Wash-in Leptogenesis with Dirac Neutrino Scatterings

Peter Maták
In collaboration with T. Blažek, J. Heeck, J. Heisig, V. Zaujec

[Phys. Rev. D 110 (2024) 055042]

COMENIUS UNIVERSITY BRATISLAVA

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Outline of this talk

- Unitarity and CPT symmetry constraints from holomorphic cutting rules [Phys. Rev. D 103 (2021) L091302]

- Leptogenesis with Dirac neutrinos and heavy-particle asymmetric decays

- Asymmetry from right-handed neutrino scatterings with a vanishing source-term [Phys. Rev. D 110 (2024) 055042]

Holomorphic cutting rules

$$S = 1 + \mathrm{i}\,T \qquad\qquad T_{fi} = (2\pi)^4 \delta^{(4)}(p_f - p_i) M_{fi} \tag{1}$$

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$$|T_{fi}|^2 = -\mathrm{i}\,T^\dagger_{if}\mathrm{i}\,T_{fi} = -\mathrm{i}\,T_{if}\mathrm{i}\,T_{fi} + \sum_n \mathrm{i}\,T_{in}\mathrm{i}\,T_{nf}\mathrm{i}\,T_{fi} - \sum_{n,k} \mathrm{i}\,T_{in}\mathrm{i}\,T_{nk}\mathrm{i}\,T_{kf}\mathrm{i}\,T_{fi} + \dots \tag{3}$$

[Coster, Stapp '70, Bourjaily, Hannesdottir, *et al.* '21, Hannesdottir, Mizera '22, Blažek, Maták '21a]

Holomorphic cutting rules

$$S = 1 + \mathrm{i}\,T \qquad\qquad T_{fi} = (2\pi)^4 \delta^{(4)}(p_f - p_i) M_{fi} \tag{1}$$

$$\begin{aligned}
\Delta|T_{fi}|^2 = |T_{fi}|^2 - |T_{if}|^2 = &\sum_n \left(\mathrm{i}\,T_{in}\mathrm{i}\,T_{nf}\mathrm{i}\,T_{fi} - \mathrm{i}\,T_{if}\mathrm{i}\,T_{fn}\mathrm{i}\,T_{ni}\right) \\
&- \sum_{n,k} \left(\mathrm{i}\,T_{in}\mathrm{i}\,T_{nk}\mathrm{i}\,T_{kf}\mathrm{i}\,T_{fi} - \mathrm{i}\,T_{if}\mathrm{i}\,T_{fk}\mathrm{i}\,T_{kn}\mathrm{i}\,T_{ni}\right) \\
&+ \ldots
\end{aligned} \tag{4}$$

[Blažek, Maták '21a, see also Roulet, Covi, Vissani '98]

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[Blažek, Maták '21a, see also Roulet, Covi, Vissani '98]

$$\sum_f \Delta|T_{fi}|^2 = 0 \tag{5}$$

[Dolgov '79, Kolb, Wolfram '80]

Holomorphic cuts and the classical Boltzmann equation

Change in # of particles $\quad\leftrightarrow\quad$ average # of their interactions

$$\dot{n}_{f_1} + 3Hn_{f_1} = \sum_{\text{all reactions}} \gamma_{fi} - \gamma_{if} \qquad\qquad \gamma_{fi} = \frac{1}{V_4}\int \prod_{k=1}^{p} [\mathrm{d}\boldsymbol{p}_k]\, f_{i_k}(\boldsymbol{p}_k) \int \prod_{l=1}^{q} [\mathrm{d}\boldsymbol{p}_l] |\, T_{fi}|^2 \tag{6}$$

$$[\mathrm{d}\boldsymbol{p}_k] = \frac{\mathrm{d}^3\boldsymbol{p}_k}{(2\pi)^3 2E_{\boldsymbol{p}_k}} \qquad\qquad |\, T_{fi}|^2 = V_4 (2\pi)^4 \delta^{(4)}(p_f - p_i) |M_{fi}|^2 \tag{7}$$

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$$\gamma_{fi} = \frac{1}{V_4} \int \prod_{k=1}^{p} [\mathrm{d}\boldsymbol{p}_k]\, f_{i_k}(\boldsymbol{p}_k) \int \prod_{l=1}^{q} [\mathrm{d}\boldsymbol{p}_l] \Big(- \mathrm{i}\, T_{if} \mathrm{i}\, T_{fi} + \sum_n \mathrm{i}\, T_{in} \mathrm{i}\, T_{nf} \mathrm{i}\, T_{fi} + \dots \Big) \tag{8}$$

