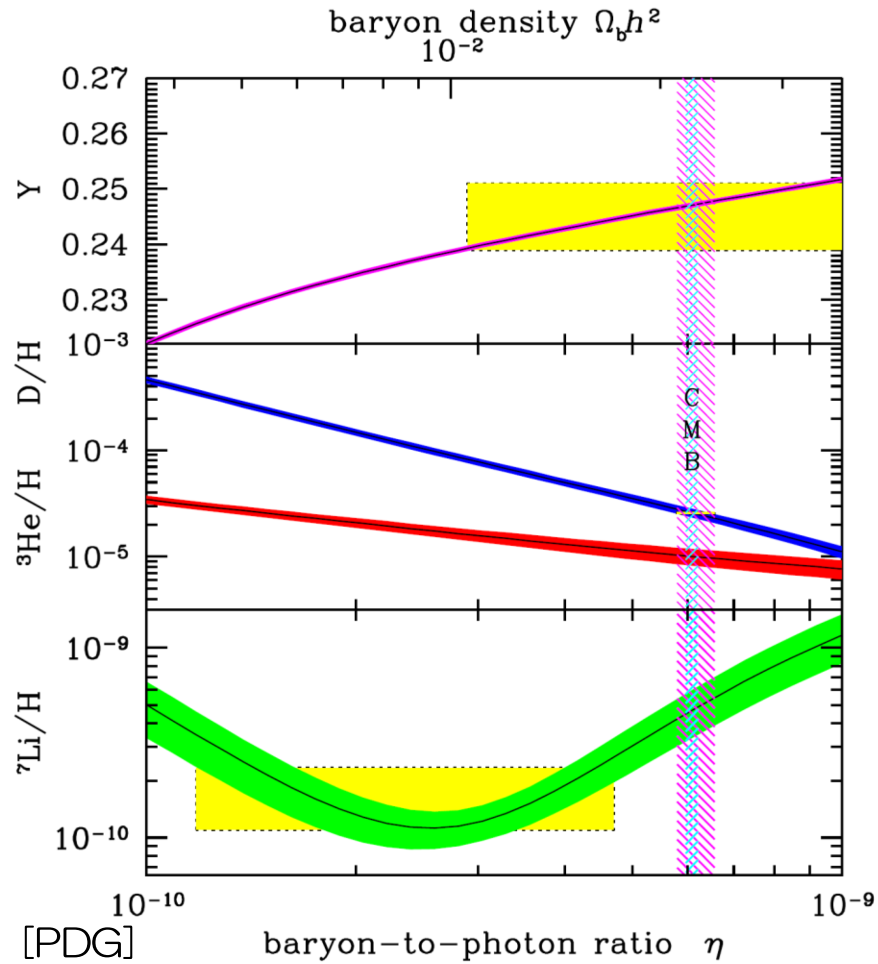
Wen Yin (KAIST)

Reference: 1907.*****

Introduction

Baryon asymmetry of the universe (BAU)

