The role of CP violating scatterings in baryogenesis

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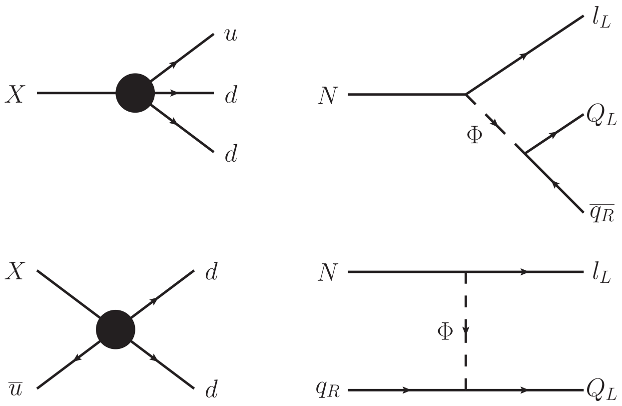
DESY theory fellows' meeting, 10 November 2015

Decays versus scatterings

$$Y_B \equiv \frac{n_B}{s} = (0.86 \pm 0.01) \times 10^{-10}$$



Scatterings or decays — which will dominate?

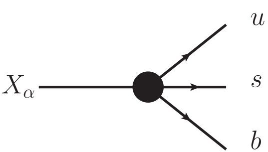
Neutron Portal

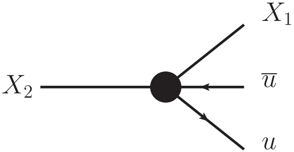
$$\mathcal{L} = \kappa_1 \overline{X_{1L}} u_R \overline{(s_R)^c} b_R + \kappa_2 \overline{X_{2L}} u_R \overline{(s_R)^c} b_R + \kappa_3 \overline{u_R} X_{1L} \overline{X_{2L}} u_R + \kappa_4 \overline{u_R} X_{1L} \overline{X_{1L}} u_R + \kappa_5 \overline{u_R} X_{2L} \overline{X_{2L}} u_R + H.c.$$

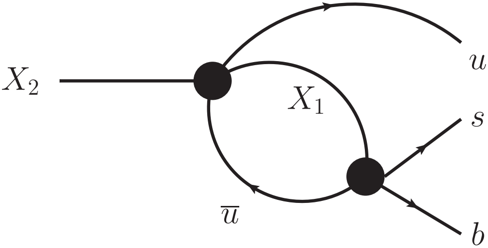
Maximum CP violation: $\kappa_1 = e^{i\pi/2}|\kappa_1|$ and $\kappa_3 = |\kappa_3|$.
Can satisfy the Sakharov Conditions.

- C. Cheung, K. Ishiwata (1304.0468)
- IB, N. F. Bell, A. Millar, K. Petraki, R. R. Volkas (1410.0108)
- P. S. Bhupal Dev, R. N. Mohapatra (1504.07196)
- H. Davoudiasl, Y. Zhang (1504.07244)
- G. Arcadi, L. Covi, M. Nardecchia (1507.05584)

Decays



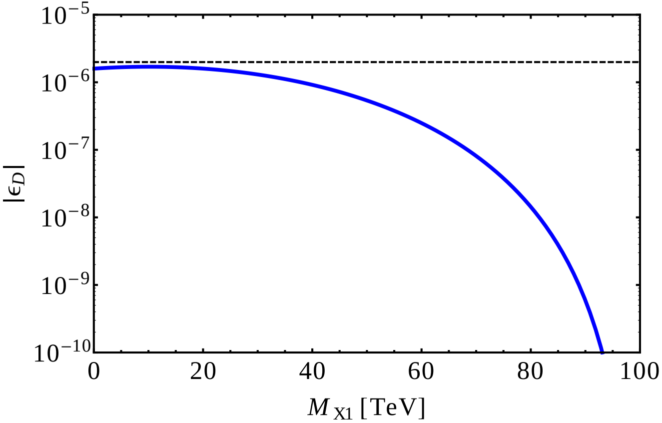




$$\Gamma(X_2 \to X_1 \overline{u} u) = \frac{|\kappa_3|^2 (M_{X2})^5}{1024\pi^3} \qquad \Gamma(X_1 \to usb) = \frac{|\kappa_i|^2 (M_{Xi})^5}{1024\pi^3}$$

