Baryogenesis in Higher Dimension Operators

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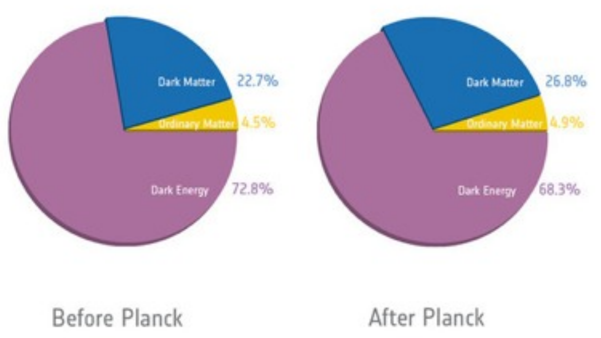
1. Introduction



We don't know
- how baryon was generated
- what dark matter (DM) is

[ESA/Planck '13]

Baryogenesis scenarios

- Leptogenesis [Fukugita, Yanagida '86]
- Affleck-Dine mechanism [Affleck, Dine '85]
- Electroweak baryogenesis [Kuzmin, Rubakov, Shaposhnikov '85]
- Asymmetric dark matter scenario [Nussinov '85; Kaplan '92]
- Gravitino decay [Cline, Raby '91]
- etc.

Gravitino decay is problematic because typically it is overproduced and its late decay may destroy successful big bang nucleosynthesis (BBN) [Weinberg '82]

However, if

- gravitino dominates the universe at its decay period
- R-parity is violated

gravitino decay can generate baryon asymmetry [Cline, Raby '91]

This idea can be extended to more generic but simpler context

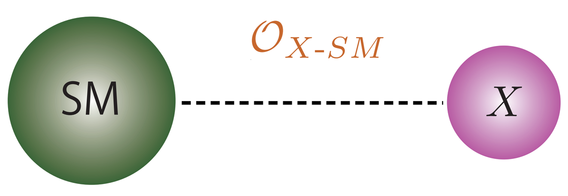
In our work,

We consider baryogenesis in a model comprised of the standard model (SM) plus gauge singlet multiplet X

→ Baryogenesis is achieved by X decay which is mediated by higher dimension operators $\mathcal{O}_{X\text{-SM}}$ which violate B, C, CP

- B violation
- C and CP violation
- Departure from equilibrium

"Sakharov's conditions" [Sakharov '67]



$$\mathcal{O}_{X\text{-SM}} \sim \frac{X u^c d^c d^c}{\Lambda^2}$$

Experimental consequences:

- X can be TeV, and the model can be tested in the experiments of n-$\bar{n}$ oscillation, flavor physics or proton decay
- Lighter component can be DM

2. The model

$$\mathcal{O}_{X\text{-SM}} = \frac{\kappa_{IJij}}{\Lambda^2}(X_I u_i^c)(\bar{X}_J \bar{u}_j^c) + \frac{\lambda_{Iijk}}{\Lambda^2}(X_I u_i^c)(d_j^c d_k^c) + \text{h.c.}$$