[Blažek, Maták '21a]

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$$f_{i_k}(\boldsymbol{p}_k) \propto \exp\left\{ -\frac{E_{\boldsymbol{p}_k}}{T} \right\} \qquad \gamma_{fi} = \frac{n_{i_1}}{n_{i_1}^{\mathrm{eq}}} \frac{n_{i_2}}{n_{i_2}^{\mathrm{eq}}} \cdots \frac{n_{i_p}}{n_{i_p}^{\mathrm{eq}}} \times \gamma_{fi}^{\mathrm{eq}} \tag{9}$$

Holomorphic cuts and the classical Boltzmann equation

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$$\Delta\gamma_{fi}^{\mathrm{eq}} = \gamma_{fi}^{\mathrm{eq}} - \gamma_{\overline{fi}}^{\mathrm{eq}} = -\Delta\gamma_{if}^{\mathrm{eq}} \qquad \sum_f \Delta\gamma_{fi}^{\mathrm{eq}} = 0 \tag{10}$$

Consequences for the asymmetry generation

$$\Delta \dot{n}_{f_1} + 3H\Delta n_{f_1} = \sum_i \sum_{f \ni f_1} \left(\frac{n_{i_1}}{n_{i_1}^{\text{eq}}} \frac{n_{i_2}}{n_{i_2}^{\text{eq}}} \cdots \frac{n_{i_p}}{n_{i_p}^{\text{eq}}} - 1 \right) \times \Delta\gamma_{fi}^{\text{eq}} + \text{wash-out terms} \tag{11}$$

$$\left.\begin{array}{l} f_1 \text{ in the final state of the contributing processes} \\[2em] \text{out-of-equilibrium initial state} \end{array}\right\} \quad \Delta n_{f_1} \text{ source term}$$

[Detailed derivation in Racker ’19]

Leptogenesis with Dirac neutrinos

- Introduced in Phys. Rev. Lett. **84** (2000) 4039 [Dick, Lindner, Ratz, and Wright 2000]
- Lepton-number conserving decays of heavy particles
- Right-handed neutrinos decoupled from the bath develop asymmetry opposite to that of standard-model leptons

$$Y_B = \frac{28}{79}\,Y_{B-L_{\mathrm{SM}}} = \frac{28}{79}\Delta_{\nu_R} \tag{12}$$

[Kuzmin, Rubakov, Shaposhnikov '85; Harvey, Turner '90]

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$$\mathcal{L} = \frac{1}{2} \bar{L}^c F_i L X_i^\dagger + \bar{e}_R^c G_i \nu_R X_i^\dagger + \mathrm{H.c.} \tag{13}$$

[Heeck, Heisig, Thapa '23a]

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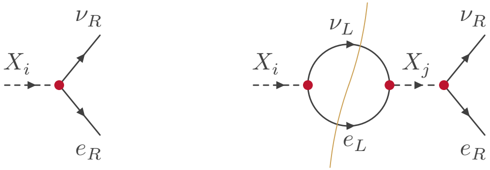

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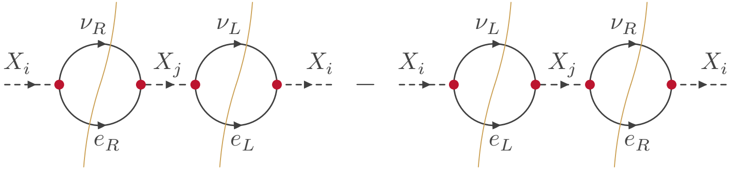
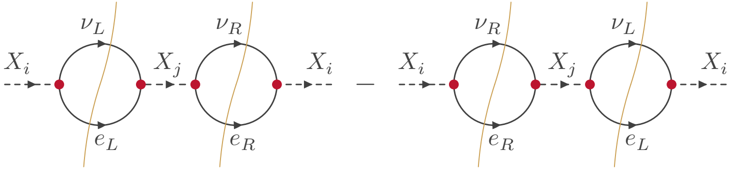
$$\Delta |T_{X_i \to \nu_R e_R}|^2 + \Delta |T_{X_i \to \nu_L e_L}|^2 = 0 \tag{14}$$