Inflationary cosmology starts baryon symmetric universe



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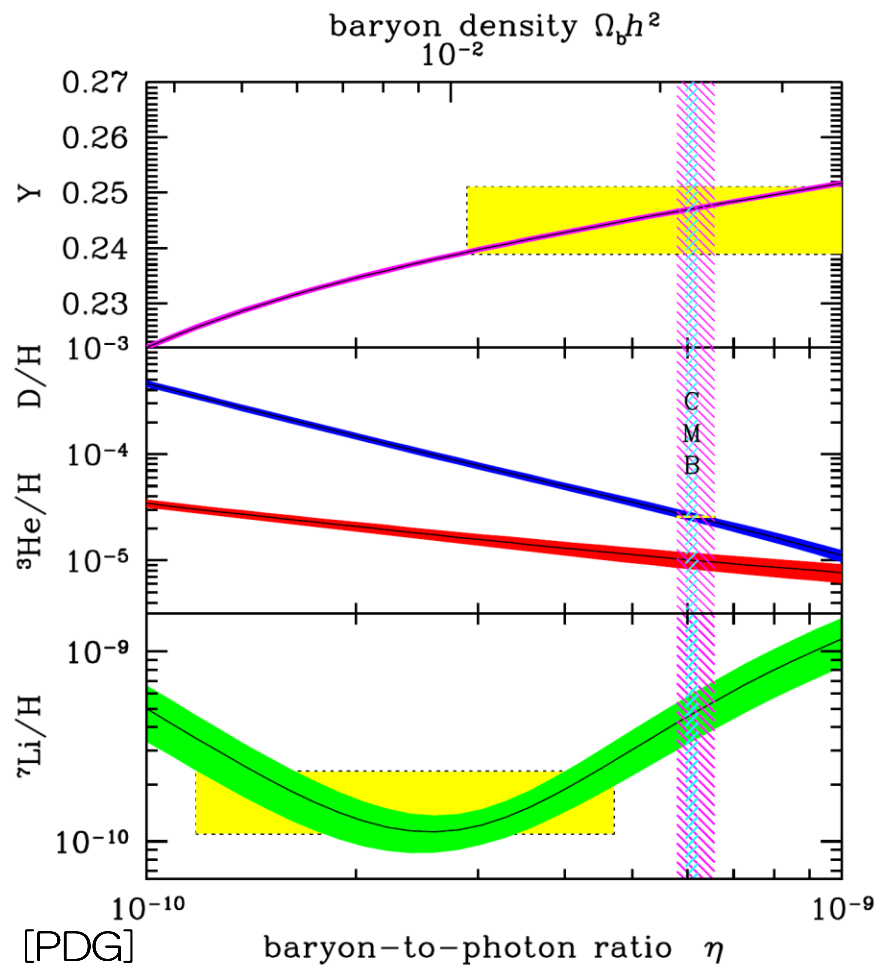
How to generate BAU?



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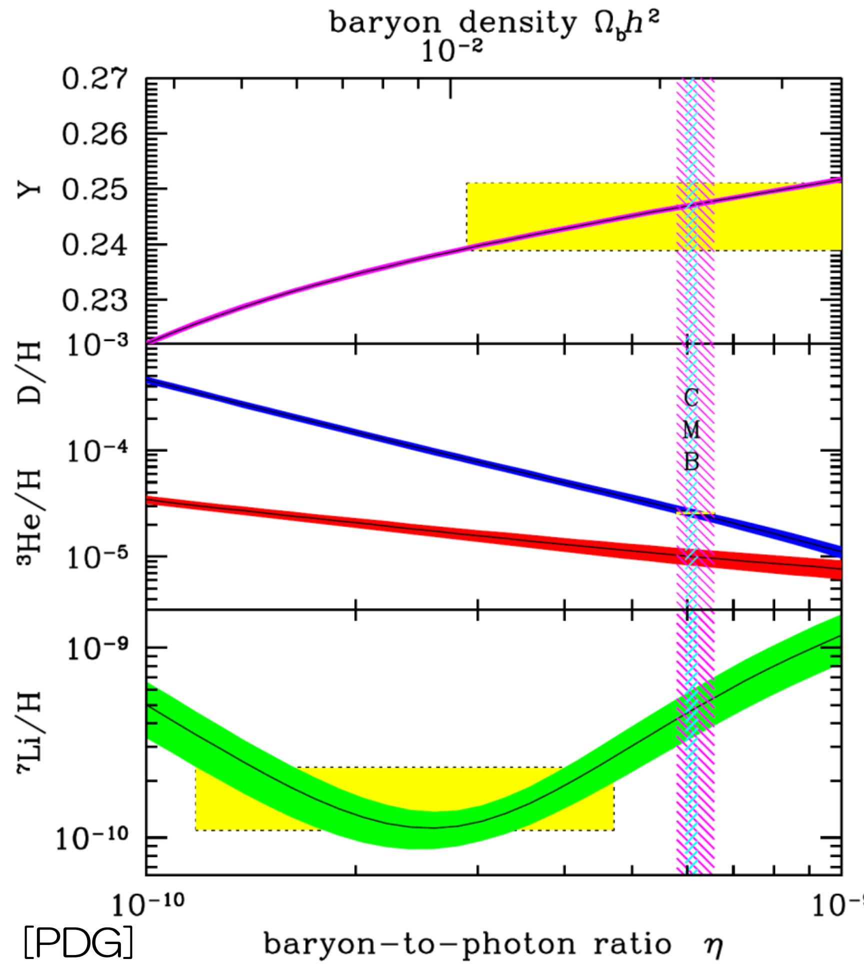
How to generate BAU?

