TBA:

Michael Shamma (He/They)
msham008@ucr.edu
mshamma@triumf.ca

Dark Interactions 2024
Vancouver, Oct. 16-18

TBA:
Talking ‘Bout Asymmetries

Michael Shamma (He/They)
msham008@ucr.edu
mshamma@triumf.ca

Dark Interactions 2024
Vancouver, Oct. 16-18

Freeze-in Cogenesis of Asymmetric Dark Matter

With P. Asadi (Oregon), M. Moore (MIT),
D. Morrissey (TRIUMF)

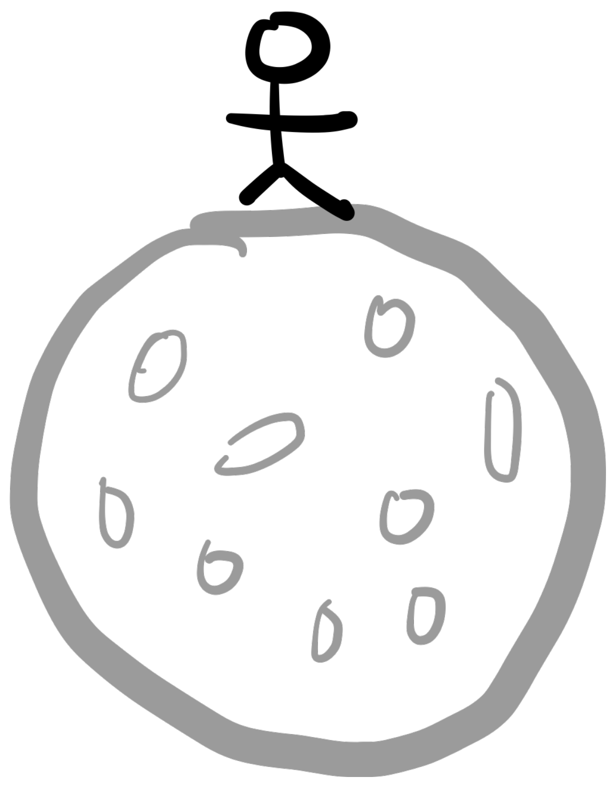
hep-ph/2411.xxxxx

Michael Shamma (He/They)
msham008@ucr.edu
mshamma@triumf.ca

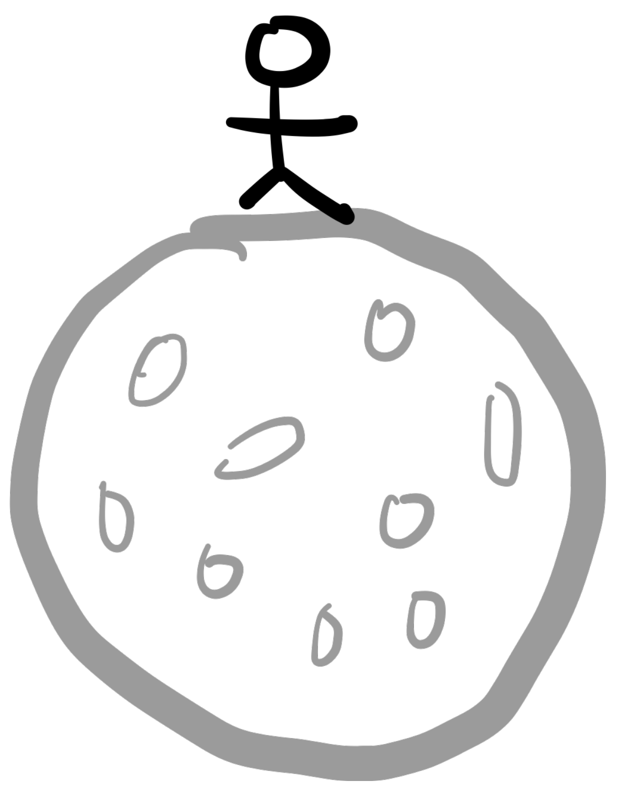
Dark Interactions 2024
Vancouver, Oct. 16-18

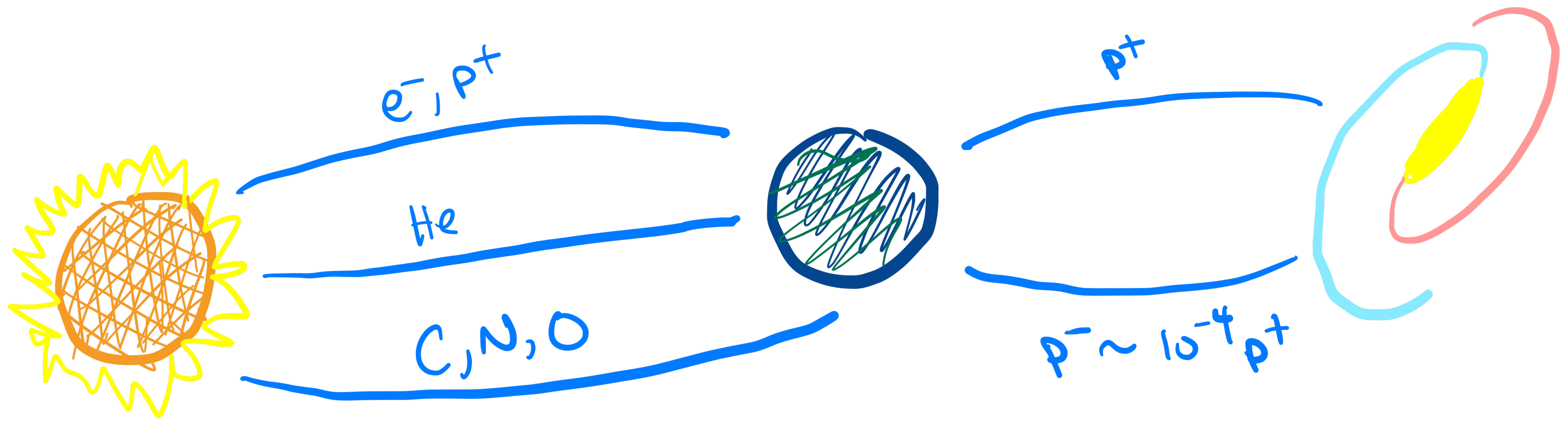
Why asymmetries?

Why asymmetries?

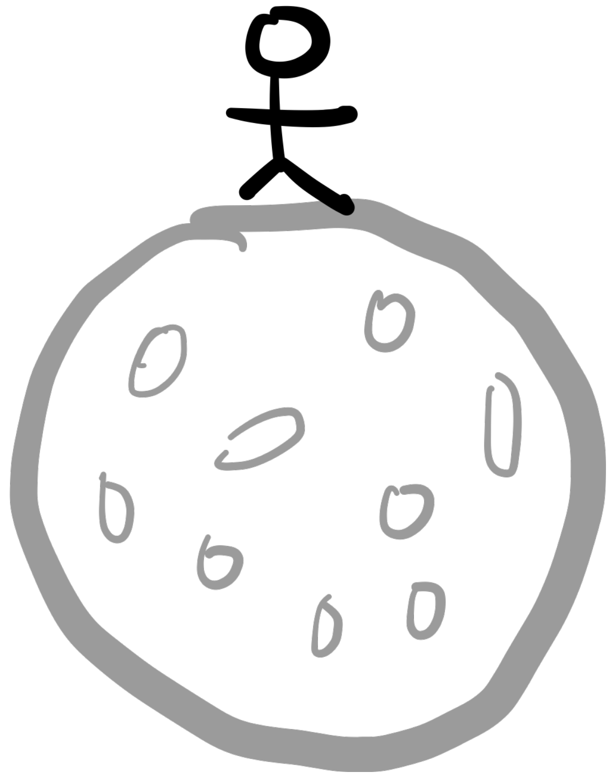


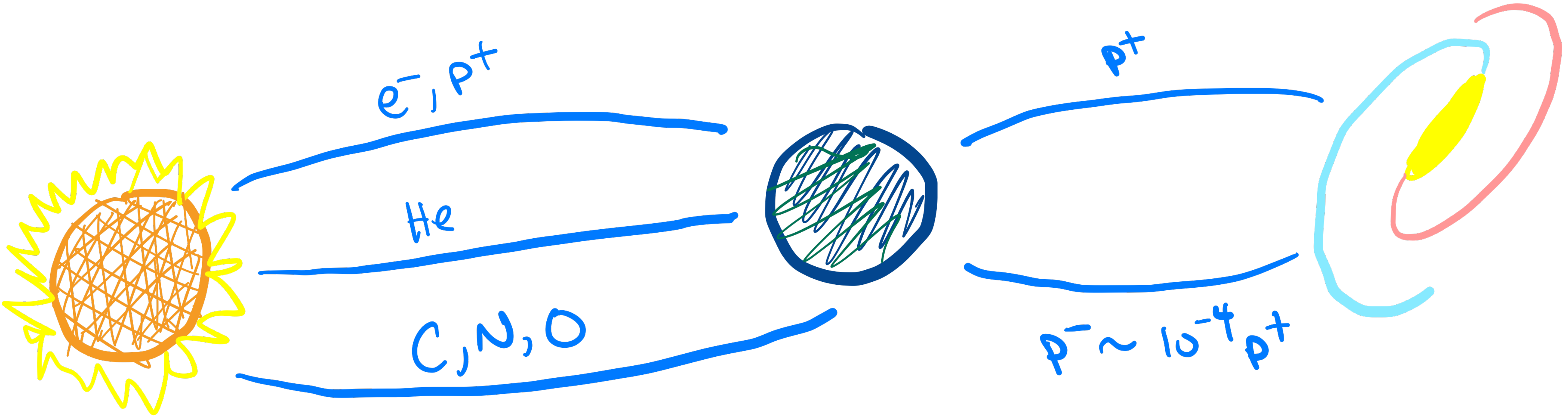
Why asymmetries?

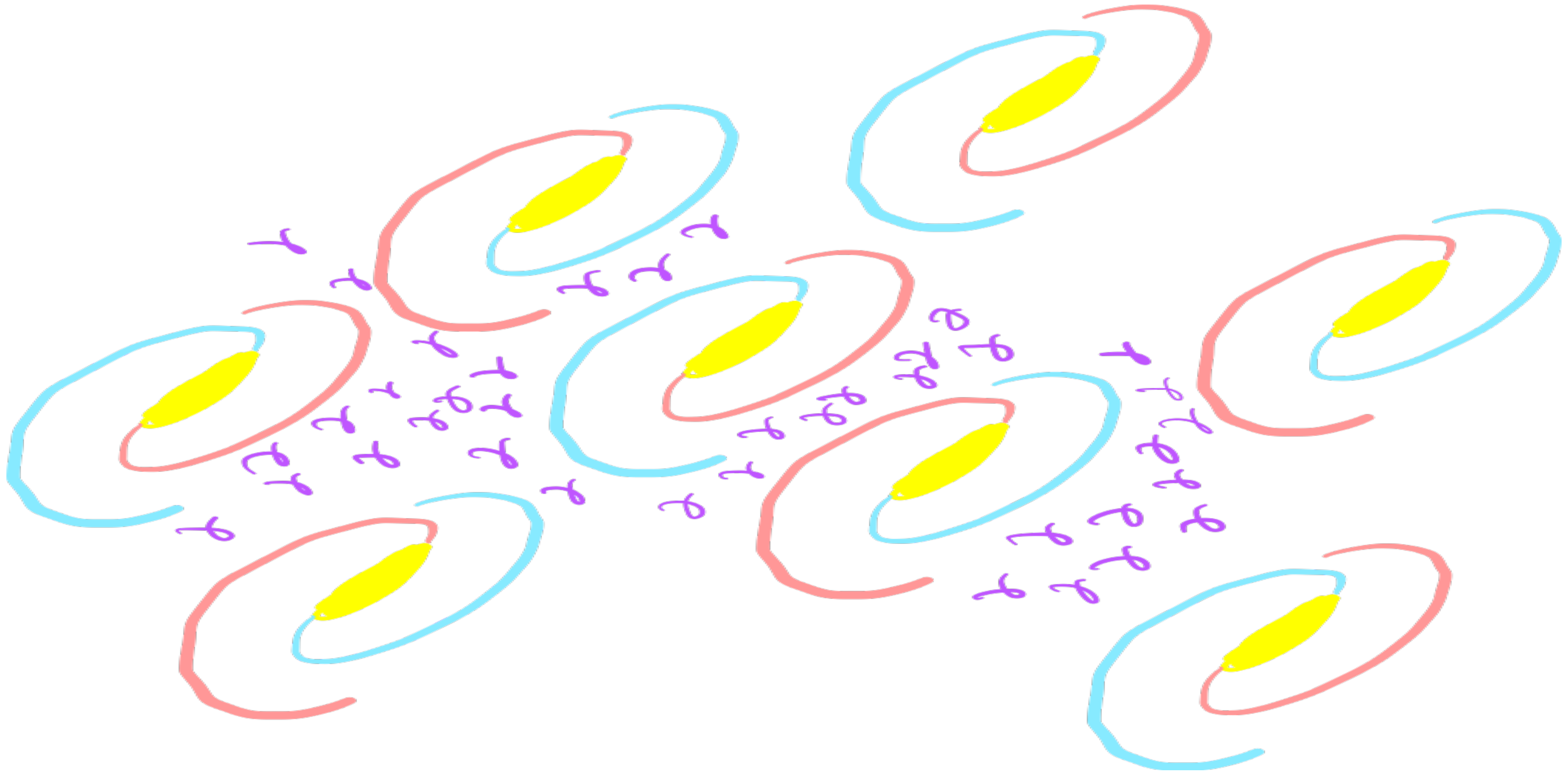




Why asymmetries?