Leptogenesis with Dirac neutrinos

$$\Delta|T_{X_i\to\nu_R e_R}|^2 = \tag{15}$$



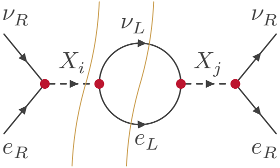
$$\Delta|T_{X_i\to\nu_L e_L}|^2 = \tag{16}$$



$$\Delta|T_{X_i\to\nu_R e_R}|^2 + \Delta|T_{X_i\to\nu_L e_L}|^2 = 0 \tag{14}$$

Leptogenesis with Dirac neutrinos

$$\Delta|T_{\nu_R e_R \to X_i}|^2 = \tag{17}$$



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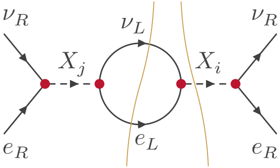
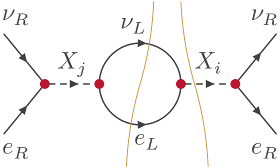


$$\Delta|T_{\nu_R e_R \to \nu_L e_L}|^2 = \tag{18}$$



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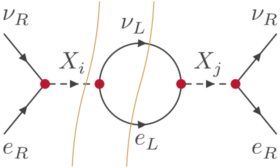

$$\Delta|T_{\nu_R e_R \to X_i}|^2 + \Delta|T_{\nu_R e_R \to \nu_L e_L}|^2 = 0 \tag{19}$$

Dirac leptogenesis without heavy particles?

$$\mathcal{L} = \frac{1}{2}\bar{L}^c F_i L X_i^\dagger + \bar{e}_R^c G_i \nu_R X_i^\dagger + \text{H.c.} \qquad\qquad M_X \gg T_\text{reh} \tag{20}$$

[Heeck, Heisig, Thapa '23b]

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[Heeck, Heisig, Thapa '23b]

$$\cancel{\Delta |T_{\nu_R e_R \to X_i}|^2} + \Delta |T_{\nu_R e_R \to \nu_L e_L}|^2 = 0 \tag{21}$$

Dirac leptogenesis without heavy particles?

$$\mathcal{L} = \frac{1}{2}\bar{L}^c F_i L X_i^\dagger + \bar{e}_R^c G_i \nu_R X_i^\dagger + \text{H.c.} \qquad M_X \gg T_\text{reh} \tag{20}$$

[Heeck, Heisig, Thapa '23b]

$SU(3)\times SU(2)\times U(1)$	spin	$(B-L)(X)$	asymmetry-generating operators
$(\mathbf{1},\mathbf{1},-1)$	0	-2	$\boxed{\nu_R e_R X^\dagger,\, LLX^\dagger}$
$(\mathbf{1},\mathbf{2},1/2)$	0	0	$\bar{H}X, \bar{\nu}_R LX, \bar{L}e_R X, \bar{Q}d_R X, \bar{u}_R QX, X^\dagger H^\dagger HH$
$(\mathbf{3},\mathbf{1},-1/3)$	0	$-2/3$	$d_R\nu_R X^\dagger, u_R e_R X^\dagger, QLX^\dagger, u_R d_R X, QQX$
$(\mathbf{3},\mathbf{1},2/3)$	0	$-2/3$	$u_R\nu_R X^\dagger, d_R d_R X$
$(\mathbf{3},\mathbf{2},1/6)$	0	$4/3$	$\bar{Q}\nu_R X, \bar{d}_R LX$
$(\mathbf{1},\mathbf{2},-1/2)$	$1/2$	-1	$\bar{X}L, \bar{\nu}_R XH, \bar{X}e_R H$

[Heeck, Heisig, Thapa '23a]

Dirac leptogenesis without heavy particles?

$$\mathcal{L} = \bar{Q}^c F_i L X_i^\dagger + \bar{d}_R^c G_i \nu_R X_i^\dagger + \bar{u}_R^c K_i e_R X_i^\dagger + \text{H.c.} \qquad M_X \gg T_{\text{reh}} \tag{22}$$

[Blažek, Heeck, Heisig, Maták, Zaujec '24]

