Wash-in leptogenesis from asymmetric Dirac neutrino scatterings

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

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

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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]

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

[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]

Unitarity and the asymmetry generation

$$\Delta \dot{n}_{f_1} + 3H\Delta n_{f_1} = \sum_i \sum_{f \ni f_1} \left(\frac{n_{i_1}}{n_{i_1}^{\rm eq}} \frac{n_{i_2}}{n_{i_2}^{\rm eq}} \dots \frac{n_{i_p}}{n_{i_p}^{\rm eq}} - 1 \right) \times \Delta\gamma_{fi}^{\rm eq} + \text{wash-out terms} \qquad (6)$$

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

[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

$$Y_B = \frac{28}{79} Y_{B-L_{\mathrm{SM}}} = \frac{28}{79} \Delta_{\nu_R} \tag{7}$$

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

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$$\mathcal{L} = \frac{1}{2} \bar{L}^c F_i L X_i^\dagger + \bar{e}_R^c G_i \nu_R X_i^\dagger + \mathrm{H.c.} \tag{8}$$

[Heeck, Heisig, Thapa '23a]

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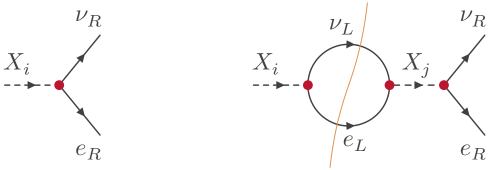

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$$\Delta |T_{X_i \to \nu_R e_R}|^2 + \Delta |T_{X_i \to \nu_L e_L}|^2 = 0 \tag{9}$$

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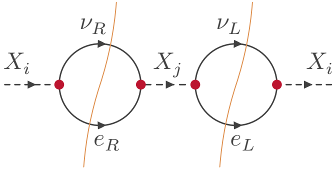

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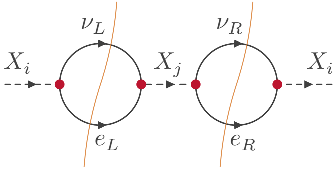

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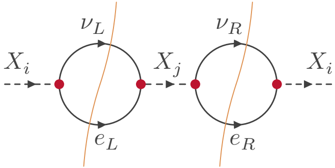
$$\Delta |T_{X_i \to \nu_L e_L}|^2 =$$



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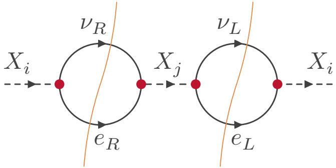

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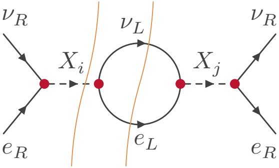
$$\Delta|T_{\nu_R e_R \to X_i}|^2 =$$


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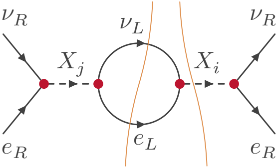

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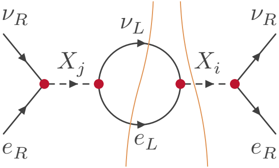
$$\Delta|T_{\nu_R e_R \to \nu_L e_L}|^2 =$$


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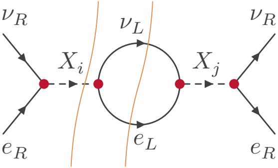

(13)

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

Dirac leptogenesis without heavy particles?

$$\mathcal{L} = \frac{1}{2}\bar{L}^c F_i L X_i^\dagger + \bar{e}_R^c G_i \nu_R X_i^\dagger + \text{H.c.} \qquad M_X \gg T_\text{reh} \tag{15}$$

[Heeck, Heisig, Thapa '23b]

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[Heeck, Heisig, Thapa '23b]

$$\cancel{\Delta|T_{\nu_R e_R \to X_i}|^2} + \Delta|T_{\nu_R e_R \to \nu_L e_L}|^2 = 0 \tag{16}$$

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[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	$\nu_R e_R X^\dagger,\, LLX^\dagger$
$(\mathbf{1},\mathbf{2},1/2)$	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]

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$$\mathcal{L} = \bar{Q}^c F_i L X_i^\dagger + \bar{d}_R^c G_i \nu_R X_i^\dagger + \bar{u}_R^c K_i e_R X_i^\dagger + \text{H.c.} \qquad M_X \gg T_\text{reh} \tag{17}$$

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

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$(\mathbf{1}, \mathbf{2}, 1/2)$	0	0	$\bar{H}X$, $\bar{\nu}_R L X$, $\bar{L} e_R X$, $\bar{Q} d_R X$, $\bar{u}_R Q X$, $X^\dagger H^\dagger H H$
$(\mathbf{3}, \mathbf{1}, -1/3)$	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	$4/3$	$\bar{Q} \nu_R X$, $\bar{d}_R L X$
$(\mathbf{1}, \mathbf{2}, -1/2)$	$1/2$	-1	$\bar{X} L$, $\bar{\nu}_R X H$, $\bar{X} e_R H$

[Heeck, Heisig, Thapa '23a]

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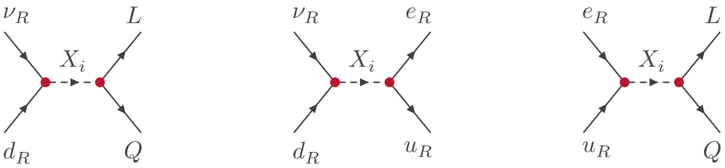

$$\langle\sigma_1 v\rangle \overset{\text{def.}}{=} \frac{\gamma^\text{eq}_{\nu_R d_R \to L Q}}{n^\text{eq}_{\nu_R} n^\text{eq}_{d_R}}, \quad \langle\sigma_2 v\rangle \overset{\text{def.}}{=} \frac{\gamma^\text{eq}_{\nu_R d_R \to e_R u_R}}{n^\text{eq}_{\nu_R} n^\text{eq}_{d_R}}, \quad \langle\sigma_3 v\rangle \overset{\text{def.}}{=} \frac{\gamma^\text{eq}_{e_R u_R \to L Q}}{n^\text{eq}_{e_R} n^\text{eq}_{u_R}} \tag{18}$$