Hereafter I consider X_1, X_2 for simplicity, and X_1 is heavier component

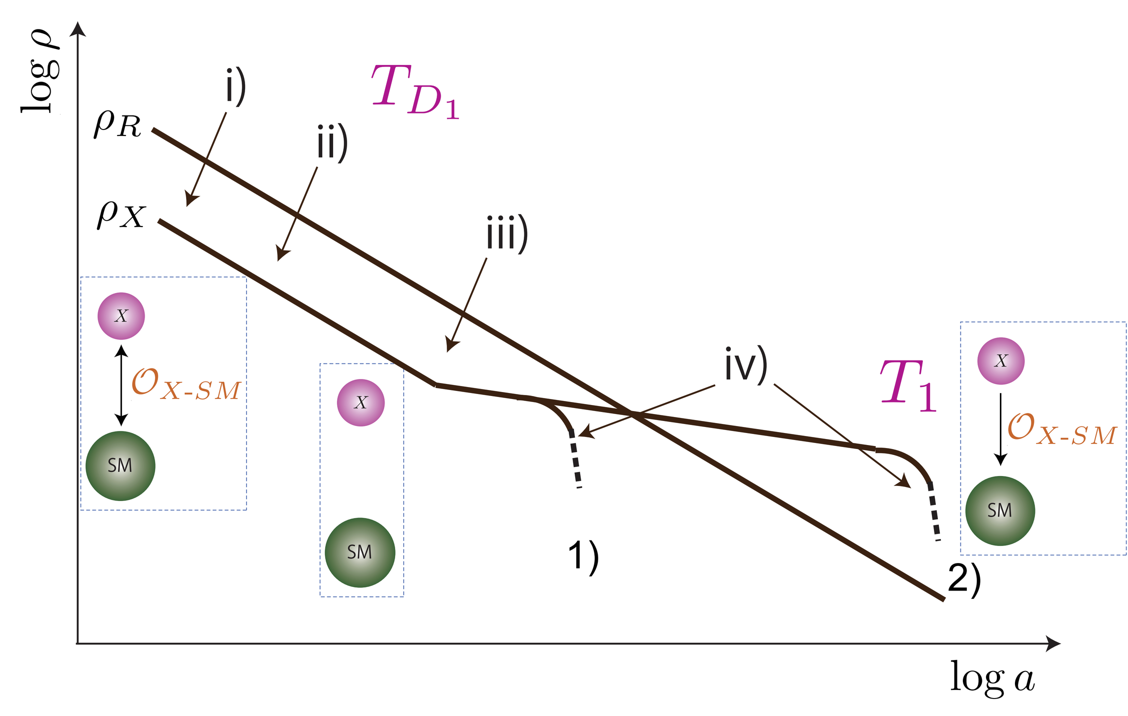
The cosmology of the model

i) X_1 is thermalized with SM sector via $\mathcal{O}_{X\text{-SM}}$

ii) X_1 decouples from SM while it's relativistic

iii) When temperature drops below its mass, X_1 redshifts as matter, then it evolves into a large fraction of the total energy

iv) X_1 decays via $\mathcal{O}_{X\text{-SM}}$ to generate baryon asymmetry



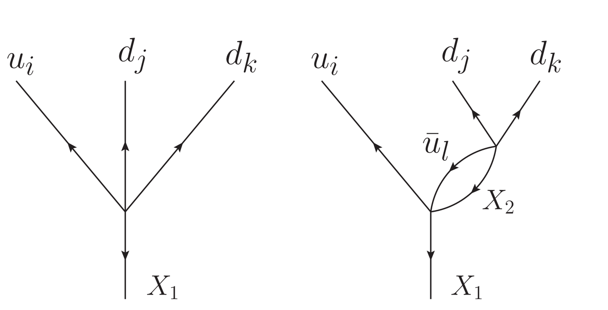
Baryon asymmetry → $\eta_B = \frac{n_B}{s} = \epsilon Y_{X_1}$

- ϵ is asymmetric parameter
- Y_{X_1} is yield variable defined as $Y_{X_1} = n_{X_1}/s$

ϵ is given by difference between the branching ratios of $X_1 \to u_i d_j d_k$ and $\bar{u}_i \bar{d}_j \bar{d}_k$

$$\to \epsilon = \sum_{ijk}(\text{Br}_{X_1\to u_i d_j d_k} - \text{Br}_{X_1 \to \bar{u}_i\bar{d}_j\bar{d}_k})$$

$$= \frac{1}{20\pi}\frac{\delta_1}{\lambda_1^2}\frac{m_1^2}{\Lambda^2}$$



$$\Gamma_{X_1\to u_i d_j d_k} - \Gamma_{X_1\to \bar{u}_i \bar{d}_j \bar{d}_k} = \sum_l \frac{\text{Im}(\lambda_{1ijk}^* \kappa_{12li}\lambda_{2ljk})}{5120\pi^4}\frac{m_1^7}{\Lambda^6}$$

$$\delta_1 = \sum_{ijkl}\text{Im}(\lambda_{1ijk}^*\kappa_{12li}\lambda_{2ljk})$$

Y_{X_1} depends on when X_1 decays:

1) Before dominating the universe

$Y_{X_1} \simeq n_{\text{eq}}/s(T_{D_1})$ T_{D_1}: decoupling temperature

2) After dominating the universe

There's large entropy production, which reheats the universe

$Y_{X_1} \simeq 3T_1/4m_1$ T_1 : *secondary* reheating temperature
m_1 : mass of X_1

$$u_i \bar{u}_j \to X_I X_J,\ u_i d_j \to X_I \bar{d}_k,\ d_j d_k \to X_I \bar{u}_i$$

$\langle\sigma v\rangle n_{\text{eq}} \sim H$ → T_{D_1} $\langle\sigma v\rangle \simeq \frac{c_1 T^2}{\Lambda^4}$

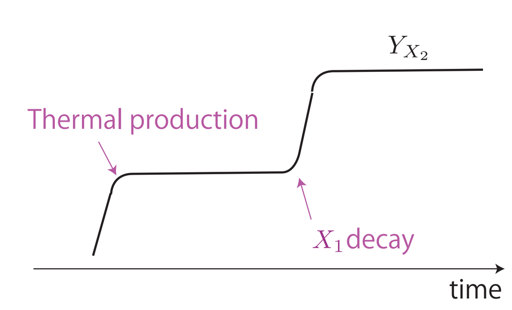
$X_1 \to u_i d_j d_k, \bar{u}_i\bar{d}_j\bar{d}_k, X_2\bar{u}_i u_j$ $\Gamma_{X_1} = \frac{\lambda_1^2}{256\pi^3}\frac{m_1^5}{\Lambda^4}$

$\Gamma_{X_1} \sim H$ → T_1 $\lambda_1^2 = \sum_{ijk}|\lambda_{1ijk}|^2 + \sum_{ij}|\kappa_{12ij}|^2/4$

X_2 can be DM

X_2 is produced
- thermally at the initial reheating
- by X_1 decay

→ $Y_{X_2} = Y_{X_2}^{\text{th}} + Y_{X_2}^{\text{dec}}$



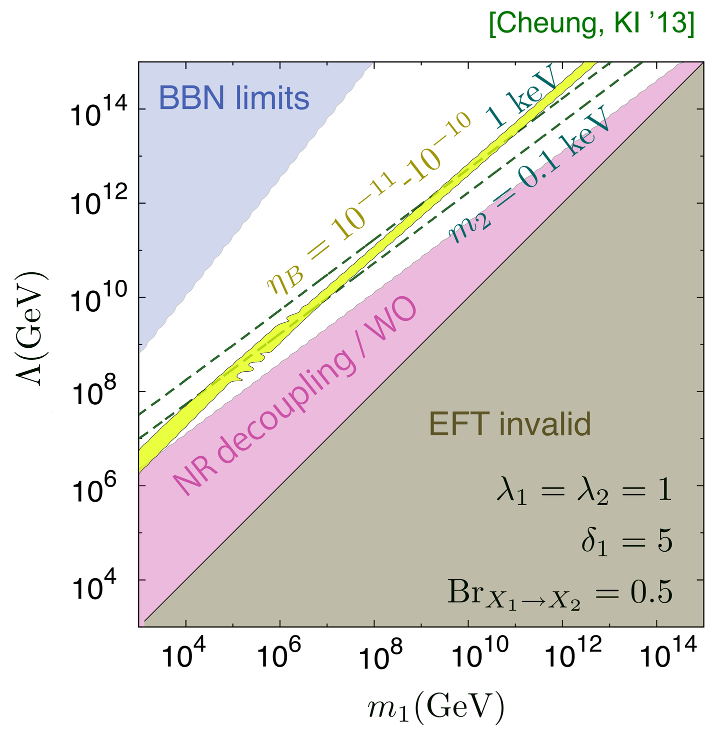
If X_2 is lighter than proton, then it can be DM