$SU(3) \times SU(2) \times U(1)$	spin	$(B-L)(X)$	asymmetry-generating operators
$(\mathbf{1}, \mathbf{1}, -1)$	0	-2	$\nu_R e_R X^\dagger$, $LLX^\dagger$
$(\mathbf{1}, \mathbf{2}, 1/2)$	0	0	$\bar{H}X$, $\bar{\nu}_R LX$, $\bar{L}e_R X$, $\bar{Q}d_R X$, $\bar{u}_R QX$, $X^\dagger H^\dagger HH$
$(\mathbf{3}, \mathbf{1}, -1/3)$	0	$-2/3$	$\boxed{d_R \nu_R X^\dagger, u_R e_R X^\dagger, QLX^\dagger}$, $u_R d_R X$, QQX
$(\mathbf{3}, \mathbf{1}, 2/3)$	0	$-2/3$	$u_R \nu_R X^\dagger$, $d_R d_R X$
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$4/3$	$\bar{Q}\nu_R X$, $\bar{d}_R LX$
$(\mathbf{1}, \mathbf{2}, -1/2)$	$1/2$	-1	$\bar{X}L$, $\bar{\nu}_R XH$, $\bar{X}e_R H$

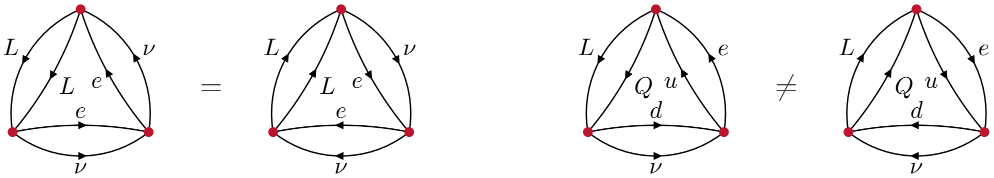
[Heeck, Heisig, Thapa '23a]

Dirac leptogenesis without heavy particles?

$$\mathcal{L} = \bar{Q}^c F_i L X_i^\dagger + \bar{d}_R^c G_i \nu_R X_i^\dagger + \bar{u}_R^c K_i e_R X_i^\dagger + \text{H.c.} \qquad M_X \gg T_\text{reh} \tag{22}$$

[Blažek, Heeck, Heisig, Maták, Zaujec '24]

$$\Delta |T_{fi}|^2 = \sum_n \left(\mathrm{i}T_{in} \mathrm{i}T_{nf} \mathrm{i}T_{fi} - \mathrm{i}T_{if} \mathrm{i}T_{fn} \mathrm{i}T_{ni} \right) - \ldots$$



[see also Roulet, Covi, Vissani '98, Botella, Nebot, Vives '06]

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[Blažek, Heeck, Heisig, Maták, Zaujec '24]

- B and L individually conserved
- first generation only, ignoring SM interactions at $T_\text{reh} > 3 \times 10^{13}$ GeV

[Bento '03, Garbrecht, Schwaller '14]

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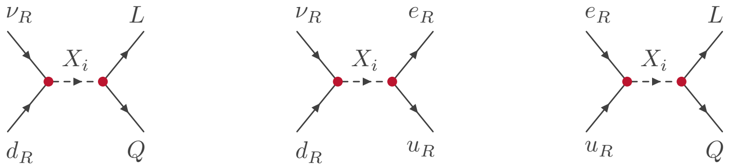
[Bento '03, Garbrecht, Schwaller '14]

$$\left.\begin{array}{lll} \Delta_{d_R} + \Delta_{u_R} + \Delta_Q = 0 & & \Delta_{\nu_R} + \Delta_{e_R} + \Delta_L = 0 \\ \Delta_{\nu_R} = \Delta_{d_R} & \Delta_L = \Delta_Q & \Delta_{e_R} = \Delta_{u_R} \end{array}\right\} \quad \Delta_a \equiv \frac{n_a - n_{\bar{a}}}{s} \tag{23}$$

Dirac leptogenesis without heavy particles?



$$\langle \sigma_1 v \rangle = \frac{16}{3\pi} \frac{T^2}{\zeta(3)^2} \sum_{i,j} \frac{F_i^* F_j G_j^* G_i}{M_i^2 M_j^2} \equiv \frac{16}{3\pi} \frac{T^2}{T_{\rm reh}^4} \frac{\alpha_1}{\zeta(3)^2} \approx \frac{T^2}{T_{\rm reh}^4} \alpha_1 \tag{24}$$