How to make an asymmetry

How to make an asymmetry

Baryogenesis: $\Delta n_B(t = 0) = 0 \rightarrow \Delta n_B(t = t_0) \neq 0$

How to make an asymmetry

Baryogenesis: $\Delta n_B(t = 0) = 0 \to \Delta n_B(t = t_0) \neq 0$

Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

How to make an asymmetry

Baryogenesis: $\Delta n_B(t=0) = 0 \rightarrow \Delta n_B(t=t_0) \neq 0$

Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

How to make an asymmetry

Baryogenesis: $\Delta n_B(t = 0) = 0 \rightarrow \Delta n_B(t = t_0) \neq 0$

Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

$$\frac{dB}{dt} = [B, H_{\text{int}}]$$

How to make an asymmetry

Baryogenesis: $\Delta n_B(t = 0) = 0 \rightarrow \Delta n_B(t = t_0) \neq 0$

Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

$$\frac{dB}{dt} = [B, H_{\text{int}}]$$

2. Violate Charge and Charge-Parity

How to make an asymmetry

Baryogenesis: $\Delta n_B(t=0) = 0 \rightarrow \Delta n_B(t=t_0) \neq 0$

Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

$$\frac{dB}{dt} = [B, H_{\text{int}}]$$

2. Violate Charge and Charge-Parity

$$\Gamma(F_L^+ \rightarrow f_L^+ + s) + \Gamma(F_R^+ \rightarrow f_R^+ + s)$$
$$\neq \Gamma(F_L^- \rightarrow f_L^- + s) + \Gamma(F_R^- \rightarrow f_R^- + s)$$

How to make an asymmetry

Baryogenesis: $\Delta n_B(t=0)=0 \to \Delta n_B(t=t_0)\neq 0$

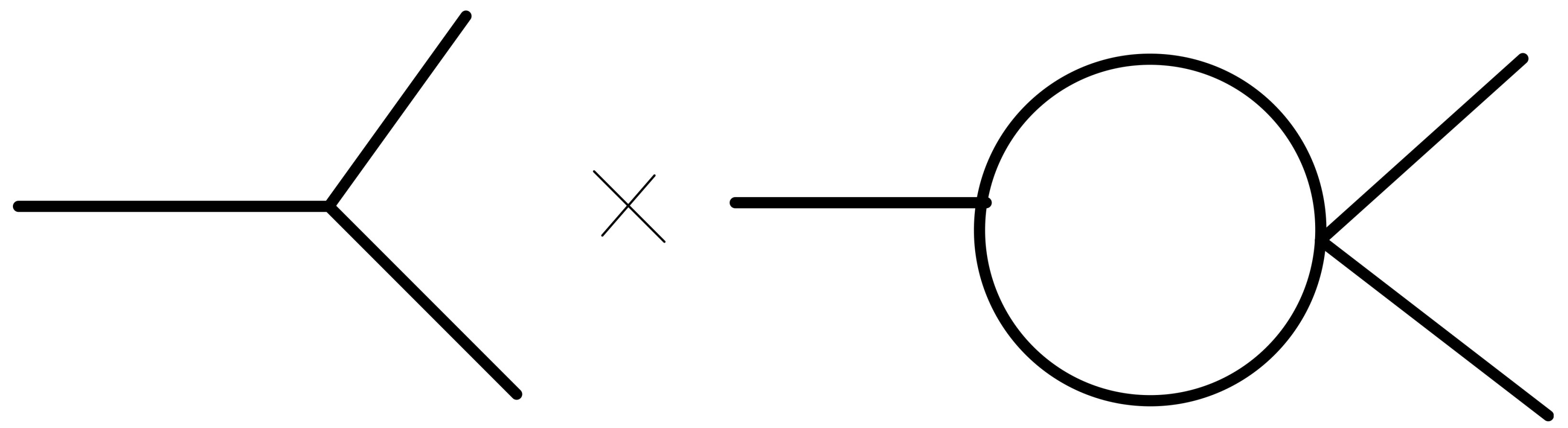
Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

$$\frac{dB}{dt}=[B,H_{\text{int}}]$$

2. Violate Charge and Charge-Parity

$$\Gamma(F_L^+\to f_L^+ + s)+\Gamma(F_R^+\to f_R^+ + s)$$
$$\neq \Gamma(F_L^-\to f_L^- + s)+\Gamma(F_R^-\to f_R^- + s)$$



$$\epsilon_{CP}\propto \text{Im}(c_t^* c_l)\text{Im}(\mathcal{A}_t^*\mathcal{A}_l)$$

How to make an asymmetry

Baryogenesis: $\Delta n_B(t=0)=0 \rightarrow \Delta n_B(t=t_0)\neq 0$

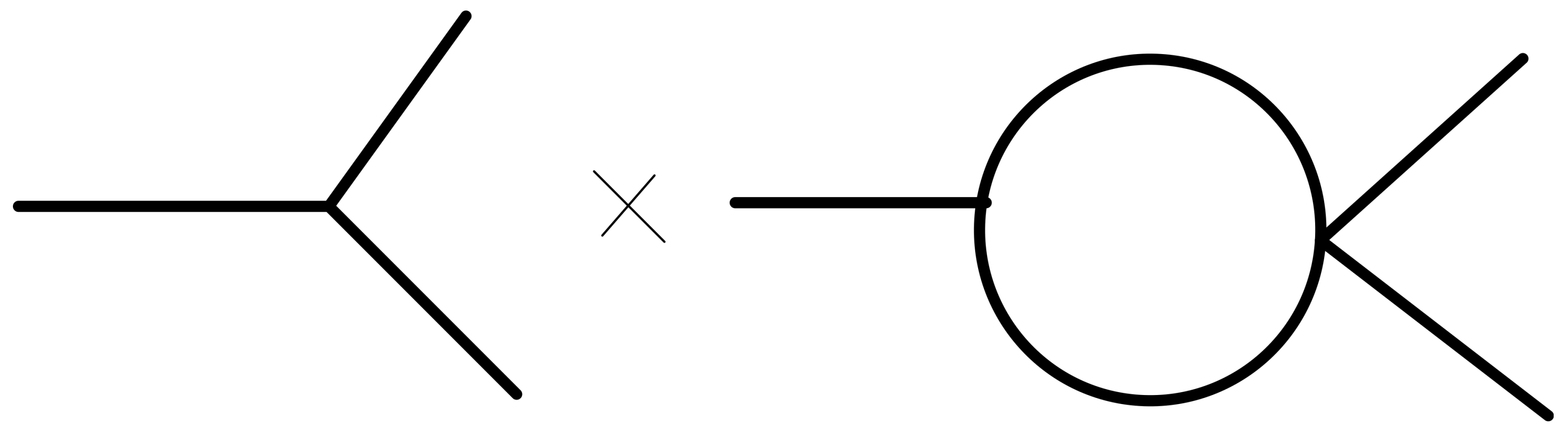
Interactions must satisfy three conditions [Sakharov, JETP Lett. 5, 24 (1967)]

1. Violate Baryon Number

$$\frac{dB}{dt}=[B,H_{\text{int}}]$$

2. Violate Charge and Charge-Parity

$$\Gamma(F_L^+ \to f_L^+ + s)+\Gamma(F_R^+ \to f_R^+ + s)$$
$$\neq \Gamma(F_L^- \to f_L^- + s)+\Gamma(F_R^- \to f_R^- + s)$$



$$\epsilon_{CP} \propto \text{Im}(c_t^* c_l)\text{Im}(\mathcal{A}_t^* \mathcal{A}_l)$$

3. Departure from Equilibrium

$$f_B^{\text{eq}}=f_{\bar{B}}^{\text{eq}}=\left[1\pm\exp\left(\sqrt{p^2+m_B^2}/T\right)\right]^{-1}$$

Asymmetric Dark Matter

Asymmetric Dark Matter

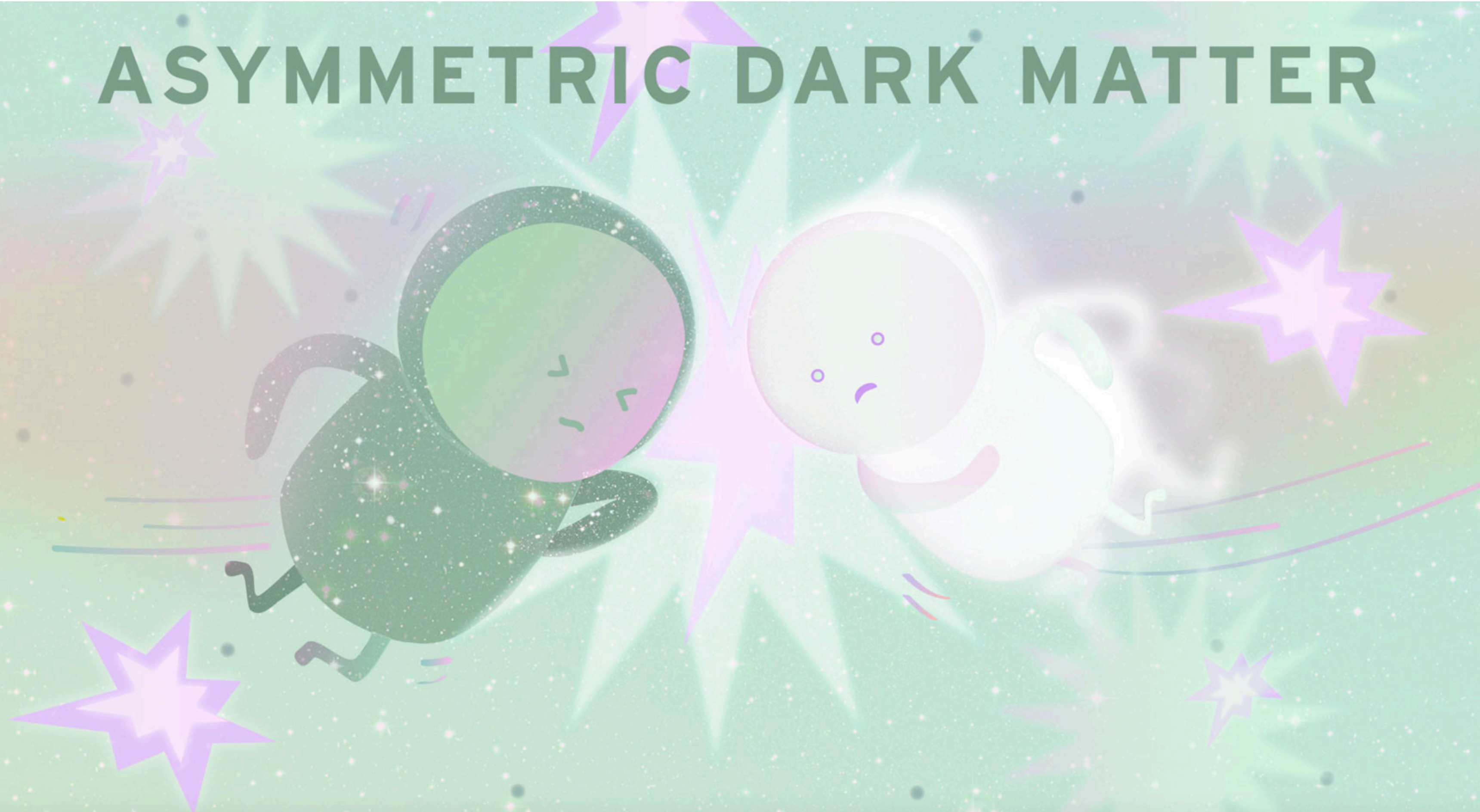
$$\left.\begin{array}{l}\Omega_{DM} \approx 0.1 \\ \Omega_B \approx 0.02\end{array}\right\} \Omega_{DM} \simeq 5\Omega_B$$

Asymmetric Dark Matter

$$\left.\begin{array}{l}\Omega_{DM} \approx 0.1 \\ \Omega_{B} \approx 0.02\end{array}\right\} \Omega_{DM} \simeq 5\Omega_{B} \Longrightarrow \text{New Physics?}$$

Asymmetric Dark Matter

$$\left.\begin{aligned}\Omega_{DM} &\approx 0.1\\ \Omega_B &\approx 0.02\end{aligned}\right\} \Omega_{DM} \simeq 5\Omega_B \Longrightarrow$$ New Physics?



$$\Omega_{ADM}/\Omega_B \simeq (Y_{ADM}/Y_B)(m_{ADM}/m_n)$$

Zurek, Phys. Rep. 2013; Petraki & Volkas Int. J. Mod.