Sakharov's criteria

[Sakharov (1967)]

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



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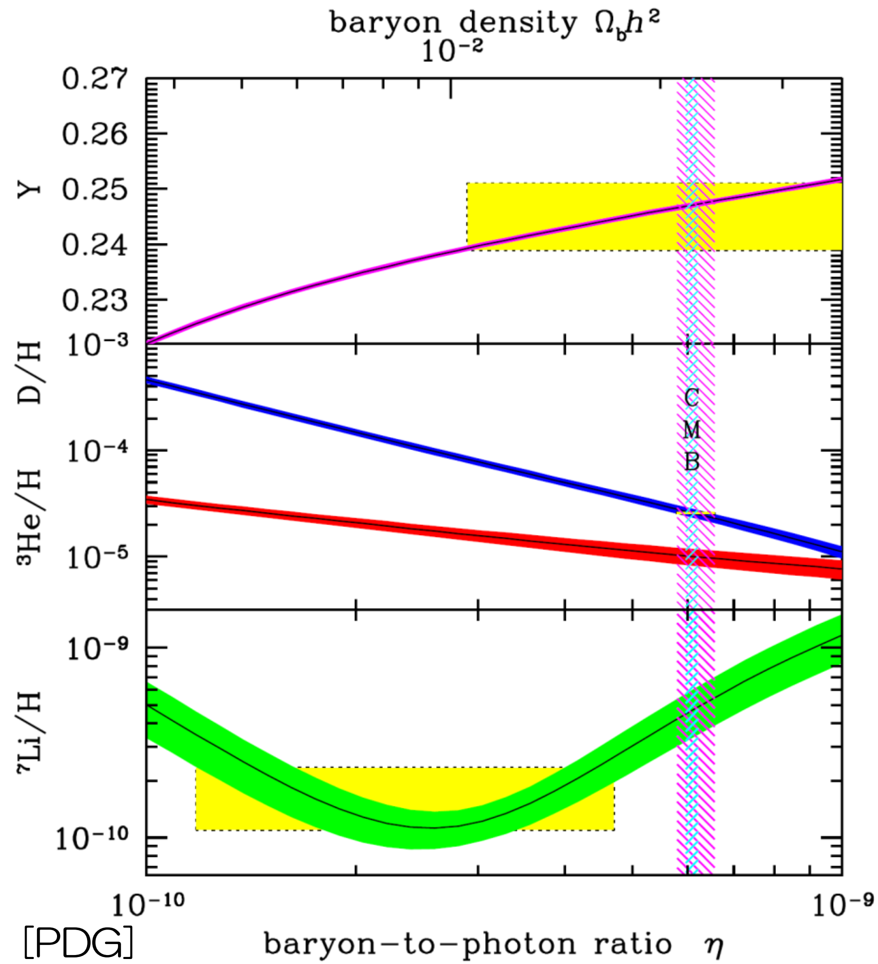

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When is the seed of BAU created?