CP violation in decays

$$\kappa_i = 10^{-14}\ \text{GeV}^{-2},\ M_{X2} = 100\ \text{TeV}.$$



$$\Gamma(X_2 \to usb) = \frac{1}{2}(1+\epsilon_D)\Gamma_{2a} \qquad \text{CP} : \epsilon_D \to -\epsilon_D \qquad \epsilon_D \sim \frac{\kappa}{16\pi} M_{X2}^2$$

Unitarity

$$W(\alpha \to \beta) =$$
$$\int \dots \int d\Pi_{\alpha 1} \dots d\Pi_{\alpha n} d\Pi_{\beta 1} \dots d\Pi_{\beta m} \delta^4 \left(\sum p_i - \sum p_j \right) (2\pi)^4$$
$$\times f_{\alpha 1} \dots f_{\alpha n} |\mathcal{M}(\alpha \to \beta)|^2$$

$$d\Pi_\psi = \frac{g_\psi d^3 p_\psi}{2E_\psi (2\pi)^3} \qquad f_\psi = e^{(\mu_\psi - E_\psi)/T}$$

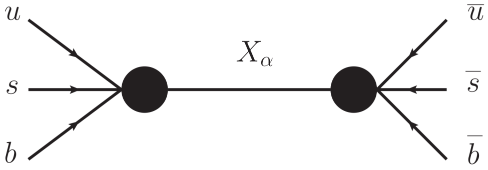
$$\sum_\beta W(\alpha \to \beta) = \sum_\beta W(\beta \to \alpha)$$
$$= \sum_\beta W(\overline{\beta} \to \overline{\alpha}) = \sum_\beta W(\overline{\alpha} \to \overline{\beta})$$

Unitarity condition for decays

Rate for $usb \to \overline{usb}$ mediated by an X_2 with on-shell part subtracted.

$$W(usb \to \overline{usb}) = (1 + \epsilon_{OS}) W_{OS}$$

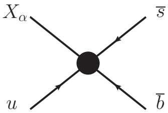
$$\mathrm{CP}: \quad \epsilon_{OS} \to -\epsilon_{OS}$$

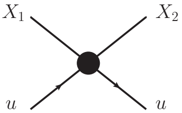


Unitarity:

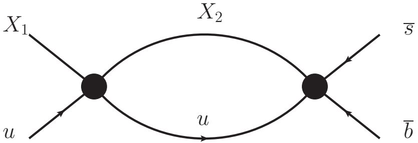
$$\epsilon_{OS} W_{OS} = \frac{1}{2} \epsilon_D n_2^{eq} \Gamma_{2A}$$

Scatterings





$$W(u + X_1 \to \bar{s} + \bar{b}) \equiv (1 + \epsilon_1) W_1$$
$$W(u + X_2 \to \bar{s} + \bar{b}) \equiv (1 + \epsilon_2) W_2$$
$$W(u + X_1 \to u + X_2) \equiv (1 + \epsilon_3) W_3$$



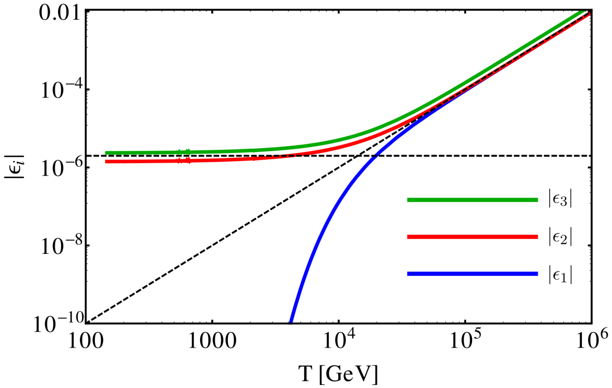
$$\frac{1}{p^2 - m^2} \to \delta(p^2 - m^2)$$

Unitarity

$$\epsilon_1 W_1 + \epsilon_3 W_3 = 0$$
$$\epsilon_2 W_2 - \epsilon_3 W_3 = 0$$
$$\epsilon_1 W_1 + \epsilon_2 W_2 = 0$$