Asymmetric Dark Matter

$$\left.\begin{array}{l}\Omega_{DM} \approx 0.1 \\ \Omega_B \approx 0.02\end{array}\right\} \Omega_{DM} \simeq 5\Omega_B \Longrightarrow \text{New Physics?}$$

Sharing vs. **Cogenesis**

$$\Omega_{ADM}/\Omega_B \simeq (Y_{ADM}/Y_B)(m_{ADM}/m_n)$$

Zurek, Phys. Rep. 2013; Petraki & Volkas Int. J. Mod.

Asymmetric Dark Matter

$$\left.\begin{array}{l}\Omega_{DM} \approx 0.1 \\ \Omega_B \approx 0.02\end{array}\right\} \Omega_{DM} \simeq 5\Omega_B \Longrightarrow \text{New Physics?}$$

Sharing vs. **Cogenesis**

Asymmetry is produced in dark or visible sector then transferred to other sector

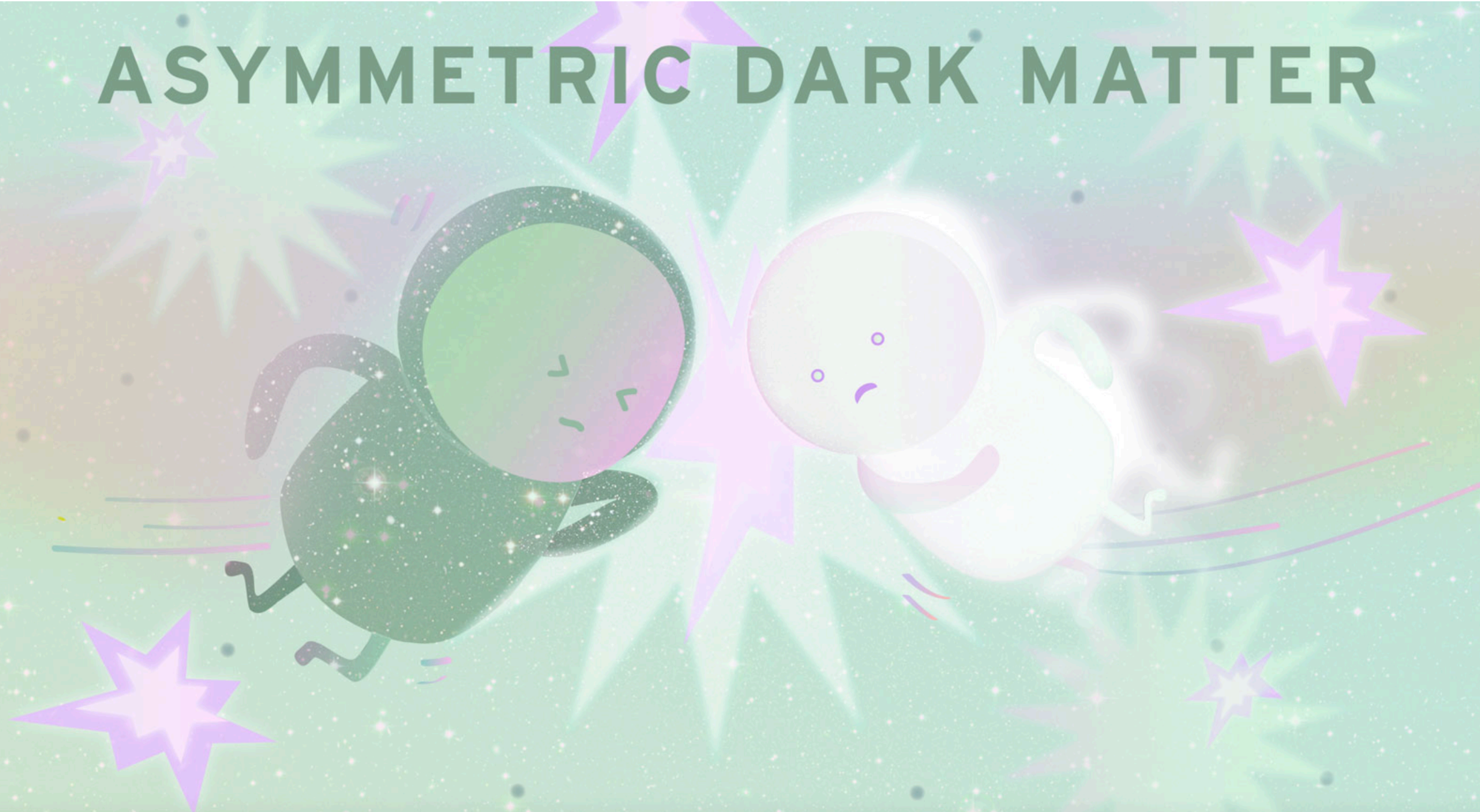
Shelton, Zurek, [1008.1997]; Buckley, Randall [1009.0270],….

$$\Omega_{ADM}/\Omega_B \simeq (Y_{ADM}/Y_B)(m_{ADM}/m_n)$$

Zurek, Phys. Rep. 2013; Petraki & Volkas Int. J. Mod.

Asymmetric Dark Matter

$$\left.\begin{array}{l}\Omega_{DM} \approx 0.1 \\ \Omega_B \approx 0.02\end{array}\right\} \Omega_{DM} \simeq 5\Omega_B \Longrightarrow \text{New Physics?}$$



Sharing vs. **Cogenesis**

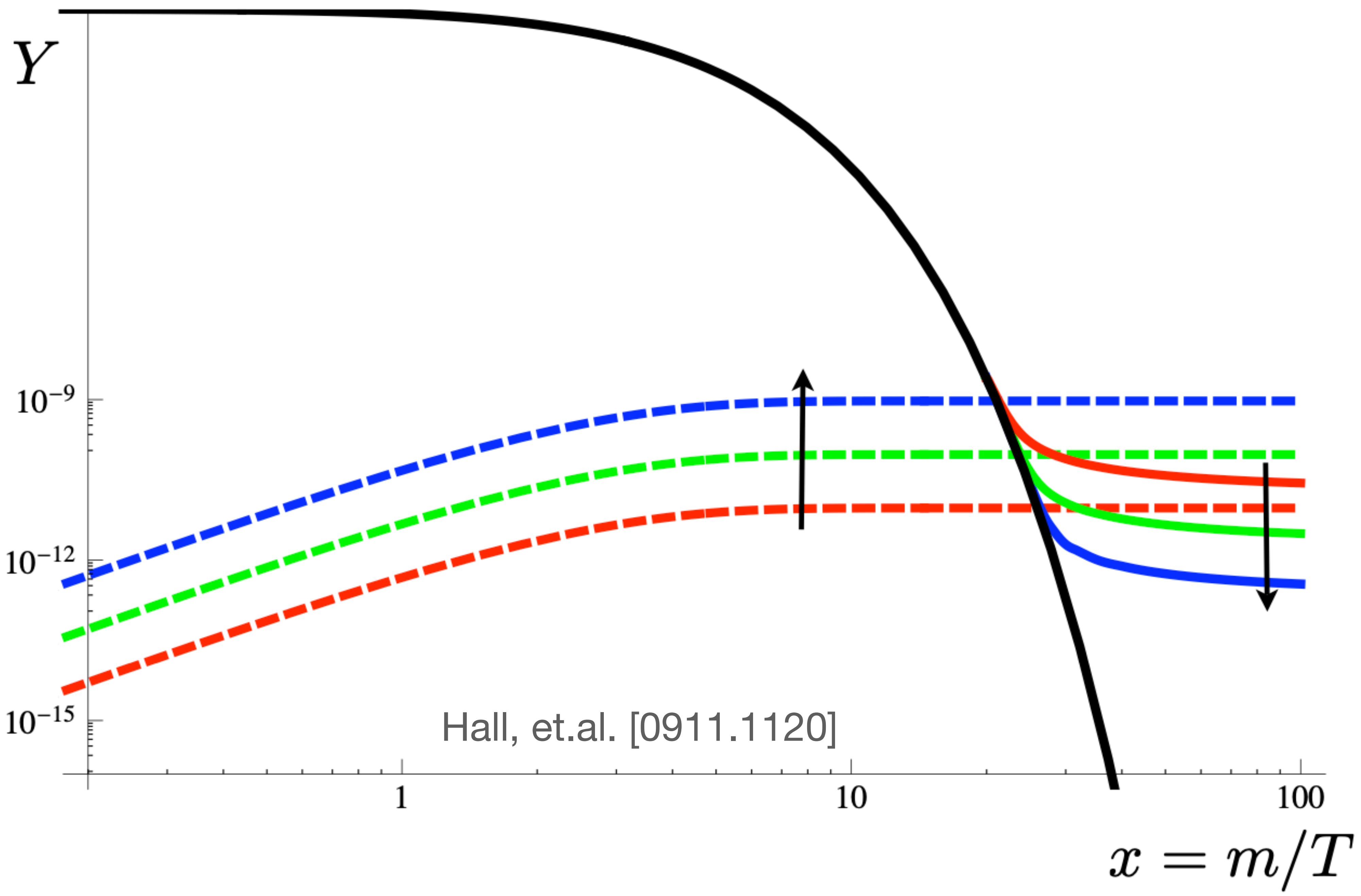
Asymmetry is produced in dark or visible sector then transferred to other sector
Shelton, Zurek, [1008.1997]; Buckley, Randall [1009.0270],….

Produce dark and visible asymmetries using the same processes or communal interactions
Hall+March-Russell+West [1010.0245], Unwin [1406.3027],…

$$\Omega_{ADM}/\Omega_B \simeq (Y_{ADM}/Y_B)(m_{ADM}/m_n)$$

Zurek, Phys. Rep. 2013; Petraki & Volkas Int. J. Mod.