Reheating temperature: T_R

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

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[Kuzmin, Rubakov, Shaposhnikov (1985)]

Sphaleron

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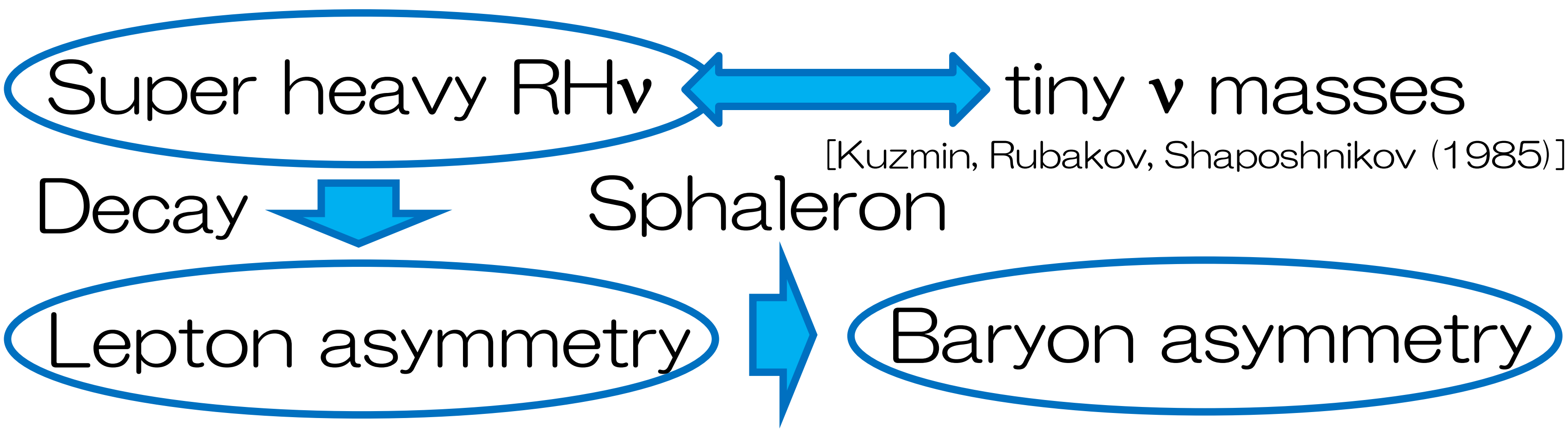

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  Lepton asymmetry ⇒ Sphaleron [Kuzmin, Rubakov, Shaposhnikov (1985)] ⇒ Baryon asymmetry

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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

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⤷ Super stringent constraint is hard to avoid

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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

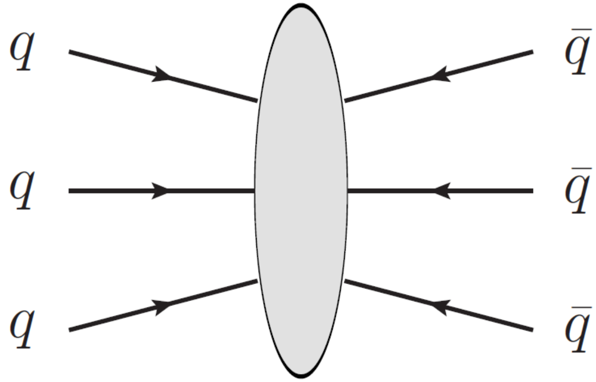
→ Super stringent constraint is hard to avoid

$\Delta B = 2$ 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

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$\Delta B = 2$ process ⇒ proton stabilization

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

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$\Delta B = 2$ 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

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

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→ Thermal plasma @preheating

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

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

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

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Thermal plasma

lose energy, thermalized and stop osc.

Mechanism

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

Mechanism

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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

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

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

Mechanism

CP violation

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

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

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analogy to ordinary neutrino oscillation!