CP violation in scatterings

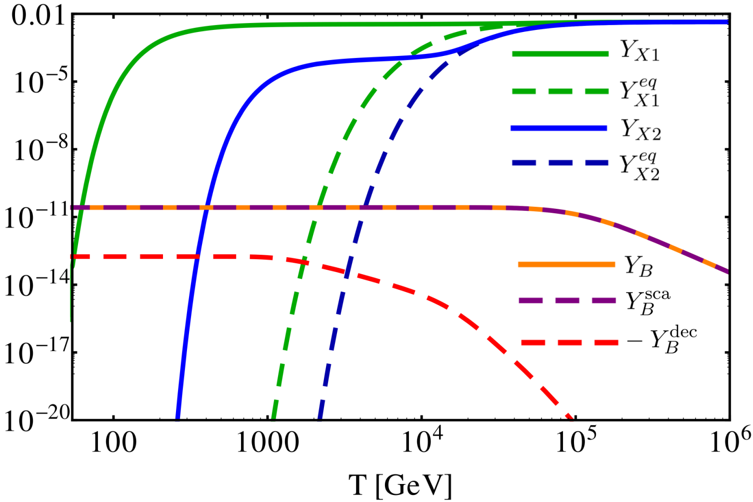
$\kappa_i = 10^{-14}\ \text{GeV}^{-2}$, $M_{X2} = 100$ TeV, $M_{X1} = 50$ TeV.



For $T \gg M_{X2}$: $\epsilon_i \sim \kappa T^2$

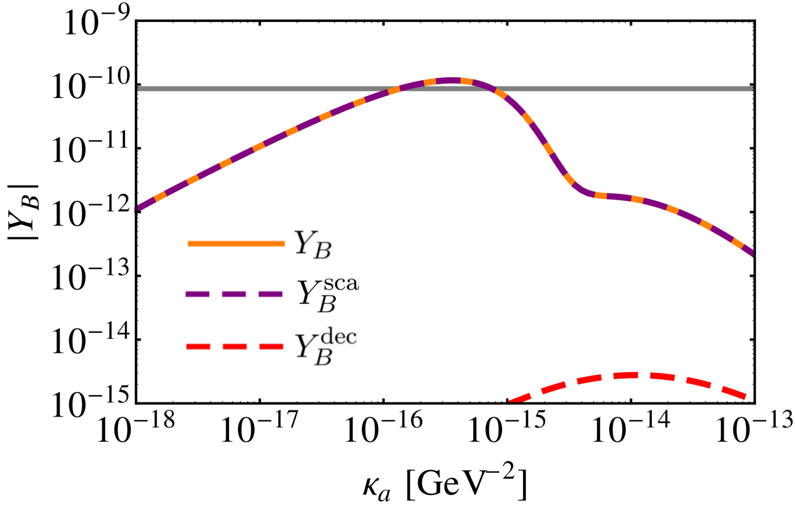
For $T \lesssim M_{X2}$: $\epsilon_{2,3} \sim \frac{1}{16\pi}\kappa M_{X2}^2$

Solution



$\kappa_i = 10^{-16}$ GeV^{-2}, $M_{X2} = 100$ TeV, $M_{X1} = 50$ TeV

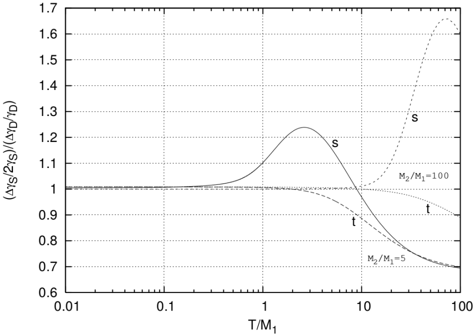
Final Asymmetry



$M_{X2} = 100$ TeV, $M_{X1} = 90$ TeV

Comparison to Leptogenesis

- Neutron Portal EFT with $[\kappa] = M^{-2}$ so the CP violation: $\epsilon_D \sim \kappa M_X^2$ while $\epsilon_i \sim \kappa T^2$.
- Leptogenesis $N + u^c \leftrightarrow L + Q^c$