$$\langle \sigma_2 v \rangle = \frac{8}{3\pi} \frac{T^2}{\zeta(3)^2} \sum_{i,j} \frac{K_i^* K_j G_j^* G_i}{M_i^2 M_j^2} \equiv \frac{8}{3\pi} \frac{T^2}{T_{\rm reh}^4} \frac{\alpha_2}{\zeta(3)^2} \approx \frac{1}{2} \frac{T^2}{T_{\rm reh}^4} \alpha_2 \tag{25}$$

$$\langle \sigma_3 v \rangle = \frac{16}{3\pi} \frac{T^2}{\zeta(3)^2} \sum_{i,j} \frac{F_i^* F_j K_j^* K_i}{M_i^2 M_j^2} \equiv \frac{16}{3\pi} \frac{T^2}{T_{\rm reh}^4} \frac{\alpha_3}{\zeta(3)^2} \approx \frac{T^2}{T_{\rm reh}^4} \alpha_3 \tag{26}$$

Dirac leptogenesis without heavy particles?

$$\frac{\mathrm{d}\,Y_{\nu_R}}{\mathrm{d}x} = -\,\frac{1}{x^4}\,\frac{\Gamma}{H}\bigg|_{T_{\mathrm{reh}}}\left(Y_{\nu_R} - Y_{\nu_R}^{\mathrm{eq}}\right) \qquad \Gamma = \frac{5}{9}\,s\,Y_{\nu_R}^{\mathrm{eq}}\Big(\langle\sigma_1\,v\rangle + \langle\sigma_2\,v\rangle\Big) \tag{27}$$

Dirac leptogenesis without heavy particles?

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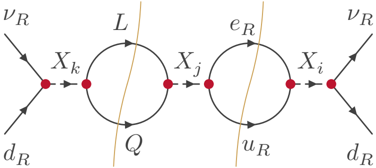
$$Y_{\nu_R}(x) = \frac{135\zeta(3)}{8\pi^4 h_*}\left(1 - \exp\left[-\,\frac{\Gamma}{\mathcal{H}}\bigg|_{T_{\mathrm{reh}}}\frac{x^3-1}{3x^3}\right]\right) \tag{28}$$

Dirac leptogenesis without heavy particles?

$$\Delta|T_{\nu_R d_R \to LQ}|^2 =$$



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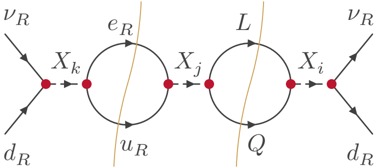
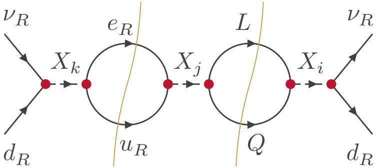


$$(29)$$

$$\Delta|T_{\nu_R d_R \to e_R u_R}|^2 =$$



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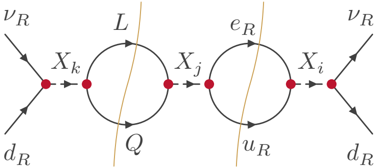

$$(30)$$

$$\Delta|T_{\nu_R d_R \to LQ}|^2 + \Delta|T_{\nu_R d_R \to e_R u_R}|^2 = 0 \tag{31}$$

[Blažek, Heeck, Heisig, Maták, Zaujec '24]

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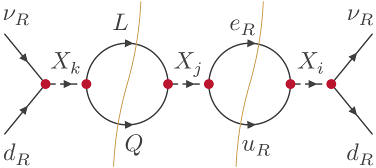

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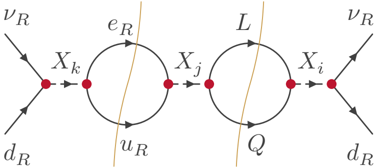
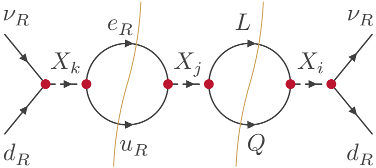


(29)

$$\Delta|T_{\nu_R d_R \to e_R u_R}|^2 =$$



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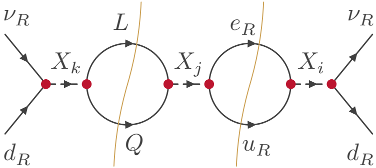


(32)

$$\Delta\langle\sigma_1 v\rangle = -\Delta\langle\sigma_2 v\rangle \equiv \frac{64}{\pi^2}\frac{T^4}{T_{\text{reh}}^6}\frac{\epsilon}{\zeta(3)^2} \approx \frac{T^4}{T_{\text{reh}}^6}\epsilon \tag{33}$$