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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

⤷ $\Gamma_{\rm BV}$

Mechanism

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↳ Γ_{BV} ⇒ B# creation rate: $\sim \dfrac{\Gamma_{\mathrm{BV}}}{\Gamma_{\mathrm{th}}}$

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

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

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

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

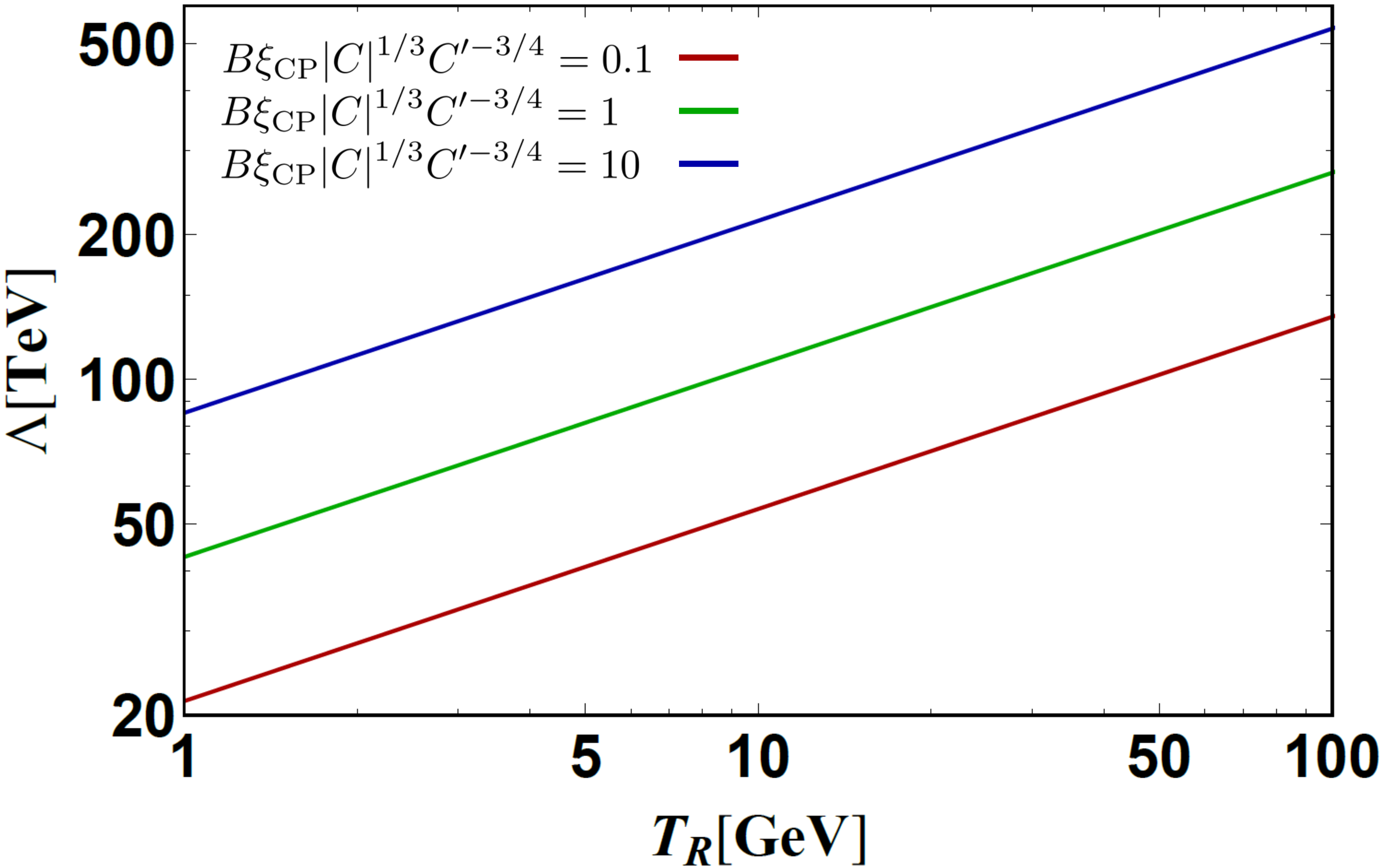
Results

Numerical check (analytic expression)

Upper bound on Λ

Results

Numerical check (analytic expression)



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Numerical check (by solving Boltzmann eq.)

