# Particle-antiparticle asymmetries from annihilations

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# Overview

CP violating decays and inverse decays have been studied extensively.
What about CP violation in $2 \leftrightarrow 2$ interactions? Can they create an asymmetry?

- Unitarity Condition
- Toy Model
- Rates and CP
- Solutions to the Boltzmann equations
- Annihilations vs Decays?

Also see WIMPy baryogenesis - Y. Cui, L. Randall, B. Shuve.

# Unitarity

$$|f\rangle = S|i\rangle, \quad \langle f| = \langle i|S^\dagger \quad \Rightarrow S^\dagger S = SS^\dagger = 1$$

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

$$\frac{dn_X}{dt} + 3Hn_X = C_X$$

$$W(\beta \to \alpha) - W(\alpha \to \beta) =$$

$$\int ... \int d\Pi_{\alpha 1}...d\Pi_{\alpha n} d\Pi_{\beta 1}...d\Pi_{\beta m} \delta^4 \left( \sum p_i - \sum p_j \right) (2\pi)^4$$

$$\times \left\{ f_{\beta 1}...f_{\beta m} |\mathcal{M}(\beta \to \alpha)|^2 - f_{\alpha 1}...f_{\alpha n} |\mathcal{M}(\alpha \to \beta)|^2 \right\}$$

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

$$\sum_\beta W(\alpha \to \beta) = \sum_\beta W(\beta \to \alpha)$$

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

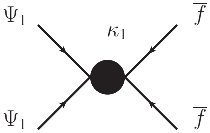
# Toy Model

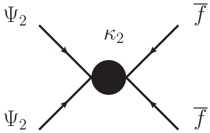
## Interaction Lagrangian

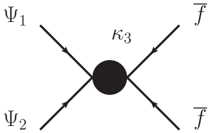
$$\mathcal{L} = \frac{1}{4}\kappa_1 \overline{\Psi_1^c}\Psi_1 \overline{f^c} f + \frac{1}{4}\kappa_2 \overline{\Psi_2^c}\Psi_2 \overline{f^c} f + \frac{1}{2}\kappa_3 \overline{\Psi_2^c}\Psi_1 \overline{f^c} f$$
$$+ \frac{1}{2}\lambda_1 \overline{\Psi_2^c}\Psi_1 \overline{\Psi_1}\Psi_1^c + \frac{1}{4}\lambda_2 \overline{\Psi_2^c}\Psi_2 \overline{\Psi_1}\Psi_1^c + \frac{1}{2}\lambda_3 \overline{\Psi_2^c}\Psi_2 \overline{\Psi_2}\Psi_1^c + H.c.$$

## Global symmetry

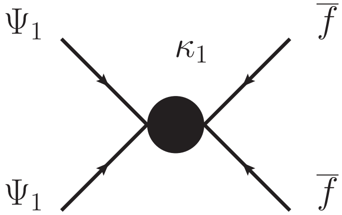
$\Delta(\Psi) - \Delta(f) = 0$ (prohibits Majorana masses).

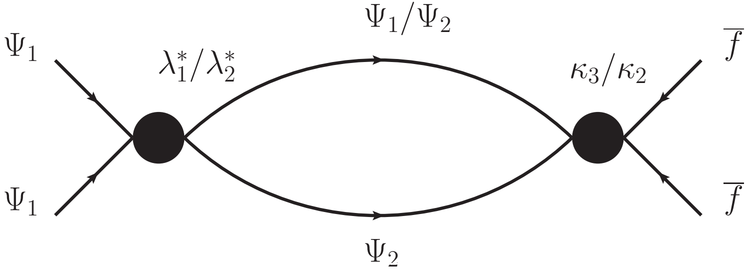


# CP violation



# CP violating rates

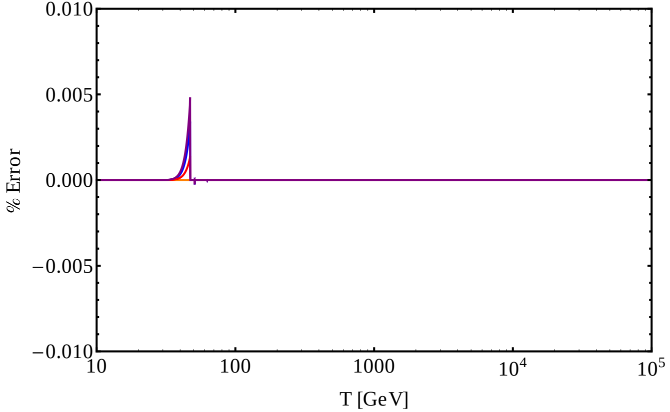
$$W(\Psi_1\Psi_1 \to \overline{f}f) \equiv (1+a_1)A_1 \qquad W(\Psi_1\Psi_1 \to \Psi_1\Psi_2) \equiv (1+a_4)A_4$$
$$W(\Psi_2\Psi_2 \to \overline{f}f) \equiv (1+a_2)A_2 \qquad W(\Psi_1\Psi_1 \to \Psi_2\Psi_2) \equiv (1+a_5)A_5$$
$$W(\Psi_1\Psi_2 \to \overline{f}f) \equiv (1+a_3)A_3 \qquad W(\Psi_2\Psi_2 \to \Psi_2\Psi_1) \equiv (1+a_6)A_6$$