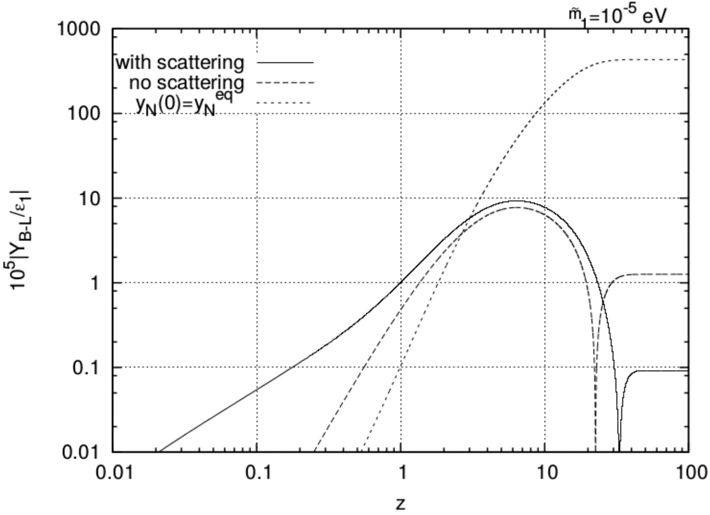


- E. Nardi, J. Racker, E. Roulet (arXiv:0707.0378).

- Dimensionless couplings and massless particles in the loop:

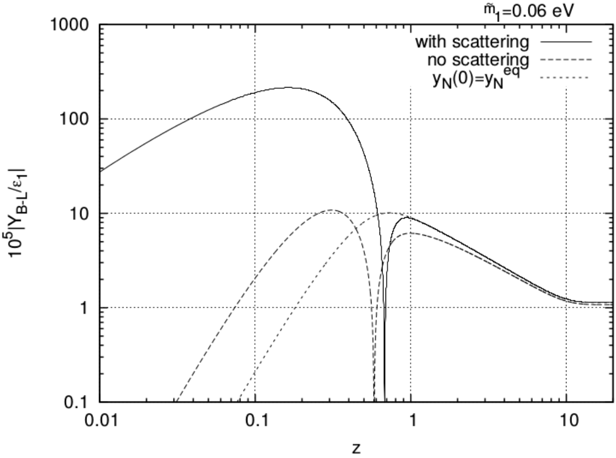
$$\epsilon_D \sim \epsilon_{2\to 2}.$$

Weak Washout



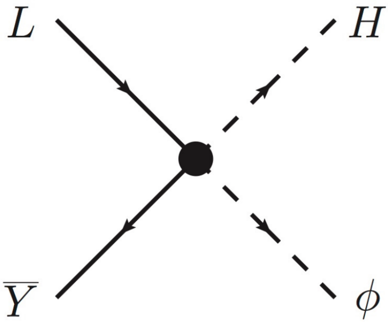
- E. Nardi, J. Racker, E. Roulet (0707.0378).

Strong Washout



- E. Nardi, J. Racker, E. Roulet (0707.0378).

Asymmetric DM and Conclusion

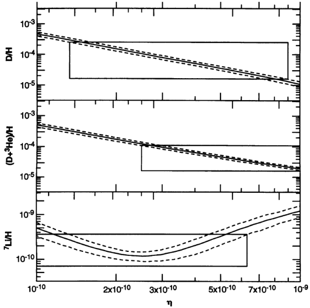


Majorana fermion Y, ADM ϕ, SM lepton doublet L, SM Higgs H.

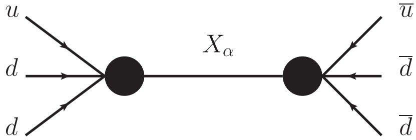
- IB, N. F. Bell, A. J. Millar, R. R. Volkas (1506.07521).

- CP violating scatterings can give the dominant contribution to Y_B.

Constraints



BBN



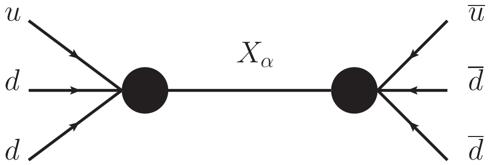
Neutron-antineutron

$$10^{-18}\text{GeV}^{-2} \lesssim \kappa_\alpha \lesssim 10^{-13}\text{GeV}^{-2}$$

(Both for $M_X \sim 1$ TeV).