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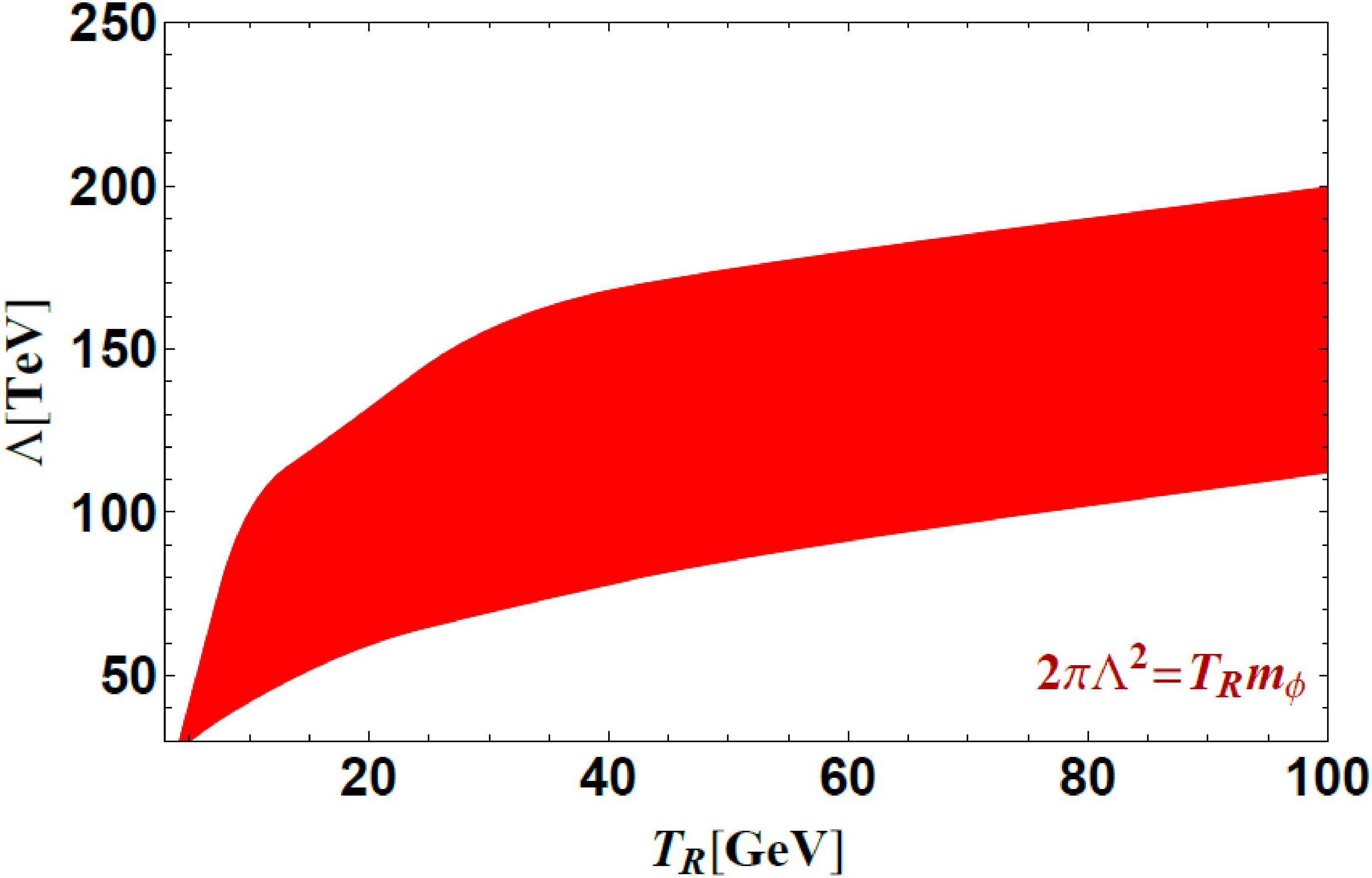

Results

Numerical check (baryon number)