Freeze-out vs. Freeze-in



Freeze-out

DM is thermal relic, density set by annihilation (generally):

$n_{DM}\langle\sigma_{\text{ann}}|\vec{v}|\rangle \lesssim H \implies Y_{DM} \propto \langle\sigma_{\text{ann}}|\vec{v}|\rangle^{-1} \sim m_w^2/g_w^4$

Freeze-in

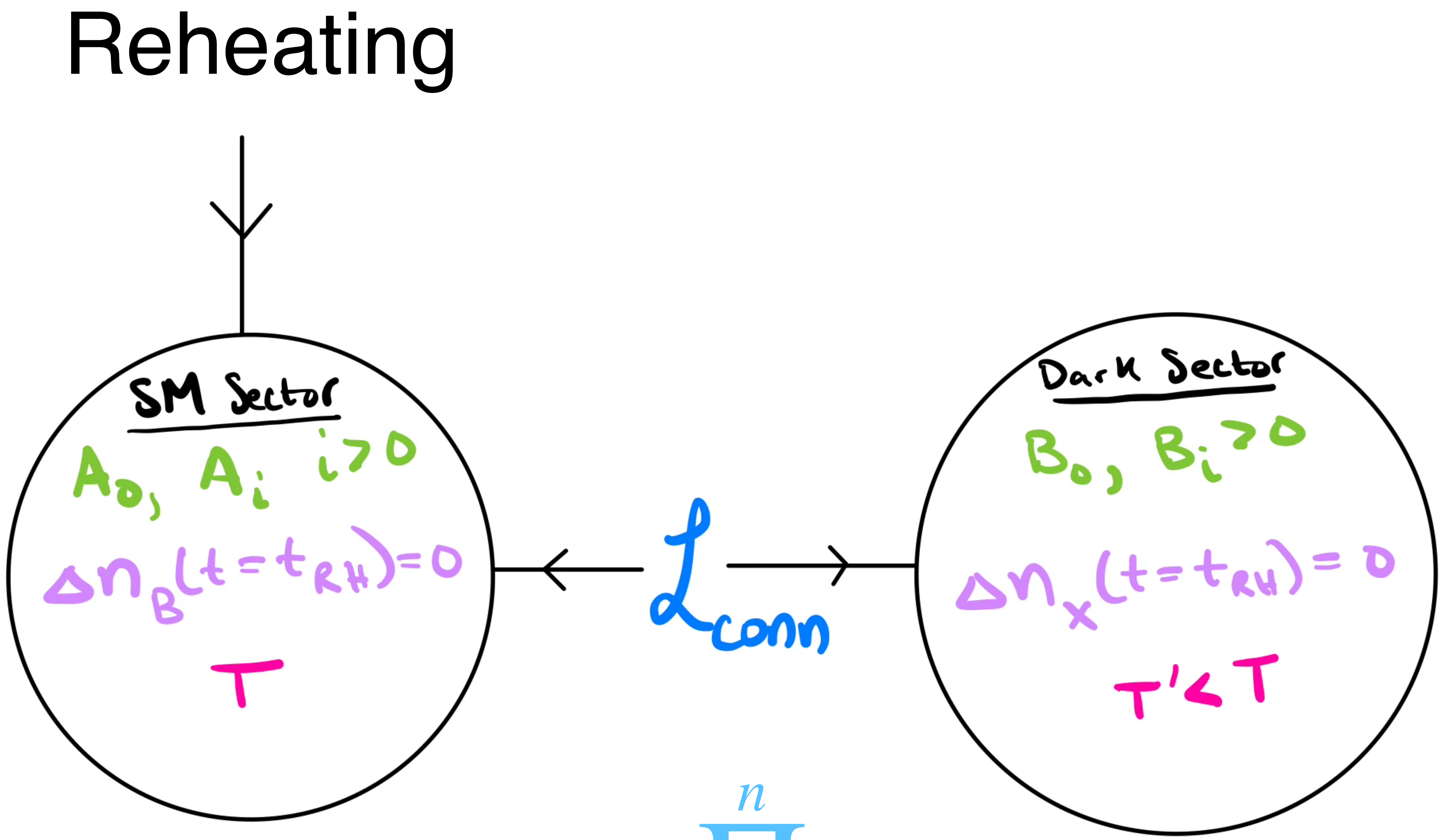
$Y_{DM}(t=0) \simeq 0$, DM has feeble interactions with the bath

Dominant DM production at $T \lesssim m_B$

DM freezes-in with abundance increasing with coupling

Asymmetric Freeze-in?

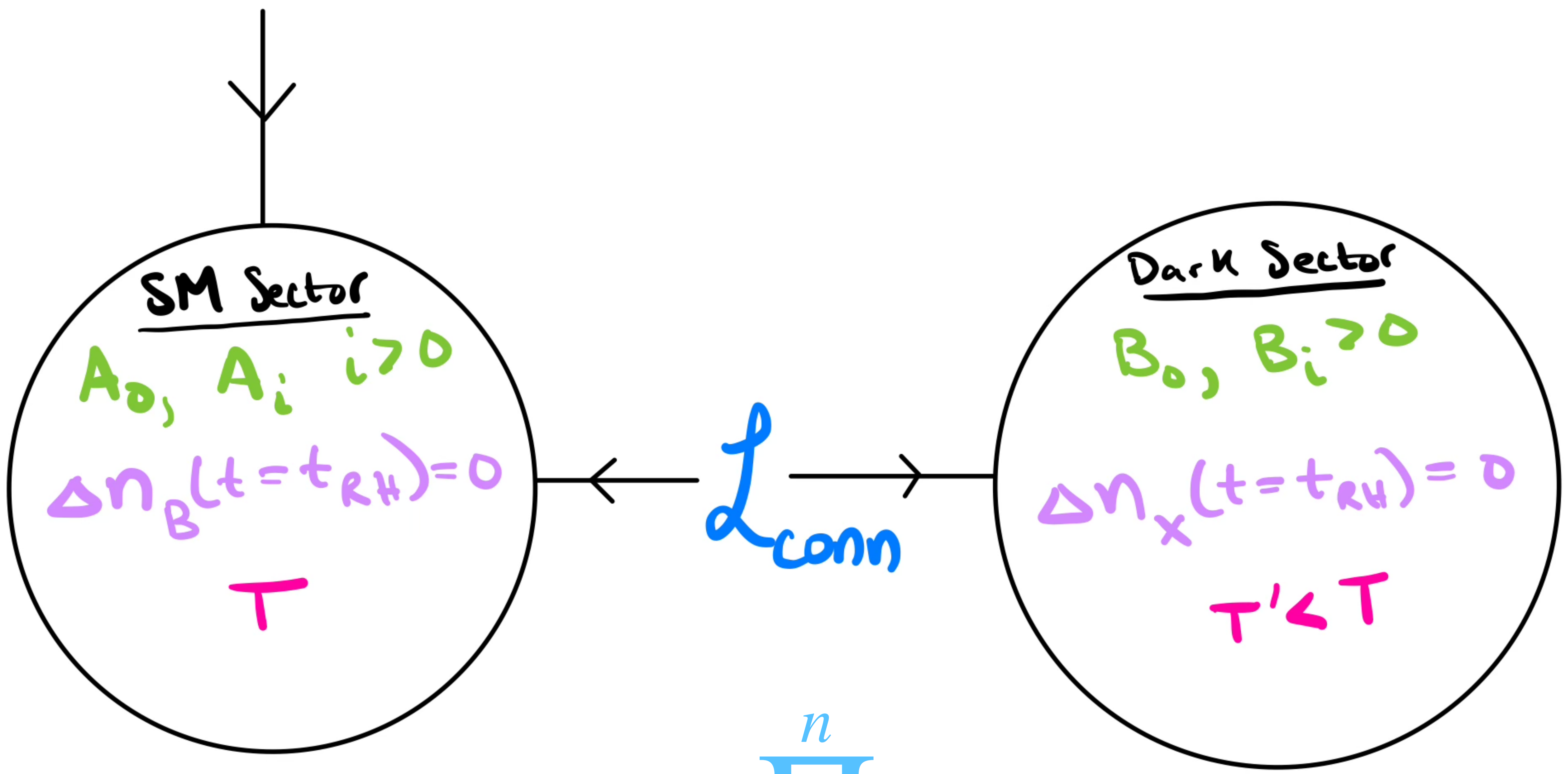
Asymmetric Freeze-in?



$$\mathscr{L}_{\text{conn}} \supset \lambda \prod_{i,j=0}^{n} A_i B_j$$

Asymmetric Freeze-in?

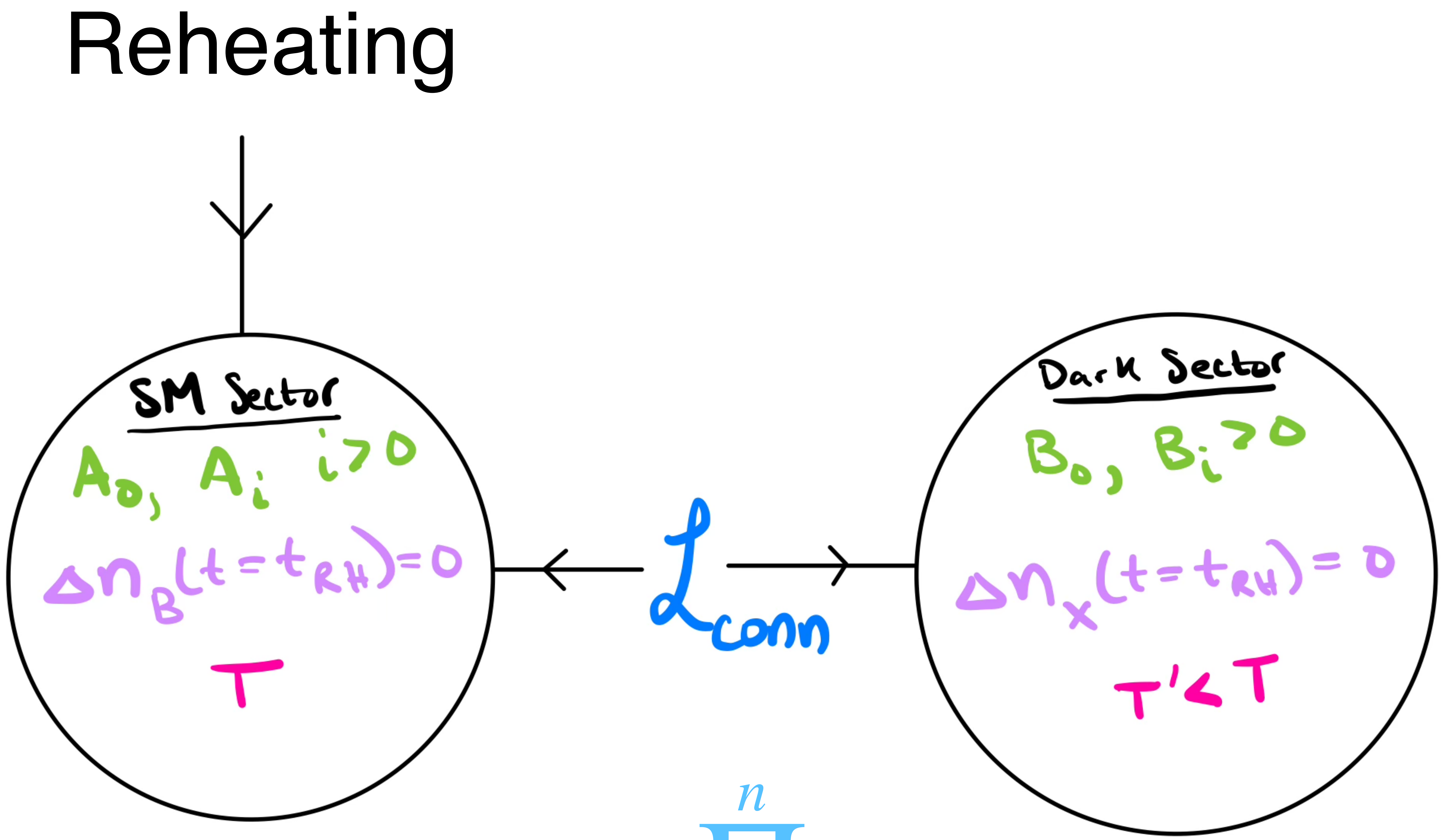
Reheating



$\mathscr{L}_{\text{conn}} \supset \lambda \prod_{i,j=0}^{n} A_i B_j$

$\mathscr{L}_{\text{conn}}$ ensures minimal transfer of energy between sectors ($0 < T' < T$)

Asymmetric Freeze-in?