CP conjugate rates: $a_i \to -a_i$ and $A_i \to A_i$. Unitarity for $\Psi_1\Psi_1$:

$$(1+a_1)A_1+(1+a_4)A_4+(1+a_5)A_5 = (1-a_1)A_1+(1-a_4)A_4+(1-a_5)A_5$$

$$a_1A_1 + a_4A_4 + a_5A_5 = 0$$
$$a_2A_2 + a_6A_6 - a_5A_5 = 0$$
$$a_3A_3 - a_4A_4 - a_6A_6 = 0$$
$$a_1A_1 + a_2A_2 + a_3A_3 = 0$$

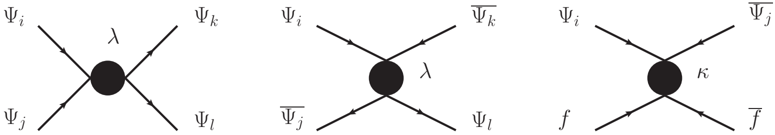
# Unitarity conditions




$$\% \text{ Error} = 100 \left( \frac{a_i A_i \pm a_j A_j \pm a_k A_k}{|a_i A_i| + |a_j A_j| + |a_k A_k|} \right)$$

# CP conserving rates

Also have to take into account:




Decay channels:

$$\Gamma(\Psi_2 \to \overline{\Psi_1 f f}) \equiv (1+\gamma_a)\Gamma_{2a}, \quad \Gamma(\Psi_2 \to \Psi_1\Psi_1\Psi_1) \equiv (1+\gamma_b)\Gamma_{2b}$$

- Unitarity: $\gamma_a\Gamma_a + \gamma_b\Gamma_B = 0$.
- Kinematically forbid the second decay channel.
- CP violation only in the $2 \to 2$ interactions!

# Boltzmann Equations

We can calculate the equilibrium rates using (J. Edsjo, P. Gondolo):

$$W(ij \to \mathrm{final}) = n_i^{eq} n_j^{eq} \langle v\sigma \rangle$$
$$= \frac{g_i g_j T}{32\pi^4} \int_{(m_j+m_i)^2}^{\infty} p_{ij} 4 E_i E_j v_{rel} \sigma K_1 \left( \frac{\sqrt{s}}{T} \right) ds$$

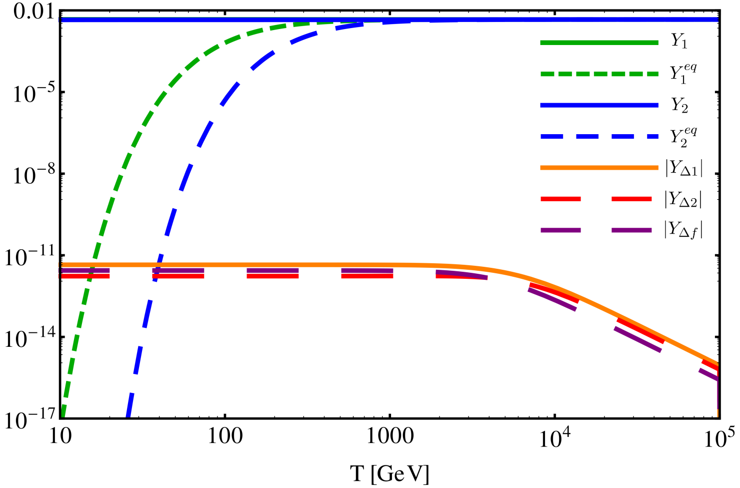
Using Maxwell-Boltzmann non-equilibrium rates are found:

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

- We assume $f$ are in thermal equilibrium with the thermal bath.
- We obtain four coupled ODEs.
- Solve for $n_{\Psi 1},\ n_{\Delta\Psi 1},\ n_{\Psi 2},\ n_{\Delta\Psi 2}$.