Neutron-antineutron oscillation

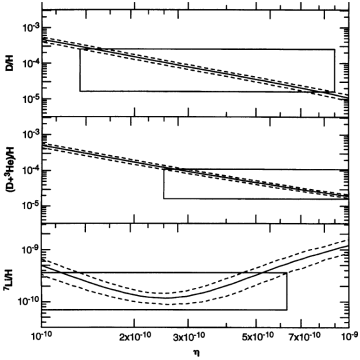
$$\mathcal{L} = \kappa X d_R u_R d_R + H.c.$$



$$\tau_{n-\overline{n}} \sim 3 \times 10^8 \text{ s} \times \left(\frac{M_X}{1 \text{ TeV}}\right)\left(\frac{10^{-13} \text{ GeV}^{-2}}{\kappa}\right)^2\left(\frac{250 \text{ MeV}}{\Lambda_{QCD}}\right)^6$$

Experiment: $\tau_{n-\overline{n}} \geq 2.4 \times 10^8$ s (free neutrons: $\tau_{n-\overline{n}} \geq 10^8$ s)

BBN constraint



Need the X_i to decay before the onset of BBN at $t \sim 1$ Sec.

$$\kappa_1 \gtrsim \left(\frac{1\ \text{TeV}}{M_{X1}}\right)^{5/2} 10^{-18}\ \text{GeV}^{-2}$$

Similar constraint on κ_2 and κ_3.

Source term

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \epsilon_3 W_3 \Big[(r_{X1}\overline{r_u} + r_{X1} r_u) - (r_{X2}\overline{r_u} + r_{X2} r_u) \Big] + \epsilon_D \Gamma_{X2a} n_{X2}^{eq} \Big[r_{X2} - (\overline{r_u r_d r_d} + r_u r_d r_d)/2 \Big] + (\text{Washout terms})$$

$$\text{where:} \quad r_\Psi \equiv \frac{n_\Psi}{n_\Psi^{eq}}$$

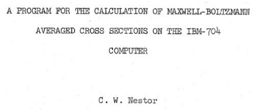
Rate calculation

Rates can be calculated using:

$$W(ij \to \mathrm{final}) = n_i^{eq} n_j^{eq} \langle v\sigma \rangle$$
$$= \frac{g_i g_j T}{8\pi^4} \int_{(m_j+m_i)^2}^{\Lambda^2} p_{ij} E_i E_j v_{rel} \sigma K_1 \left(\frac{\sqrt{s}}{T} \right) ds$$

Using Maxwell-Boltzmann statistics non-equilibrium rates are found:

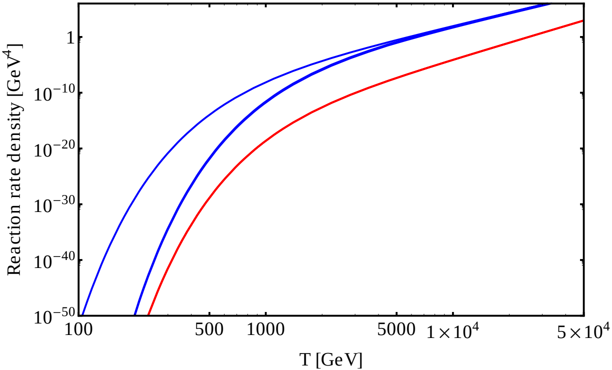
$$W^{neq}(ij \to \mathrm{final}) = (n_i n_j) \langle v\sigma \rangle$$


A PROGRAM FOR THE CALCULATION OF MAXWELL-BOLTZMANN AVERAGED CROSS SECTIONS ON THE IBM-704 COMPUTER

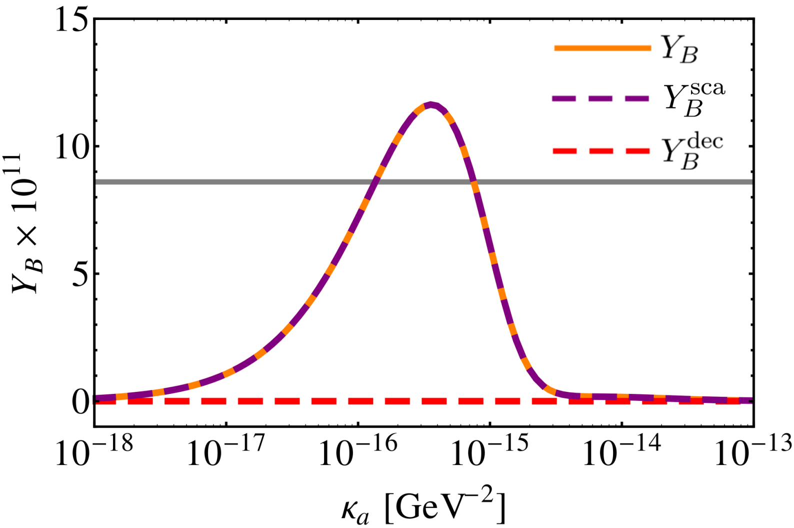
C. W. Nestor

CP violation in annihilations

$\kappa_i = 10^{-14}$ GeV^{-2}, $M_{X2} = 20$ TeV, $M_{X1} = 10$ TeV, $\theta_1 = \pi/2$