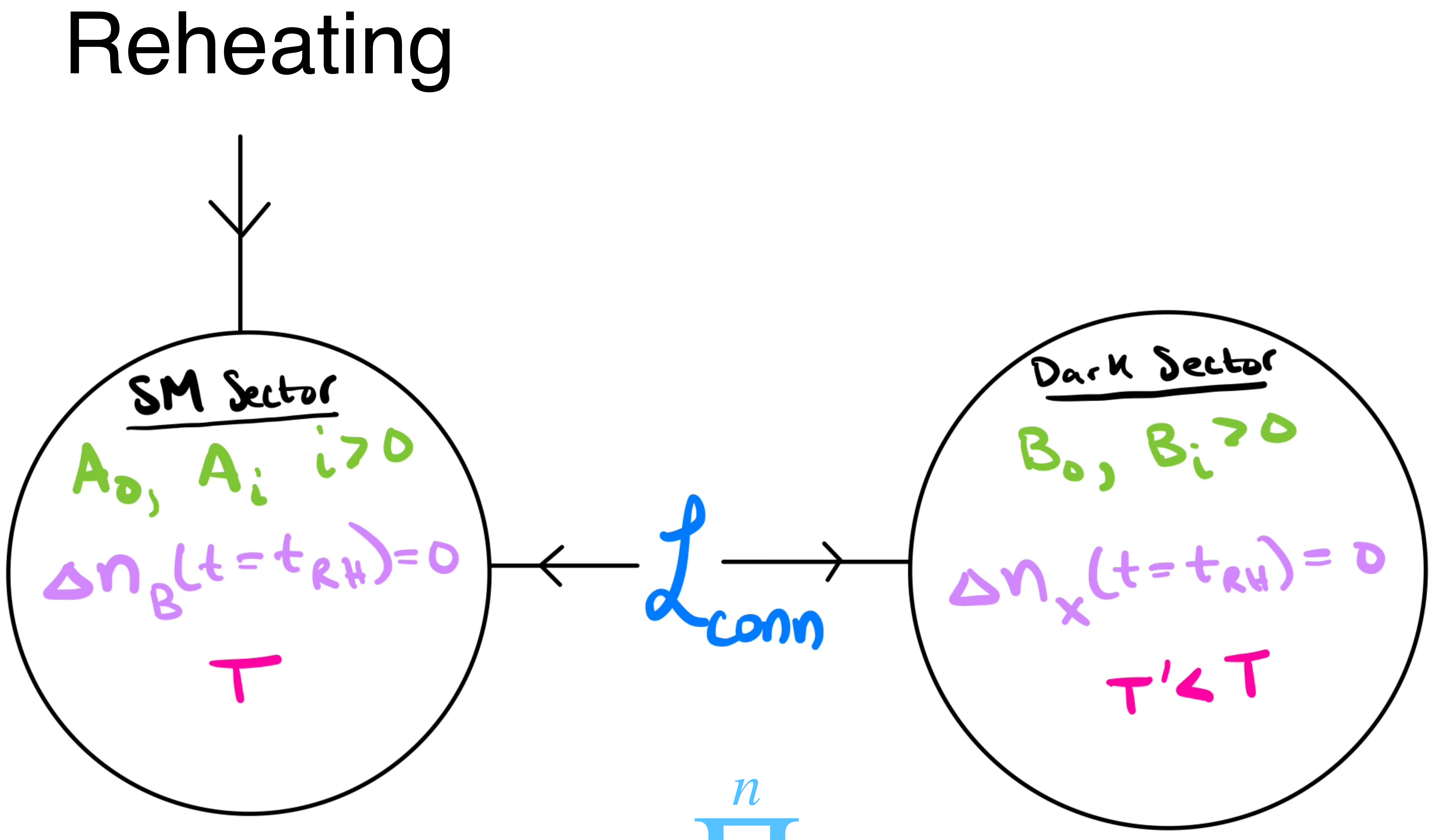
$$\mathscr{L}_{\text{conn}} \supset \lambda \prod_{i,j=0}^{n} A_i B_j$$

$\mathscr{L}_{\text{conn}}$ ensures minimal transfer of energy between sectors ($0 < T' < T$)

Small λ ensures the sectors do not equilibrate with one another

Hall, March-Russell, West [1010.0245]

Asymmetric Freeze-in?



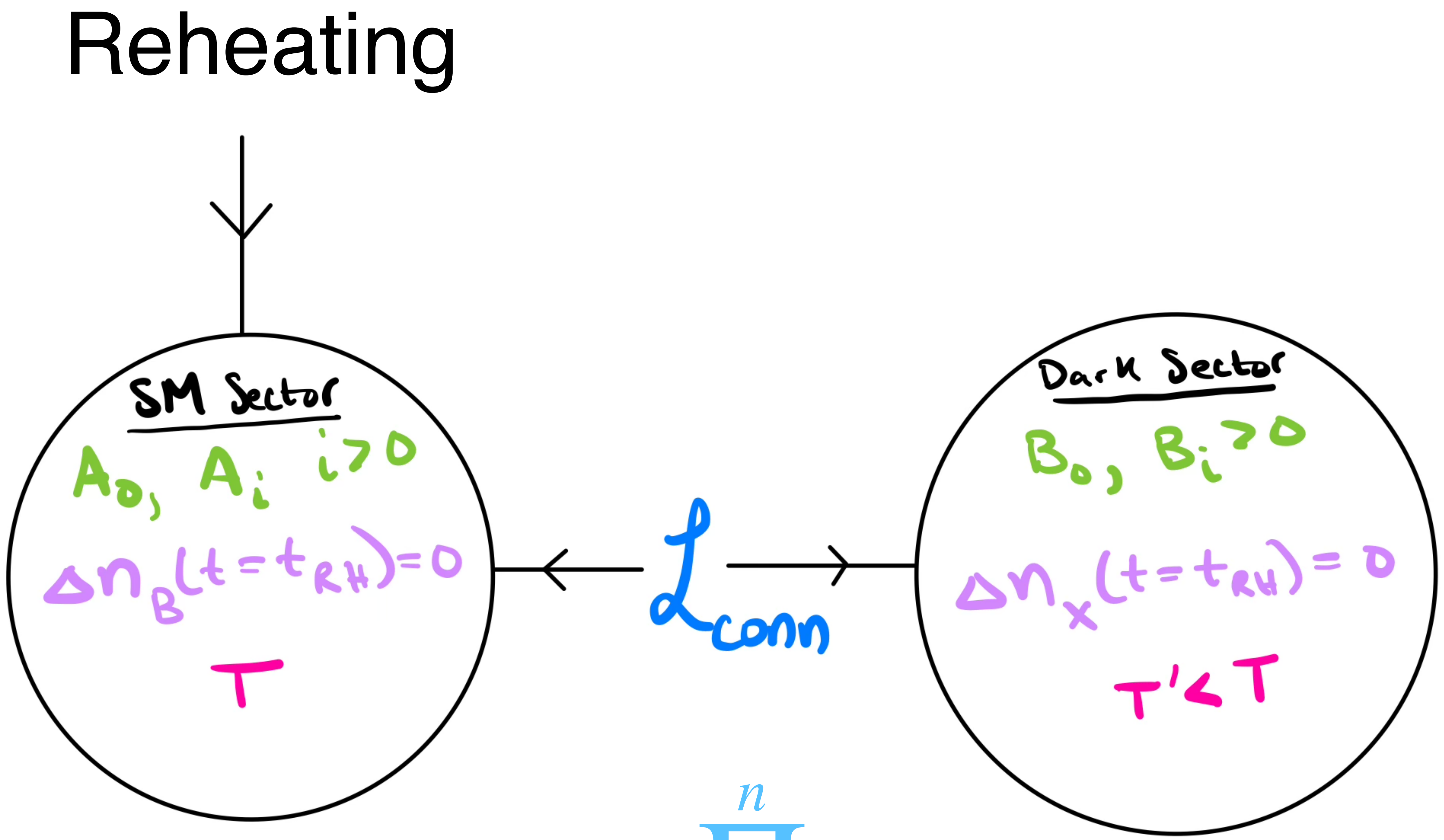
$$\mathscr{L}_{\text{conn}} \supset \lambda \prod_{i,j=0}^{n} A_i B_j$$

$\mathscr{L}_{\text{conn}}$ ensures minimal transfer of energy between sectors ($0 < T' < T$)

Small λ ensures the sectors do not equilibrate with one another
Hall, March-Russell, West [1010.0245]

$\lambda \ll 1 \implies$ depleting the symmetric component difficult

Asymmetric Freeze-in?



$$\mathscr{L}_{\rm conn} \supset \lambda \prod_{i,j=0}^{n} A_i B_j$$

$\mathscr{L}_{\rm conn}$ ensures minimal transfer of energy between sectors ($0 < T' < T$)

Small λ ensures the sectors do not equilibrate with one another
Hall, March-Russell, West [1010.0245]

$\lambda \ll 1 \implies$ depleting the symmetric component difficult

$\mathscr{L}_{\rm conn}$ transforms under $B-L$ and X but if total is conserved, CPT and Unitarity require asymmetries vanish at leading order in λ Hook [1105.3728]; Unwin [1406.3027]; Baldes, et. al. [1407.4566];

Additional States and Interactions

NLO in λ: CP can be violated if there are additional processes with differing particle number!

Model:

$$\mathscr{L} = -y_i L \cdot H N_i - \lambda_i \chi \phi N_i - M_i N_i N_i + \text{h.c.},\ i = 1,2$$

Field Content:

SM Fields: LH lepton L, Higgs doublet H

SM singlets: Majorana N_i, Dirac χ, complex scalar ϕ

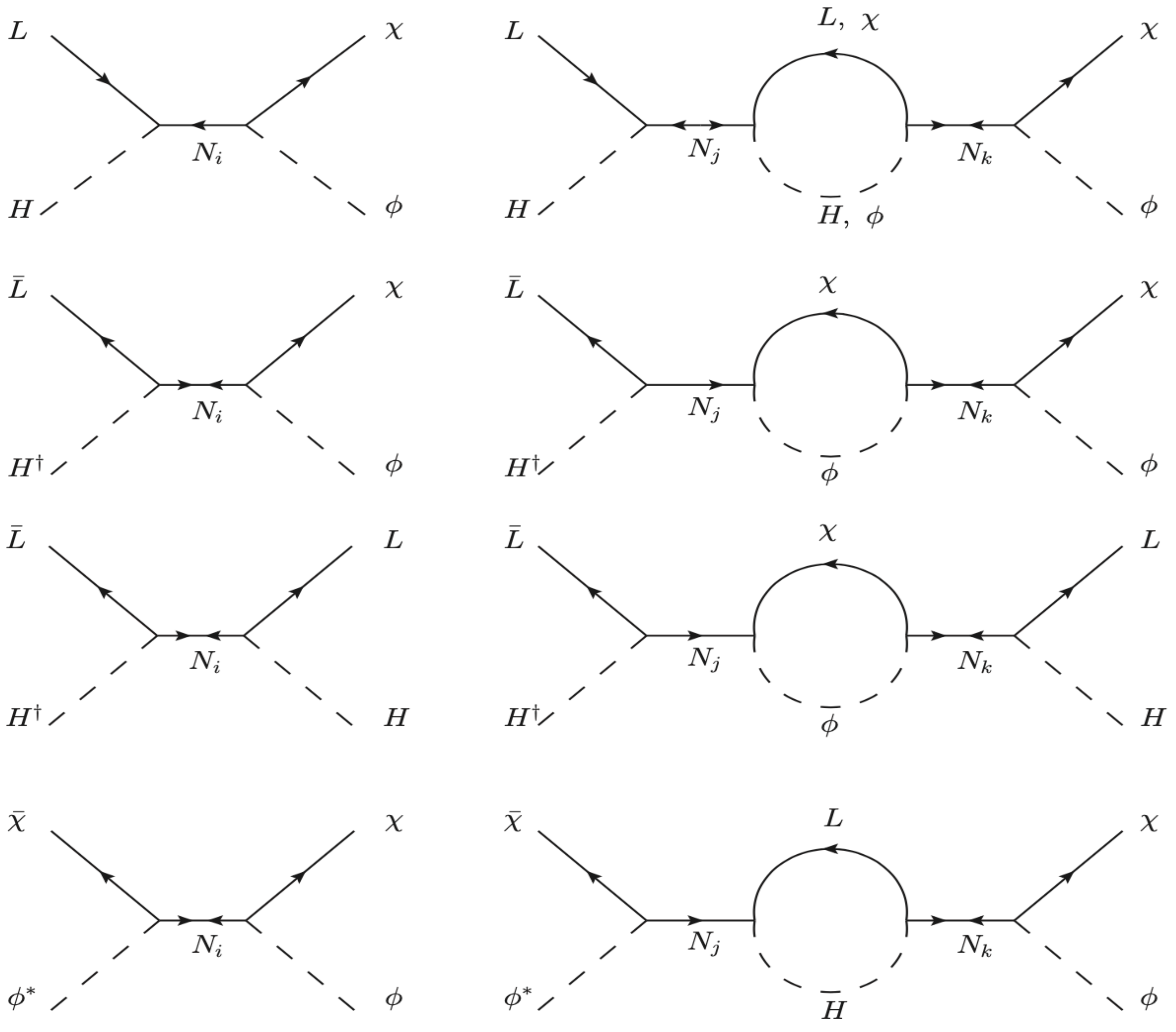
Lepton Number: $L_\phi = -(1 - L_\chi)$

Cosmology:

Assume the universe reheats to SM only and $m_{N_i} > 5\ T_{\text{RH}} > m_\chi, m_\phi \ldots N_i$ never produced on-shell (Dirac ν version see Blažek, et. al. [2404.16934])

With $m_\phi > m_\chi$, dark hypercharge ensures χ is stable… DM?