[Blažek, Heeck, Heisig, Maták, Zaujec '24]

Freeze-in and wash-in

$$\left(\frac{\mathrm{d}\Delta_L}{\mathrm{d}x}\right)_{\text{source}} = -\left(\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x}\right)_{\text{source}} \quad \to \quad \left(\frac{\mathrm{d}\Delta_{\nu_R}}{\mathrm{d}x}\right)_{\text{source}} = 0 \tag{34}$$

$$\left(\frac{\mathrm{d}\Delta_L}{\mathrm{d}x}\right)_{\text{wash-out}} \neq -\left(\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x}\right)_{\text{wash-out}} \quad \to \quad \left(\frac{\mathrm{d}\Delta_{\nu_R}}{\mathrm{d}x}\right)_{\text{wash-in}} \neq 0 \tag{35}$$

[see also Domcke, Kamada, Mukaida, Schmitz, Yamada '21, Aristizabal, Nardi, Muñoz '09]

Freeze-in and wash-in

$$\frac{\mathrm{d}\Delta_L}{\mathrm{d}x} = \frac{Y_{\nu_R}^{\mathrm{eq}}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg\{\Delta\langle\sigma_1 v\rangle\left(Y_{\nu_R}^{\mathrm{eq}} - Y_{\nu_R}\right) + \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right)$$
$$+ \frac{8}{9}\langle\sigma_1 v\rangle\left[\Delta_L - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y_{\nu_R}^{\mathrm{eq}}}\left(\Delta_L - \frac{3}{2}\Delta_{\nu_R}\right)\right]\Bigg\} \tag{36}$$

$$\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x} = \frac{Y_{\nu_R}^{\mathrm{eq}}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg\{\Delta\langle\sigma_2 v\rangle\left(Y_{\nu_R}^{\mathrm{eq}} - Y_{\nu_R}\right) - \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right)$$
$$+ \frac{8}{9}\langle\sigma_2 v\rangle\left[2\Delta_{e_R} - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y_{\nu_R}^{\mathrm{eq}}}\left(2\Delta_{e_R} - \frac{3}{2}\Delta_{\nu_R}\right)\right]\Bigg\} \tag{37}$$

[Blažek, Heeck, Heisig, Maták, Zaujec ’24]

Freeze-in and wash-in

$$\begin{aligned}\frac{\mathrm{d}\Delta_L}{\mathrm{d}x} = & \frac{Y^{\mathrm{eq}}_{\nu_R}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\left\{\Delta\langle\sigma_1 v\rangle\left(Y^{\mathrm{eq}}_{\nu_R} - Y_{\nu_R}\right) + \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right)\right. \\ & \left. \boxed{+\frac{8}{9}\langle\sigma_1 v\rangle\left[\Delta_L - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}}\left(\Delta_L - \frac{3}{2}\Delta_{\nu_R}\right)\right]}\right\}\end{aligned} \tag{36}$$

$$\begin{aligned}\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x} = & \frac{Y^{\mathrm{eq}}_{\nu_R}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\left\{\Delta\langle\sigma_2 v\rangle\left(Y^{\mathrm{eq}}_{\nu_R} - Y_{\nu_R}\right) - \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right)\right. \\ & \left. \boxed{+\frac{8}{9}\langle\sigma_2 v\rangle\left[2\Delta_{e_R} - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}}\left(2\Delta_{e_R} - \frac{3}{2}\Delta_{\nu_R}\right)\right]}\right\}\end{aligned} \tag{37}$$

[Blažek, Heeck, Heisig, Maták, Zaujec ’24]

Freeze-in and wash-in

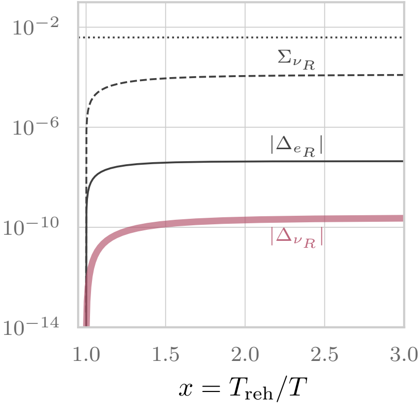
$$\frac{\mathrm{d}\Delta_{\nu_R}}{\mathrm{d}x} = \frac{Y^{\mathrm{eq}}_{\nu_R}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\left\{\frac{5}{9}\langle\sigma_1 v\rangle\left(5+\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}}\right)\Delta_{\nu_R} + \frac{1}{9}\langle\sigma_2 v\rangle\left(17+3\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}}\right)\Delta_{\nu_R} + \frac{8}{9}(\langle\sigma_1 v\rangle - 2\langle\sigma_2 v\rangle)\left(1+\frac{1}{4}\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}}\right)\Delta_{e_R}\right\} \tag{38}$$