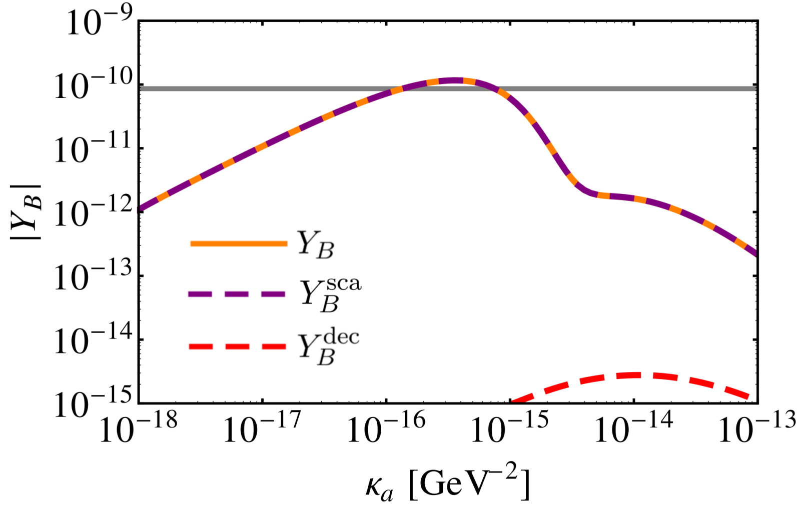


Blue: Annihilation rates W_i.
Red: CP violation $|\epsilon_i W_i|$.