Then, requiring that $\Omega_{X_2} = m_2 Y_{X_2}(s/\rho_c)_0 \simeq \Omega_{\text{DM}}$

→ m_2 is determined

3. Numerical results

[Cheung, KI '13]



Successful baryogenesis in a wide parameter region: can be TeV (when $\Lambda \sim 10^6$ GeV)

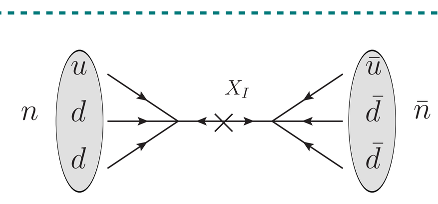
Baryon asymmetry and DM can be explained when $m_2 \sim 0.1$-1 keV

Cosmological constraints:
- X_1 should decouple relativistically
- X_1 should decay before BBN
- X_2 should be kept in out of equilibrium after X_1 decay

Experimental consequences:

$$\mathcal{O}_{X\text{-SM}} = \frac{\lambda_{Iijk}}{\Lambda^2}(X_I u_i^c)(d_j^c d_k^c) + \frac{\lambda'_{Iijk}}{\Lambda^2}(X_I d_j^c)(u_i^c d_k^c) + \cdots$$

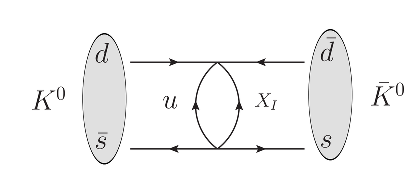
- Neutron-antineutron oscillation [Goity, Sher '95] [Abe et al. '11]



$$\Lambda \gtrsim 10^6\ \text{GeV}\ |\lambda'_{I111}|^{1/2}\left(\frac{1\ \text{TeV}}{m_I}\right)^{1/4}$$

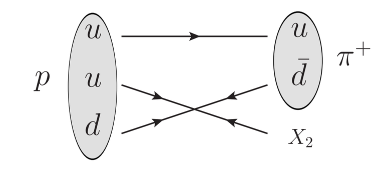
→ The region $m_1 \sim \text{TeV}(\Lambda \sim 10^6\ \text{GeV})$ may be tested

- K^0-$\bar{K}^0$ mixing [Beringer et al. '12] [Buras, Guadagnoli '08; Buras, Guadagnoli, Isidori '10; Laiho, Lunghi, Van de Water '09; Mescia, Vitro '12]



$$\Lambda \gtrsim 10^4\ \text{GeV}\ \text{Im}(\lambda'^*_{I111}\lambda'_{I122})^{1/4}\left(\frac{m_I}{1\ \text{TeV}}\right)^{1/2}$$

- Proton decay [Beringer et al. '12] [Aoki et al. '08]



$$\Lambda \gtrsim 10^{15}\ \text{GeV}\ \lambda_2^{1/2}\left(\frac{\Lambda_{\text{QCD}}}{250\ \text{MeV}}\right)$$

We must assume hierarchical flavor structure in λ'_{2ijk} (e.g. minimal flavor violation)

4. Conclusion

We have considered a model which consists of SM and additional singlet Majorana fermions X

In this framework, X are produced and decay via higher dimension operators which violate B, C, CP

As a result,
- The observed baryon asymmetry is generated by X decay
- Light components ($\mathcal{O}(\text{keV})$) can be DM
- The model may be tested in the experiments of n-$\bar{n}$ oscillation, flavor physics or proton decay

Two possible scenarios in this model;

Baryogenesis with
1) unstable X_2 (no DM candidate)
2) stable X_2 (which is DM candidate)

Then, for each case, the model may be testable in
1) n-$\bar{n}$ oscillation or K^0-$\bar{K}^0$ mixing
2) Proton decay