Freeze-in Asymmetries



UV Freeze-in: Dark sector frozen in and establishes (minimum) dark temperature

$\xi_\chi \equiv T_\chi / T \neq 1$

CP Violation: CP Asymmetries ensured through the introduction of χ, ϕ and m_N

χ, ϕ sector out of equilibrium $\Longrightarrow$

$f_L f_H \neq f_\chi f_\phi$

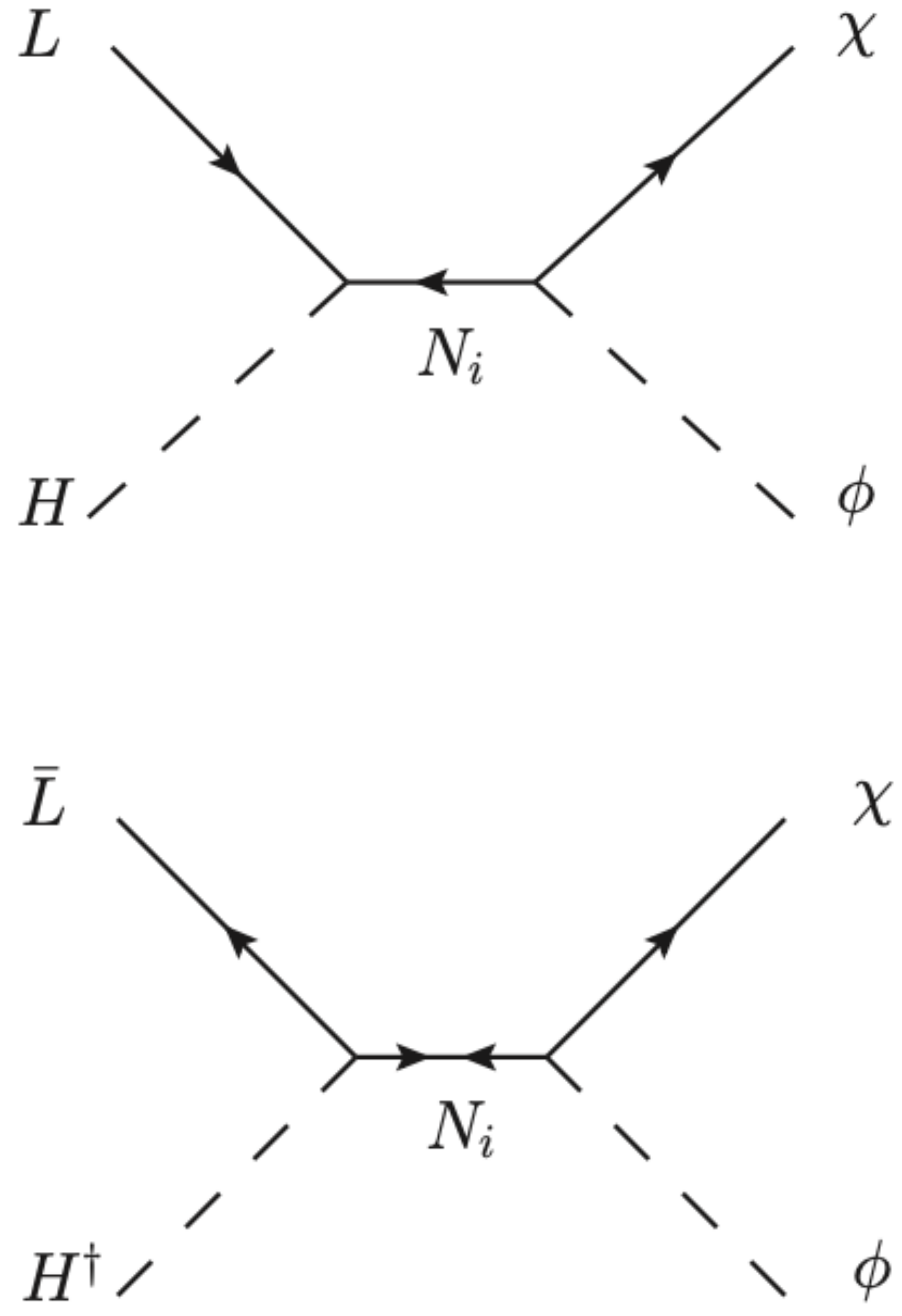
Net asymmetry can be produced!

Energy Transfer

Energy Transfer: Processes such as $LH \to \chi\phi$ transfer energy into dark sector, establish T_χ…

$$\xi_\chi^3 \frac{d\xi_\chi}{dT} = -\frac{150 m_{\rm Pl}\sigma_0}{1.66 g_*^{1/2}(2\pi)^5}\left[\left(1-\xi_\chi^7\right)F_1(m_i, y_i, \lambda_i) + \frac{35T^2}{4m_1^2}\left(1-\xi_\chi^9\right)F_2(m_i, y_i, \lambda_i)\right]$$

Sakharov conditions require $T_\chi \neq T$ for non-vanishing asymmetries to arise

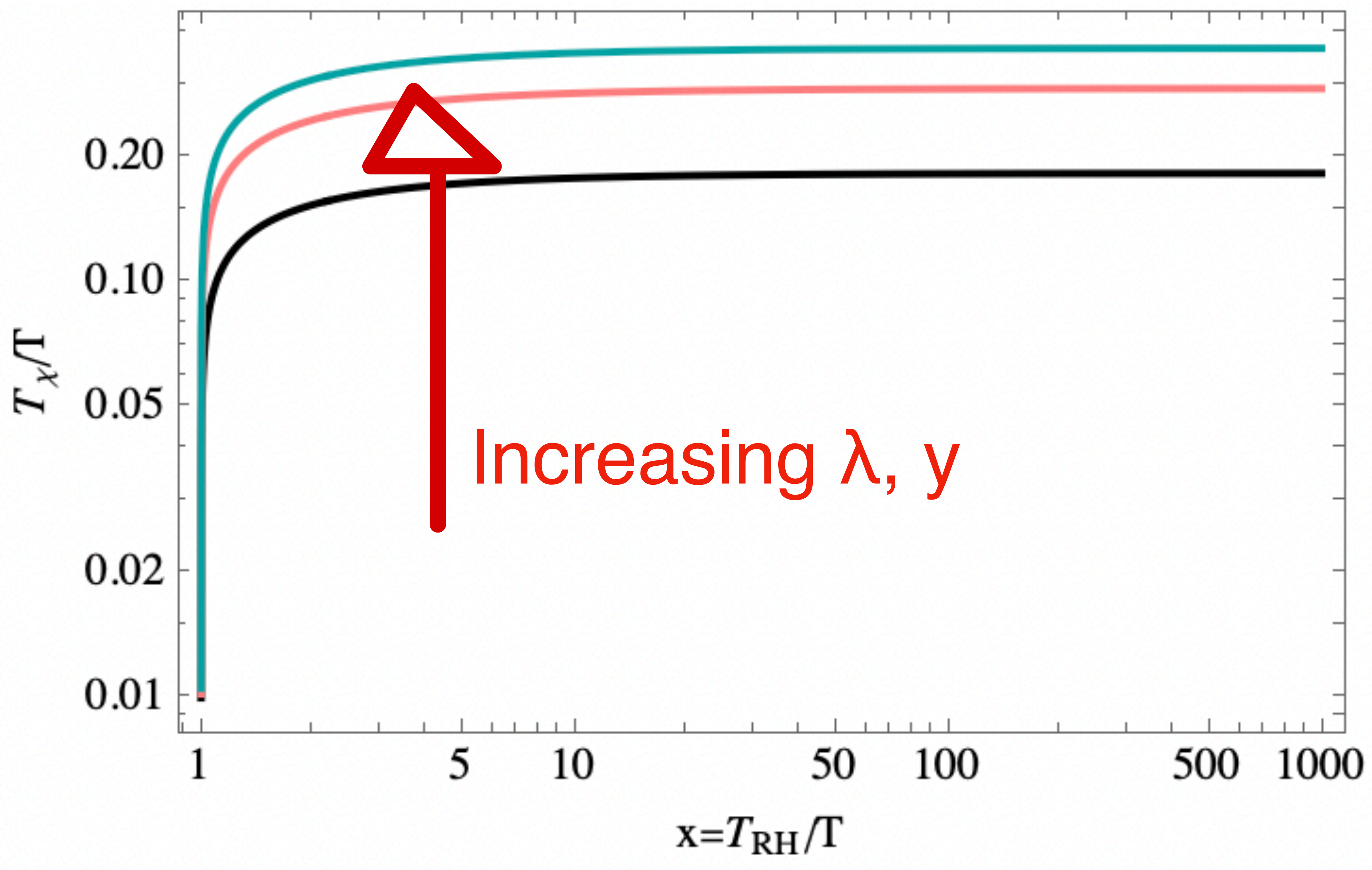


Energy Transfer

Energy Transfer: Processes such as $LH \to \chi\phi$ transfer energy into dark sector, establish T_χ…

$$\xi_\chi^3 \frac{d\xi_\chi}{dT} = -\frac{150 m_{\rm Pl}\sigma_0}{1.66 g_*^{1/2}(2\pi)^5}\left[\left(1-\xi_\chi^7\right)F_1(m_i, y_i, \lambda_i) + \frac{35T^2}{4m_1^2}\left(1-\xi_\chi^9\right)F_2(m_i, y_i, \lambda_i)\right]$$

Sakharov conditions require $T_\chi \neq T$ for non-vanishing asymmetries to arise