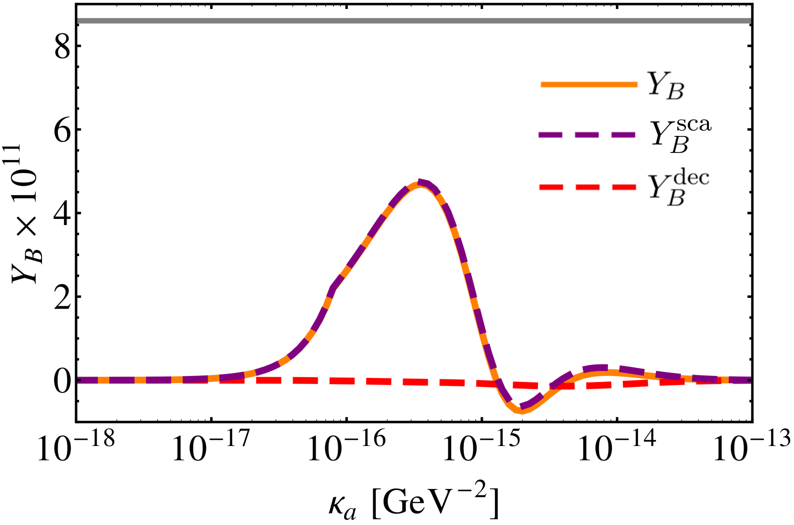
$M_{X2} = 100$ TeV, $M_{X1} = 90$ TeV

Final Asymmetry



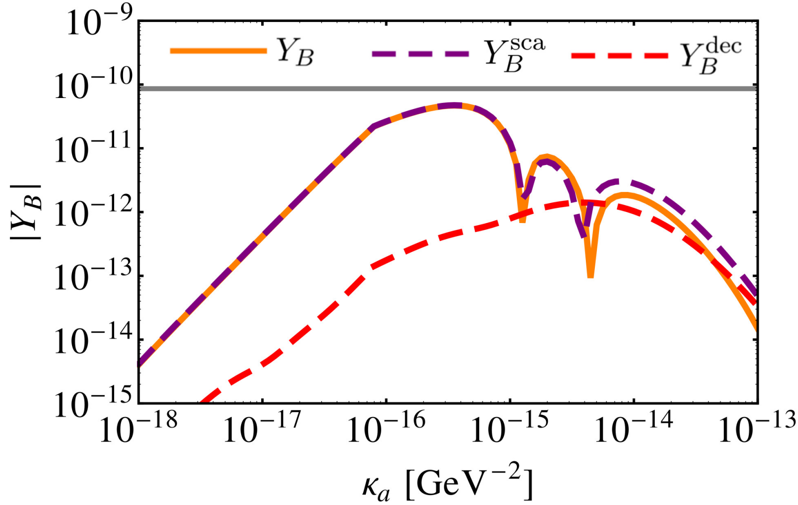
$M_{X2} = 100$ TeV, $M_{X1} = 90$ TeV

Final asymmetry 2



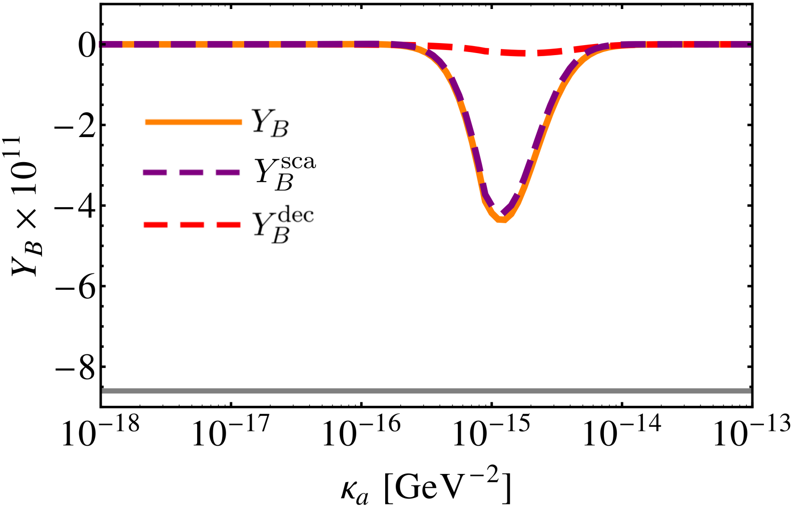
$M_{X2} = 100$ TeV, $M_{X1} = 50$ TeV

Final asymmetry 2



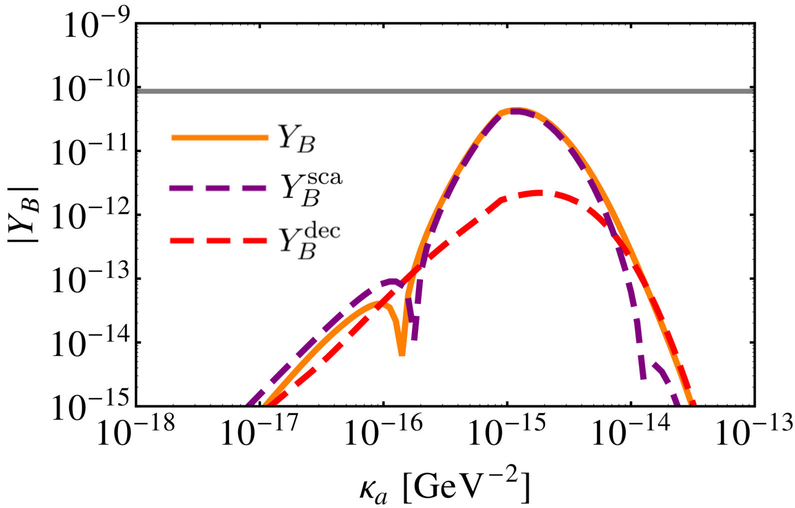
$M_{X2} = 100$ TeV, $M_{X1} = 50$ TeV

Final asymmetry 3



$M_{X2} = 100$ TeV, $M_{X1} = 10$ TeV

Final asymmetry 3



$M_{X2} = 100$ TeV, $M_{X1} = 10$ TeV

Boltzmann equations

- Take into account all $2 \to 2$ processes.
- Assume X_1 and X_2 are in kinetic equilibrium with the thermal bath.
- We obtain three coupled ODEs: n_{X1}, n_{X2}, n_{B-L}.
- Do standard change of variable $t \to T$ using:

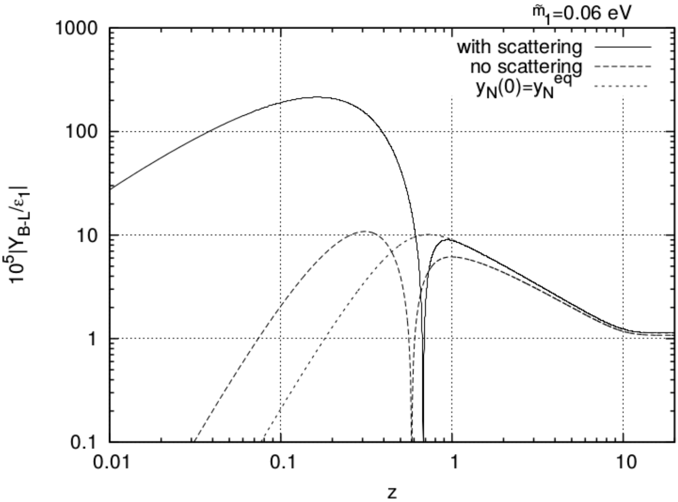
$$\frac{1}{2t} = H = \sqrt{\frac{8\pi G}{3}\rho} = \frac{1.66 g_*^{1/2} T^2}{M_{Pl}}$$

- Express in terms of $Y = n/s$ where:

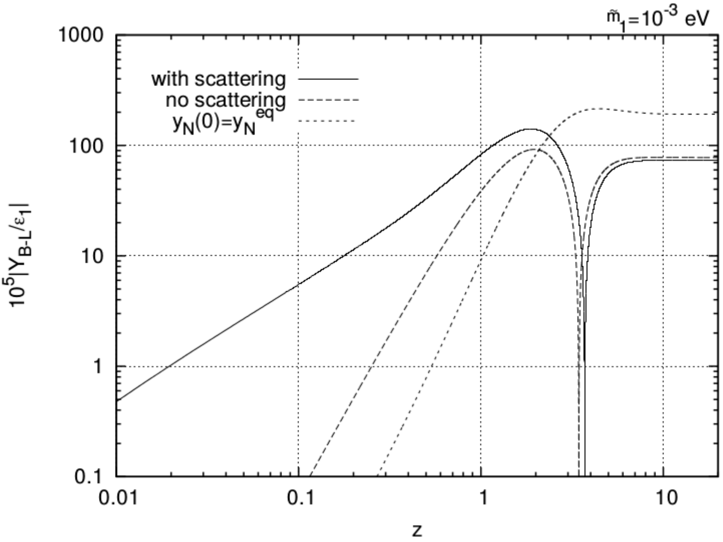
$$s = \frac{2\pi^2}{45} g_s T^3$$

- Solve for Y_{X1}, Y_{X2}, $Y_{\Delta B-L}$.

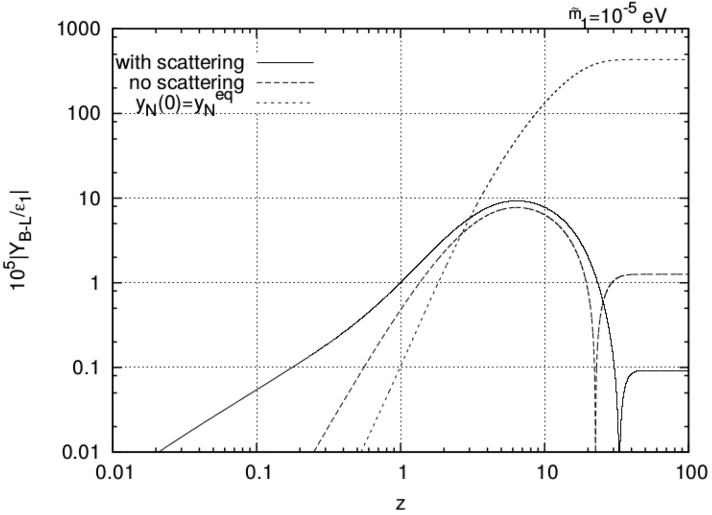
Strong Washout



Intermediate Washout



Weak Washout



Unitarity

$$\sum_\beta |\mathcal{M}(\alpha \to \beta)|^2 = \sum_\beta |\mathcal{M}(\beta \to \alpha)|^2$$
$$= \sum_\beta |\mathcal{M}(\overline{\beta} \to \overline{\alpha})|^2 = \sum_\beta |\mathcal{M}(\overline{\alpha} \to \overline{\beta})|^2$$