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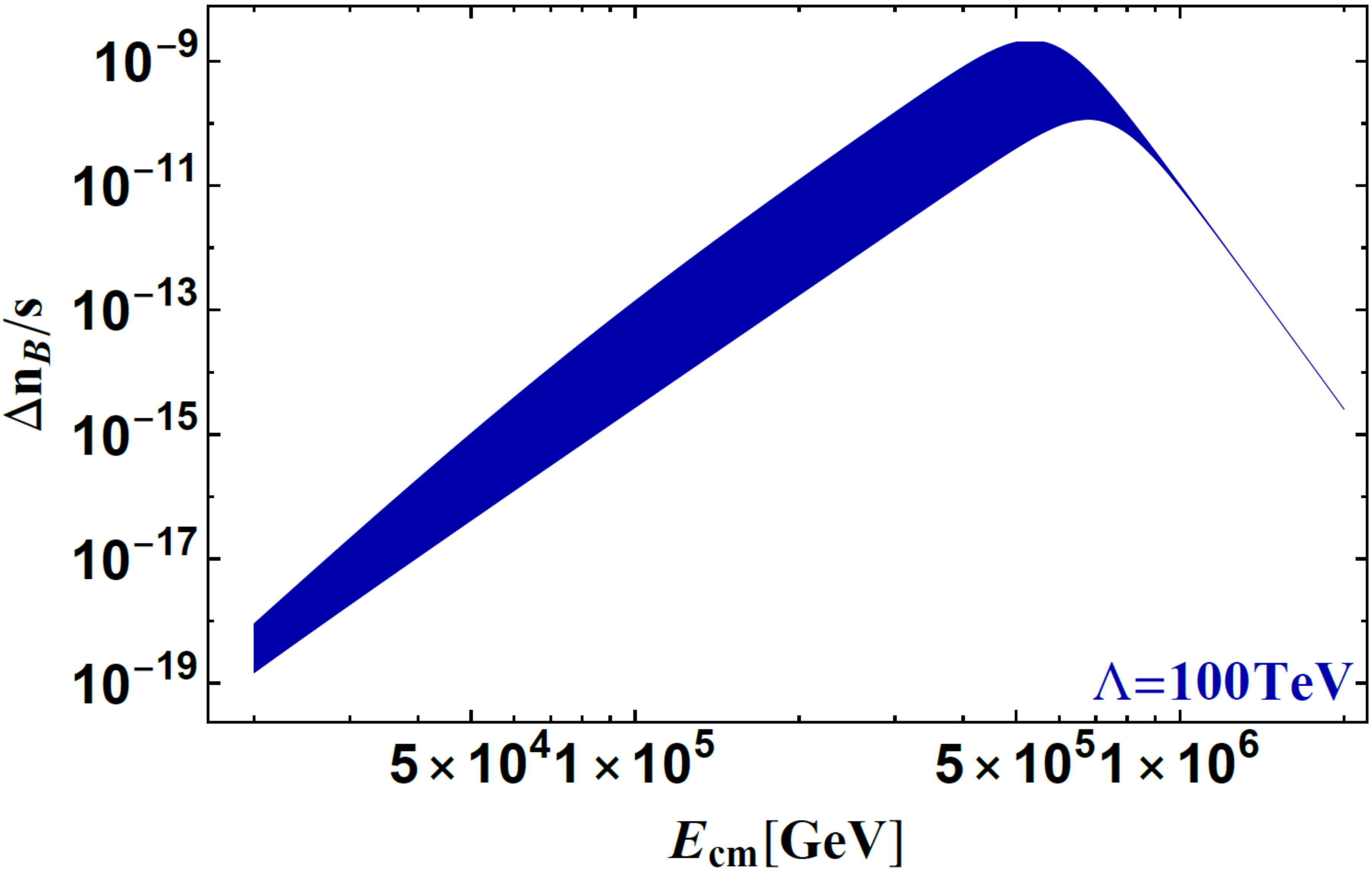

Conclusions

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

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

Sufficient amount of BAU can be produced!

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

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

⮑ 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

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

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

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

Perturbativity of scattering cross section

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

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

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

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