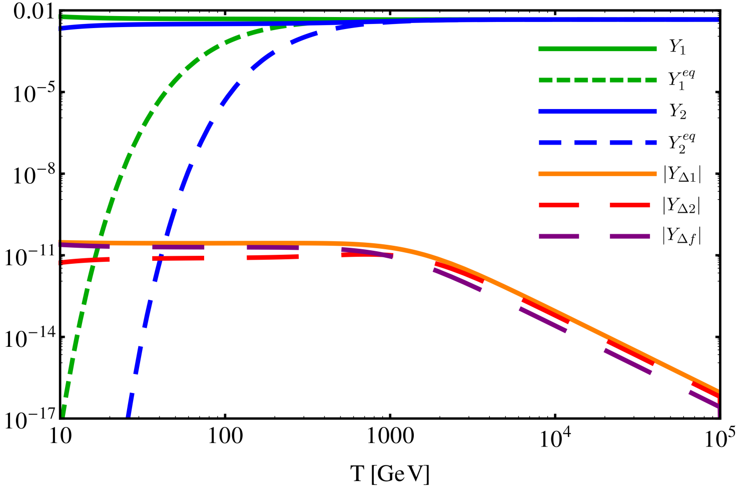
# Example Solution 1

$M_{\Psi 2} = 1000$ GeV, $M_{\Psi 1} = 400$ GeV, $M_f = 50$ GeV,
$|\kappa_i| = |\lambda_i| = 10^{-14}$ GeV$^{-2}$



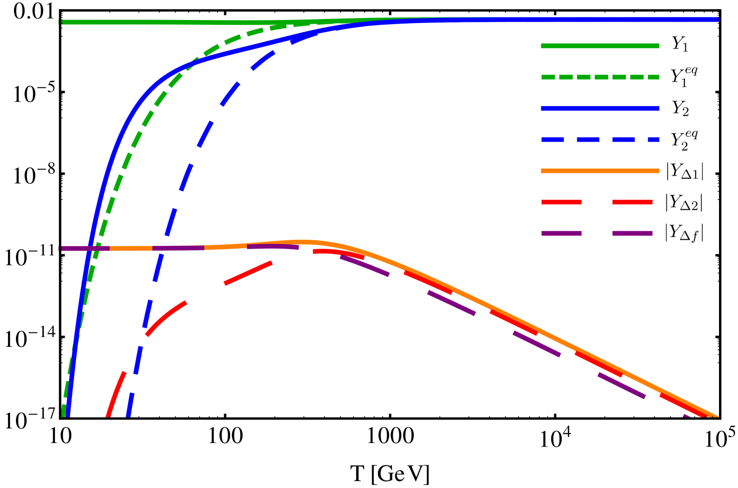
# Example Solution 2

$M_{\Psi 2} = 1000$ GeV, $M_{\Psi 1} = 400$ GeV, $M_f = 50$ GeV,
$|\kappa_i| = |\lambda_i| = 10^{-13}$ GeV$^{-2}$



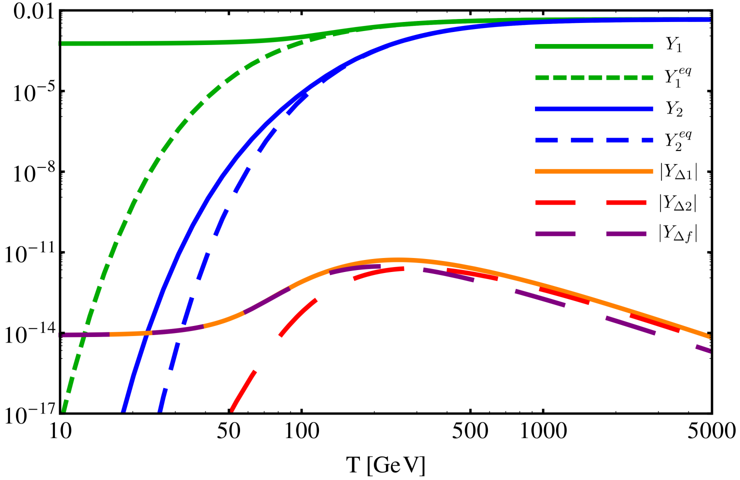
# Example Solution 3

$M_{\Psi 2} = 1000$ GeV, $M_{\Psi 1} = 400$ GeV, $M_f = 50$ GeV,
$|\kappa_i| = |\lambda_i| = 10^{-12}$ GeV$^{-2}$



# Example Solution 4

$M_{\Psi 2} = 1000$ GeV, $M_{\Psi 1} = 400$ GeV, $M_f = 50$ GeV,
$|\kappa_i| = |\lambda_i| = 10^{-11}$ GeV$^{-2}$

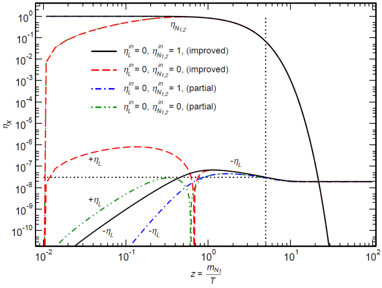


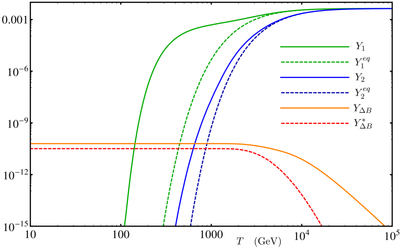
# Decays versus annihilations – Resonant Leptogenesis

- What if CP is violated in decays as well?
- The decays and annihilations will both contribute the final asymmetry.
- Which will dominate?