$$\frac{Y_{\nu_R}}{Y^{\mathrm{eq}}_{\nu_R}} = 1 - \exp\left[-\frac{\Gamma}{\mathcal{H}}\bigg|_{T_{\mathrm{reh}}}\frac{x^3-1}{3x^3}\right] \tag{39}$$

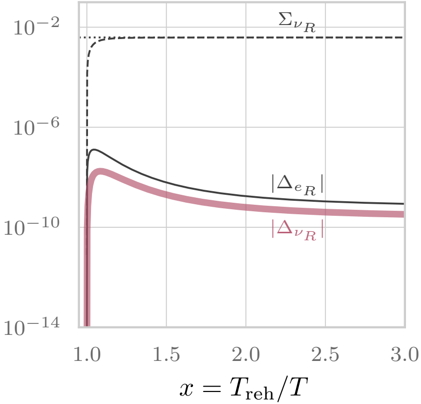
[Blažek, Heeck, Heisig, Maták, Zaujec '24]

Numerical solution for $T_{\rm reh} = 10^{14}\,\mathrm{GeV}$

$\alpha_1 = 1.3 \times 10^{-5}, \epsilon = 1.3 \times 10^{-8}$



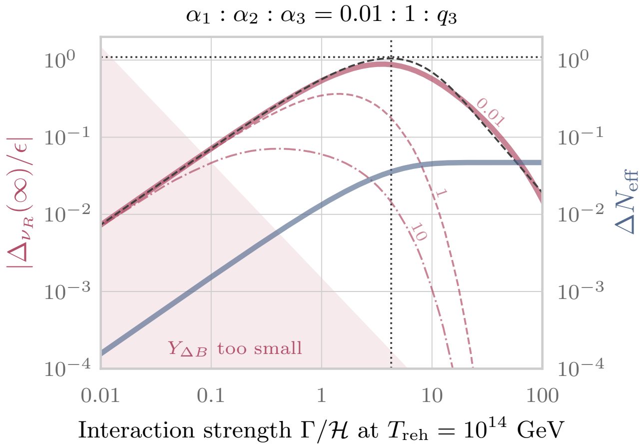
$\alpha_1 = 2.6 \times 10^{-3}, \epsilon = 4.9 \times 10^{-7}$



$$\langle \sigma_1 v \rangle = 1.5 \times 10^{-33}\ \mathrm{GeV}^{-2}/x^2$$
$$|\Delta\langle \sigma_1 v \rangle| = 6.0 \times 10^{-36}\ \mathrm{GeV}^{-2}/x^4$$

$$\langle \sigma_1 v \rangle = 3.1 \times 10^{-31}\ \mathrm{GeV}^{-2}/x^2$$
$$|\Delta\langle \sigma_1 v \rangle| = 2.2 \times 10^{-34}\ \mathrm{GeV}^{-2}/x^4$$

Numerical solution for $T_{\rm reh} = 10^{14}\ \mathrm{GeV}$



$$\left|\frac{\Delta_{\nu_R}(\infty)}{\epsilon}\right|_{\max} \simeq \frac{0.05}{\sqrt{g_*}h_*}\frac{M_{\rm Pl}}{T_{\rm reh}}$$

$$\alpha_{1,3} \ll \alpha_2 \simeq 5.1\sqrt{g_*}\frac{T_{\rm reh}}{M_{\rm Pl}}$$

$$\alpha_{2,3} \ll \alpha_1 \gg 5.1\sqrt{g_*}\frac{T_{\rm reh}}{M_{\rm Pl}}$$

[Blažek, Heeck, Heisig, Maták, Zaujec ’24]

Summary

- Holomorphic cutting rules allow for easy tracking of asymmetry cancellations due to the CPT and unitarity constraints.

- Leptogenesis with ν_R as the only out-of-equilibrium particles is possible. Their asymmetry is washed in, although the source term vanishes.

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Thank you for your attention!