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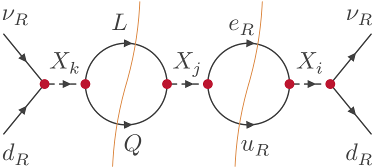
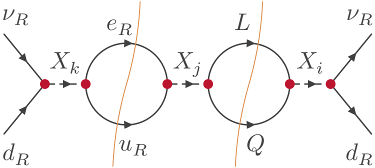
$$\Delta|T_{\nu_R d_R \to LQ}|^2 =$$ 

$-$ 

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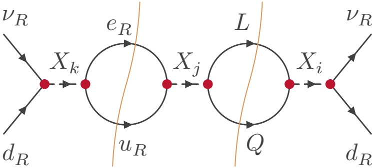
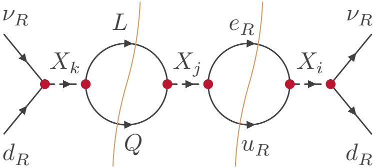
$$\Delta|T_{\nu_R d_R \to e_R u_R}|^2 =$$ 

$-$ 

(20)

$$\Delta|T_{\nu_R d_R \to LQ}|^2 + \Delta|T_{\nu_R d_R \to e_R u_R}|^2 = 0 \qquad \Delta\langle\sigma_1 v\rangle = -\Delta\langle\sigma_2 v\rangle \tag{21}$$

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

Freeze-in and wash-in

$$\left(\frac{\mathrm{d}\Delta_L}{\mathrm{d}x}\right)_{\text{source}} = -\left(\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x}\right)_{\text{source}} \quad \to \quad \left(\frac{\mathrm{d}\Delta_{\nu_R}}{\mathrm{d}x}\right)_{\text{source}} = 0 \tag{22}$$

$$\left(\frac{\mathrm{d}\Delta_L}{\mathrm{d}x}\right)_{\text{wash-out}} \neq -\left(\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x}\right)_{\text{wash-out}} \quad \to \quad \left(\frac{\mathrm{d}\Delta_{\nu_R}}{\mathrm{d}x}\right)_{\text{wash-in}} \neq 0 \tag{23}$$

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

Freeze-in and wash-in

$$\frac{\mathrm{d}\Delta_L}{\mathrm{d}x} = \frac{Y_{\nu_R}^{\mathrm{eq}}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg\{\Delta\langle\sigma_1 v\rangle\left(Y_{\nu_R}^{\mathrm{eq}} - Y_{\nu_R}\right) + \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right) + \frac{8}{9}\langle\sigma_1 v\rangle\left[\Delta_L - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y_{\nu_R}^{\mathrm{eq}}}\left(\Delta_L - \frac{3}{2}\Delta_{\nu_R}\right)\right]\Bigg\} \tag{24}$$

$$\frac{\mathrm{d}\Delta_{e_R}}{\mathrm{d}x} = \frac{Y_{\nu_R}^{\mathrm{eq}}}{H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg\{\Delta\langle\sigma_2 v\rangle\left(Y_{\nu_R}^{\mathrm{eq}} - Y_{\nu_R}\right) - \frac{10}{9}\langle\sigma_3 v\rangle\left(\Delta_L - 2\Delta_{e_R}\right) + \frac{8}{9}\langle\sigma_2 v\rangle\left[2\Delta_{e_R} - \frac{17}{8}\Delta_{\nu_R} + \frac{1}{4}\frac{Y_{\nu_R}}{Y_{\nu_R}^{\mathrm{eq}}}\left(2\Delta_{e_R} - \frac{3}{2}\Delta_{\nu_R}\right)\right]\Bigg\} \tag{25}$$

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

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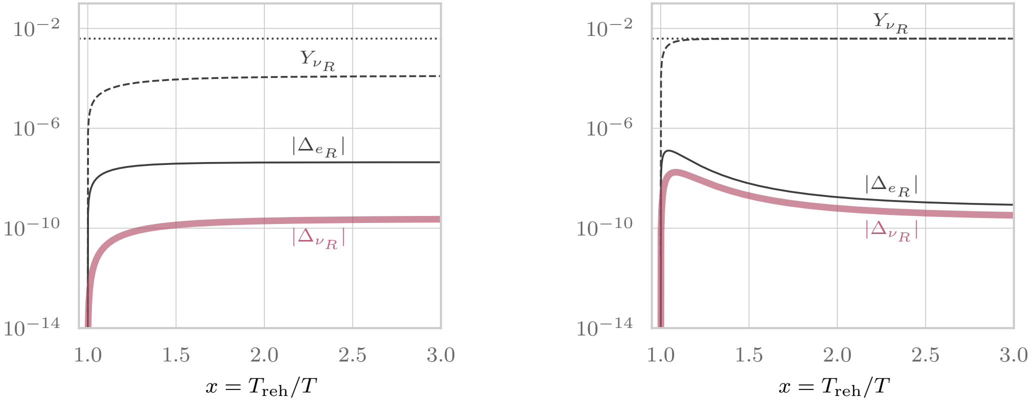
[Blažek, Heeck, Heisig, Maták, Zaujec ’24]

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



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

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

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!