$N + u^c \leftrightarrow L + Q^c$

$X + \overline{d} \leftrightarrow u + d$



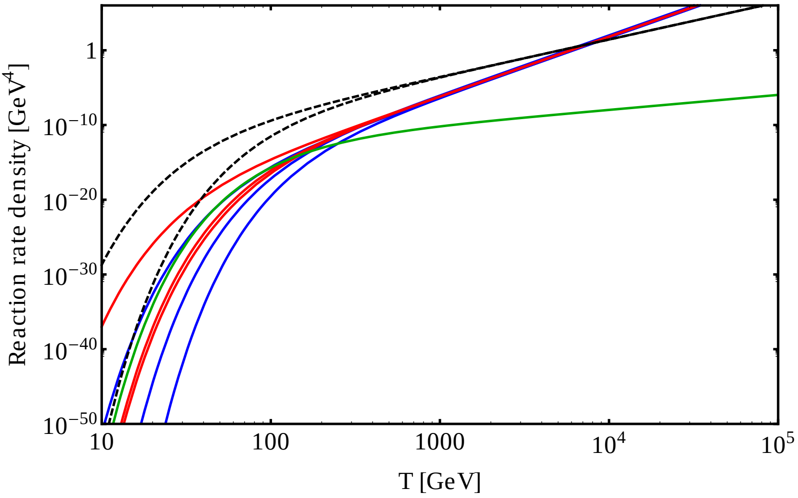

-A. Pilaftsis, T. E. Underwood

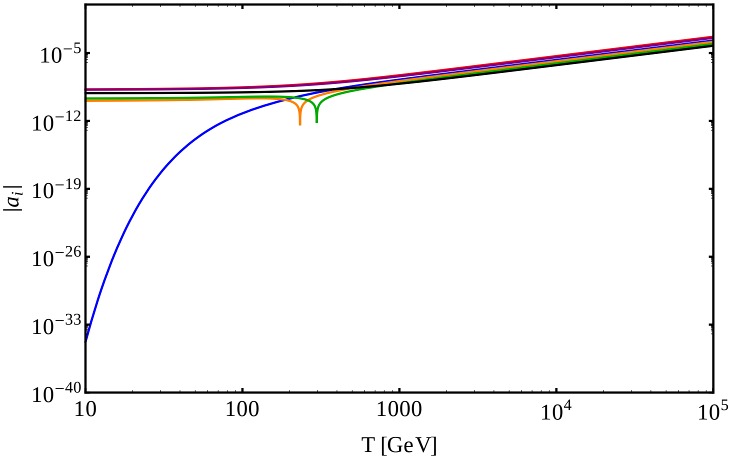
-Work in progress

# Conclusion

- Generating an asymmetry using $2 \leftrightarrow 2$ interactions is possible.
- ADM or baryogenesis model which uses only $2 \leftrightarrow 2$ interactions?
- Investigating CP violating $2 \leftrightarrow 2$ interactions – competing with decays – in baryogenesis.

# Backup slides – Rates






$$a_i = \frac{a_i A_i}{A_i}$$

# Backup slides – Cross section

$\Psi_1\Psi_1 \to \overline{f}\overline{f}$

$$4E_1E_2\sigma v = \frac{|\kappa_1|^2 p_f}{\pi\sqrt{s}}\left[E_1E_2 + p_i^2 - m_1^2\right]\left[E_3E_4 + p_f^2 - m_f^2\right]$$

$$4E_1E_2(\sigma - \overline{\sigma})v = \left\{\mathrm{Im}[\kappa_1^*\lambda_1^*\kappa_3]g(m_1, m_2) + \frac{1}{2}\mathrm{Im}[\kappa_1^*\lambda_2^*\kappa_2]g(m_2, m_2)\right\}$$
$$\times \frac{4p_f}{\pi\sqrt{s}}\left[E_1E_2 + p_i^2 - m_1^2\right]\left[E_3E_4 + p_f^2 - m_f^2\right]$$

$$g(m_i, m_j) = -\frac{1}{8\pi}\left[s-(m_i+m_j)^2\right]\sqrt{1 - \frac{2(m_i^2 + m_j^2)}{s} + \frac{(m_i^2 - m_j^2)^2}{s^2}}$$