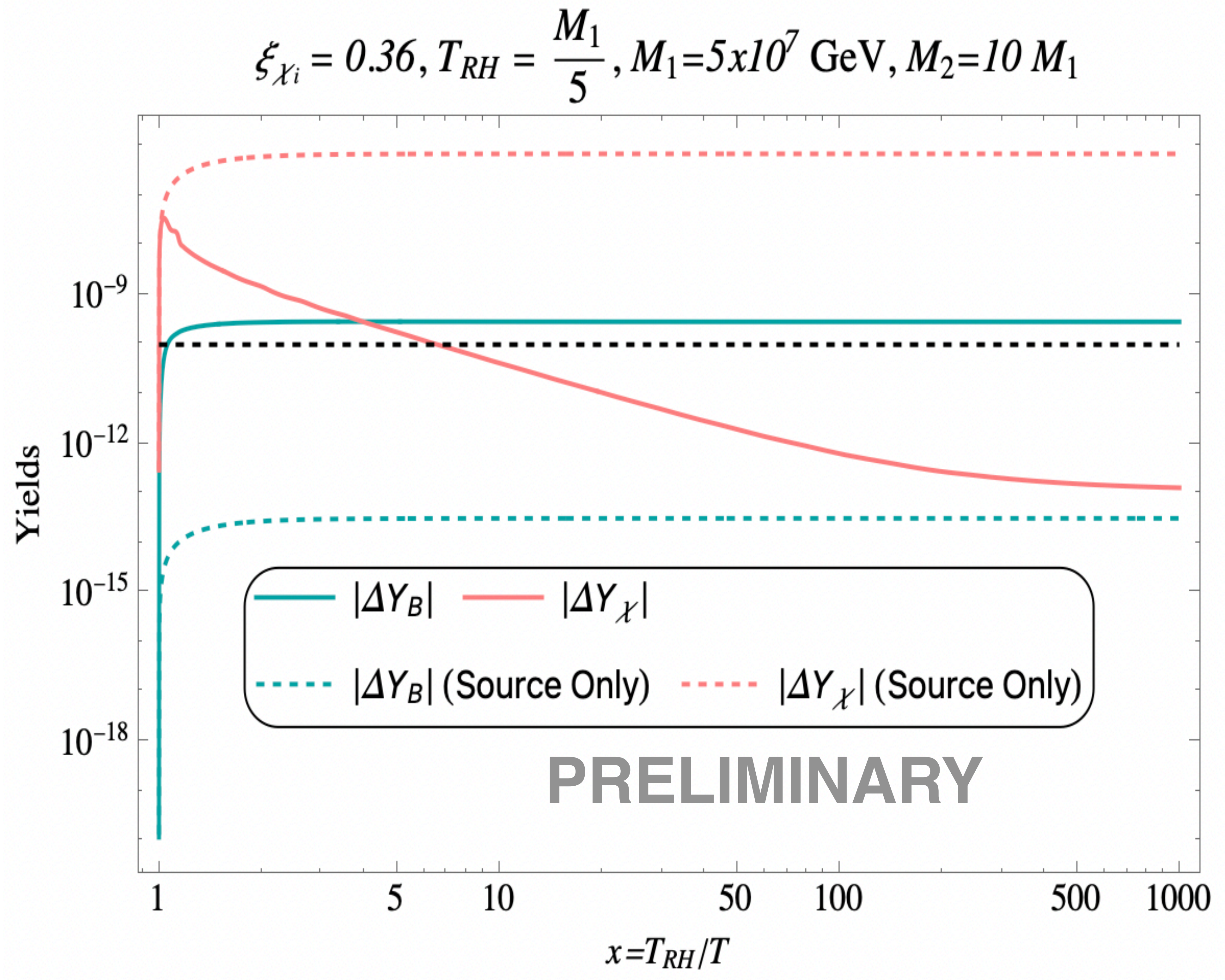


Freeze-in Cogenesis of Heavy ADM

Asymmetry Generation: Determined by asymmetries $\epsilon_{L,\chi}$ in scattering processes, mediated by $N_{1,2}$

$$\frac{d\Delta Y_L}{dx} \propto (1-\xi_\chi^8)\epsilon_L x^{-4}, \quad \frac{d\Delta Y_\chi}{dx} \propto (1-\xi_\chi^8)\epsilon_\chi x^{-4}$$

+Wash-out and Wash-in Terms



ADM mass: fixed by the asymmetries

Sphalerons convert lepton asymmetry to baryon asymmetry

$$\Delta Y_B = c_s \Delta Y_L \implies \Omega_{ADM}/\Omega_B = c_s^{-1}(Y_{ADM}/\Delta Y_L)(m_\chi/m_p) \implies$$

$$m_\chi \approx 5c_s(\Delta Y_L/\Delta Y_\chi)m_p \approx 5 \text{ TeV}$$

Symmetric Component?

Symmetric Component: A large symmetric component is also frozen in at tree-level

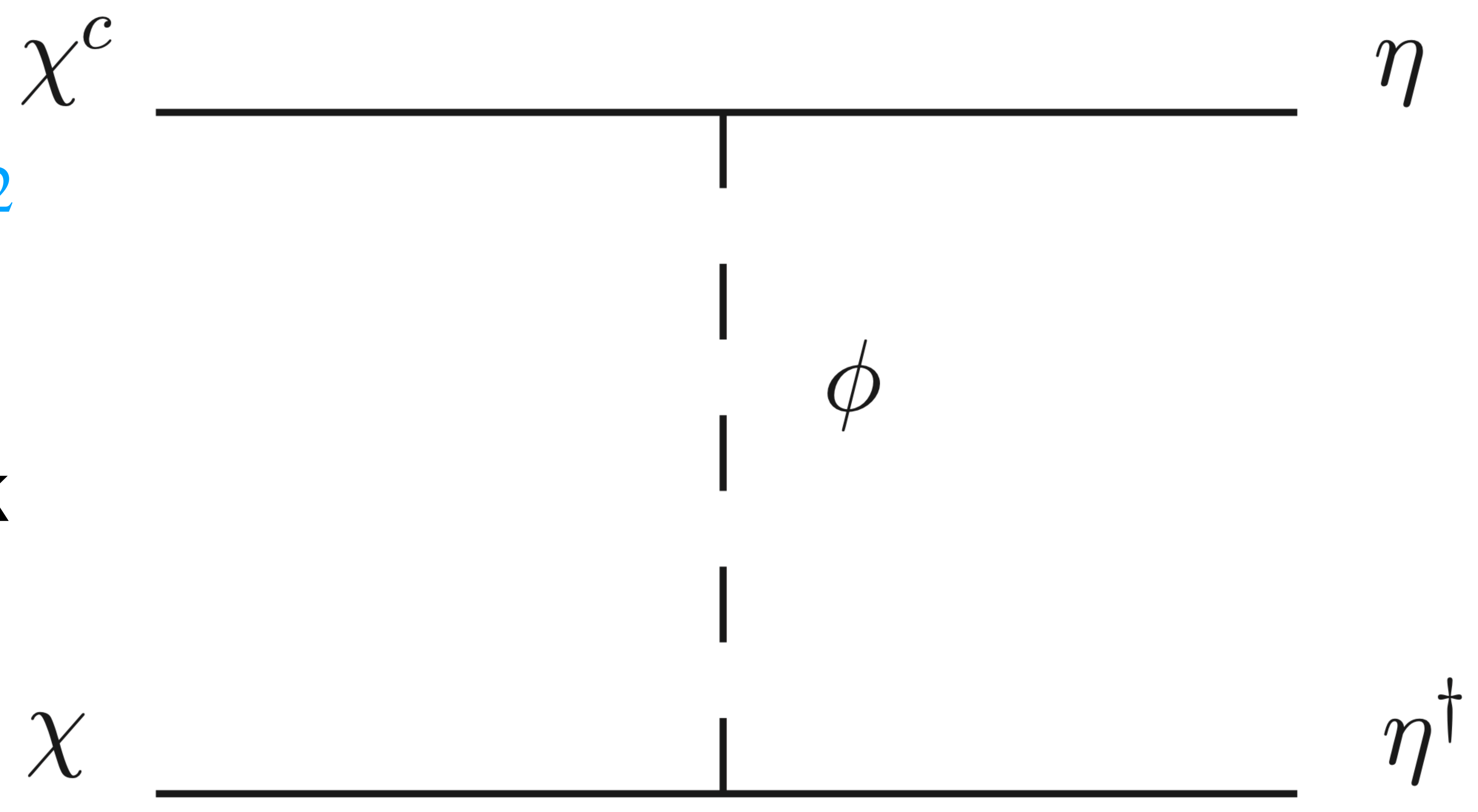
$$\frac{d\Sigma Y_\chi}{dx} \propto (1-\xi_\chi^8)\sigma(LH \to \chi\phi)x^{-4} + (1-\xi_\chi^6)\sigma(\bar{L}H^\dagger \to \chi\phi)x^{-2}$$

Depletion: Transfer symmetric component into a dark sink

Bhattiprolu et. al. [2312.43152]

Introduce a single flavor of massless fermions

$$\mathscr{L} = -\kappa\phi\chi^c\eta + \mathrm{h.c.}$$



Takeaways

Theoretical constraints with freezing-in asymmetric dark matter: no CPV

Caveat: particle number violation permits CP Violation even with (separately) equilibrated dark sector

Can freeze-in sufficient lepton and dark asymmetry via scattering when $T_{\rm RH} < m_N$

Wash-in/Wash-out play a key role! Give rise to $\Delta Y_L \gg \Delta Y_\chi \Longrightarrow m_{\rm ADM} \gg m_p$

Lots of things I didn't get to, happy to answer questions!

Takeaways

Theoretical constraints with freezing-in asymmetric dark matter: no CPV

Caveat: particle number violation permits CP Violation even with (separately) equilibrated dark sector

Can freeze-in sufficient lepton and dark asymmetry via scattering when $T_{\rm RH} < m_N$

Wash-in/Wash-out play a key role! Give rise to $\Delta Y_L \gg \Delta Y_\chi \Longrightarrow m_{\rm AD}$

Lots of things I didn't get to, happy to answer questions!

Thank You!

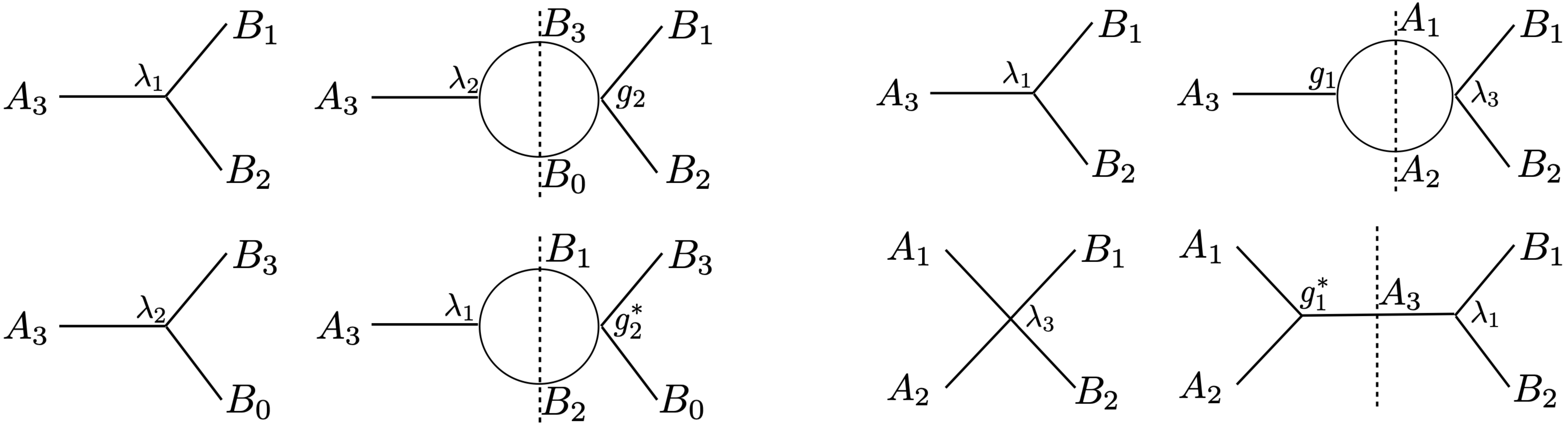
Backup

Asymmetric Freeze-in

Model:

$$\mathscr{L}_{\text{conn}} \supset \lambda_1 A_3 B_1^\dagger B_2^\dagger + \lambda_2 A_3 B_3^\dagger B_0^\dagger + \lambda_3 A_1 A_2 B_1^\dagger B_2^\dagger + \lambda_4 A_1 A_2 B_0^\dagger B_3^\dagger + g_1 A_3 A_1^\dagger A_2^\dagger + g_2 B_3 B_0 B_1^\dagger B_2^\dagger$$

Hook [1105.3728]

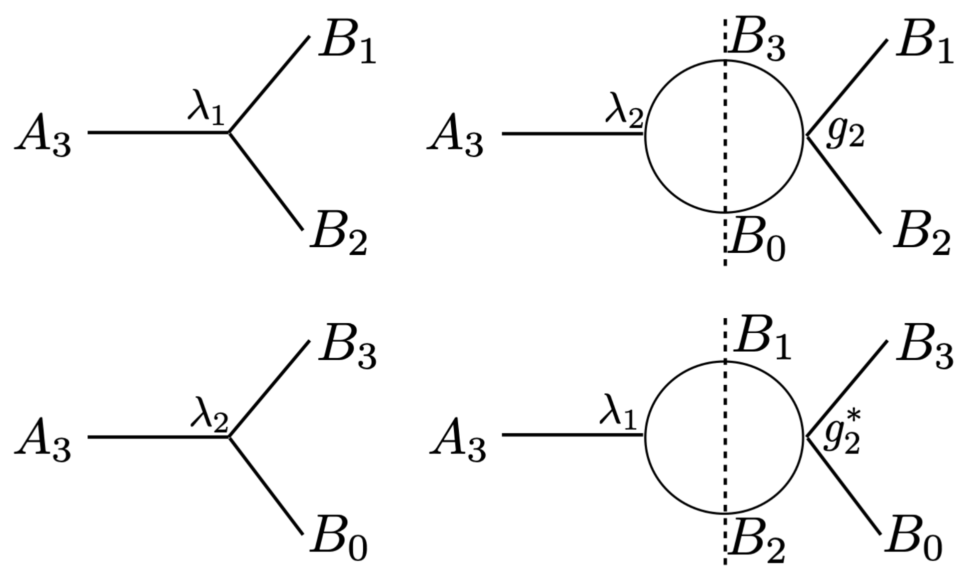


Asymmetric Freeze-in

Cancellation is required by CPT and unitarity Hook [1105.3728]

Asymmetric Freeze-in

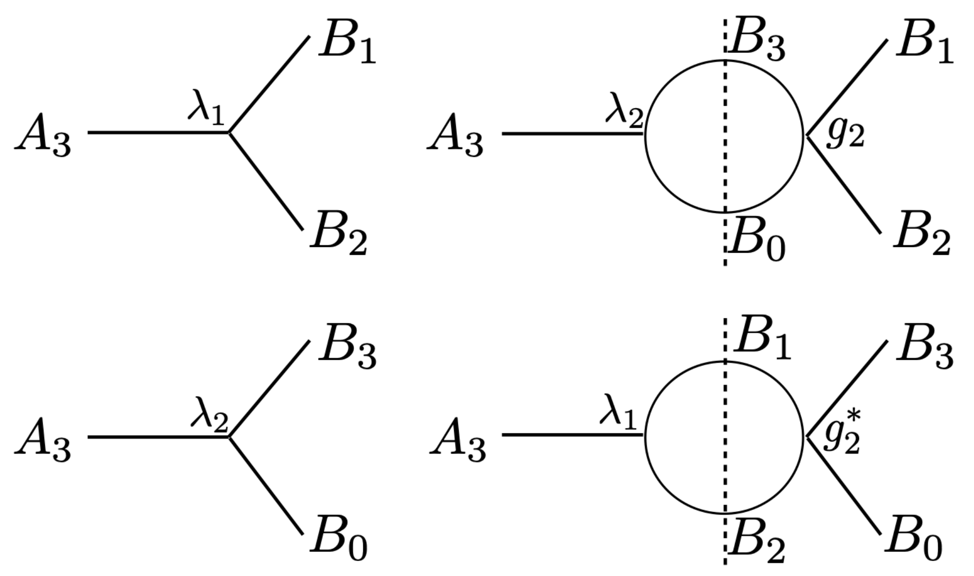
Cancellation is required by CPT and unitarity Hook [1105.3728]



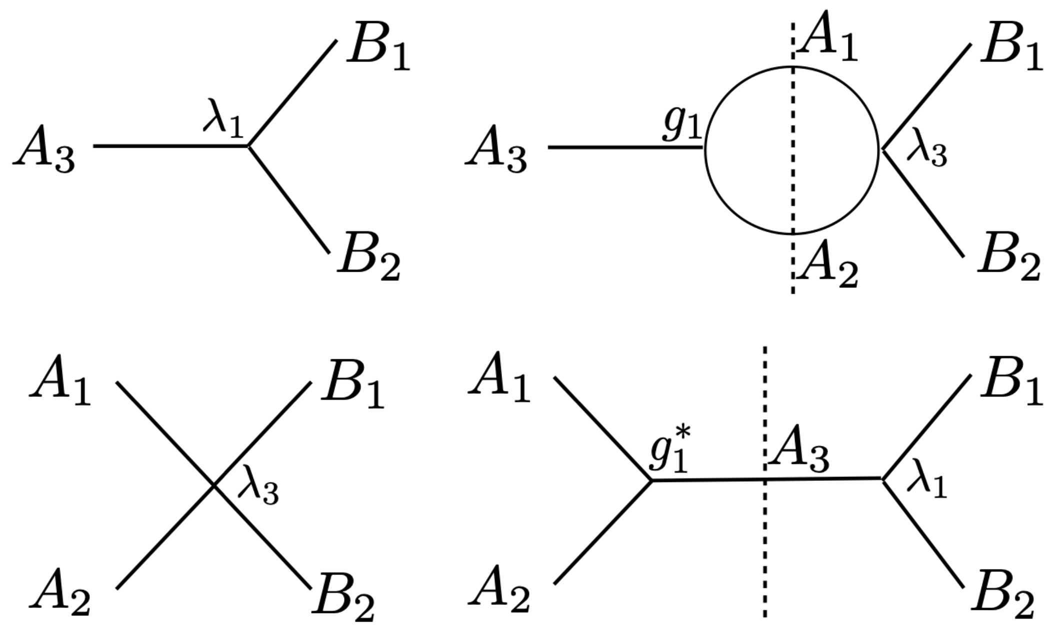
$$\Longrightarrow \frac{\dot{n}_{A_3\to B_1+B_2}}{\dot{n}_{A_3\to B_0+B_3}} = \frac{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1\lambda_2^*g_2^*)f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})}{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1^*\lambda_2 g_2)f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})} = -1$$

Asymmetric Freeze-in

Cancellation is required by CPT and unitarity Hook [1105.3728]



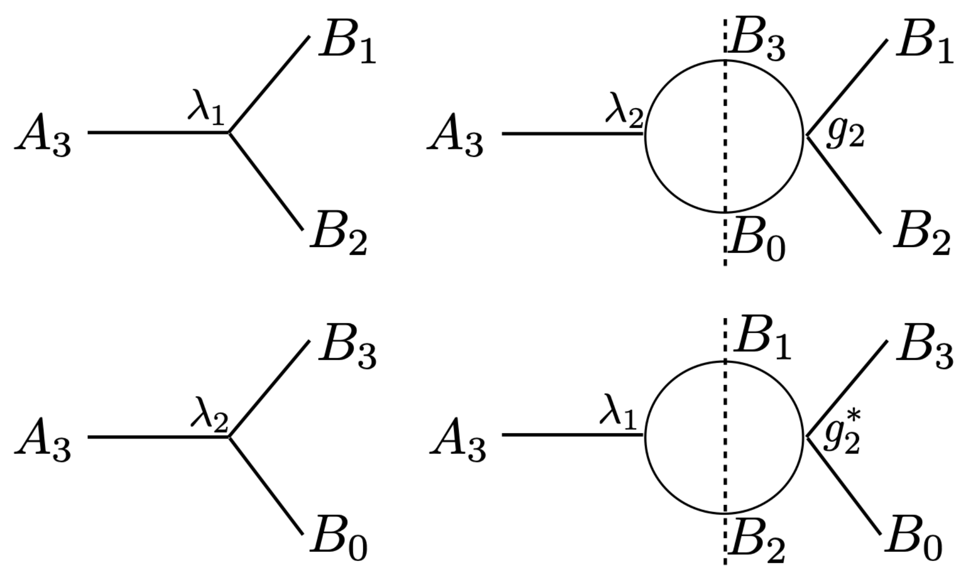
$$\Longrightarrow \frac{\dot{n}_{A_3\to B_1+B_2}}{\dot{n}_{A_3\to B_0+B_3}} = \frac{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1\lambda_2^* g_2^*) f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})}{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1^*\lambda_2 g_2) f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})} = -1$$



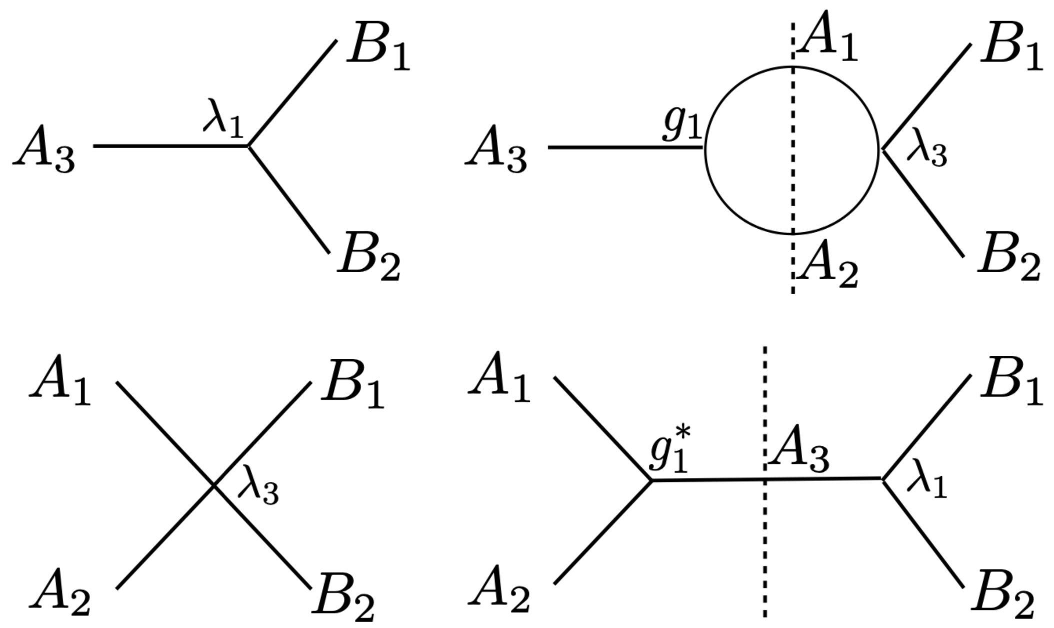
$$\Longrightarrow \frac{\dot{n}_{A_3\to B_1+B_2}}{\dot{n}_{A_1+A_2\to B_0+B_3}} = \frac{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1\lambda_3^* g_1^*) f_{A_3}(1\pm f_{A_1})(1\pm f_{A_2})(1\pm f_{B_1})(1\pm f_{B_2})}{\int \Pi \mathrm{Im}(\mathscr{A}_0^*\mathscr{A}_1)\mathrm{Im}(\lambda_1^*\lambda_3 g_1) f_{A_1} f_{A_2}(1\pm f_{A_3})(1\pm f_{B_1})(1\pm f_{B_2})}$$

Asymmetric Freeze-in

Cancellation is required by CPT and unitarity Hook [1105.3728]



$$\Longrightarrow \frac{\dot{n}_{A_3\to B_1+B_2}}{\dot{n}_{A_3\to B_0+B_3}} = \frac{\int \Pi \mathrm{Im}(\mathcal{A}_0^*\mathcal{A}_1)\mathrm{Im}(\lambda_1\lambda_2^* g_2^*) f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})}{\int \Pi \mathrm{Im}(\mathcal{A}_0^*\mathcal{A}_1)\mathrm{Im}(\lambda_1^*\lambda_2 g_2) f_{A_3}(1\pm f_{B_1})(1\pm f_{B_2})(1\pm f_{B_0})(1\pm f_{B_3})} = -1$$



$$\Longrightarrow \frac{\dot{n}_{A_3\to B_1+B_2}}{\dot{n}_{A_1+A_2\to B_0+B_3}} = \frac{\int \Pi \mathrm{Im}(\mathcal{A}_0^*\mathcal{A}_1)\mathrm{Im}(\lambda_1\lambda_3^* g_1^*) f_{A_3}(1\pm f_{A_1})(1\pm f_{A_2})(1\pm f_{B_1})(1\pm f_{B_2})}{\int \Pi \mathrm{Im}(\mathcal{A}_0^*\mathcal{A}_1)\mathrm{Im}(\lambda_1^*\lambda_3 g_1) f_{A_1} f_{A_2}(1\pm f_{A_3})(1\pm f_{B_1})(1\pm f_{B_2})}$$

$A_3 \to A_1 + A_2$ enforces

$$f_{A_1} f_{A_2}(1\pm f_{A_3}) = f_{A_3}(1\pm f_{A_1})(1\pm f_{A_2})$$

Unitarity and CPT

Unitarity$\Longrightarrow$

$$\sum_f |\mathscr{M}(i \to f)|^2 = \sum_f |\mathscr{M}(f \to i)|^2$$ Hook [1105.3728]; Unwin [1406.3027]; Baldes, et. al. [1407.4566];

Collision terms$\Longrightarrow$

$$\mathscr{C} = \sum_f \int \ldots \int d\Pi_{i_1} \ldots d\Pi_{i_n} d\Pi_{f_1} \ldots d\Pi_{f_m} \delta^4\left(\sum_{i=1}^{n} p_i - \sum_{j=1}^{m} p_j\right)(2\pi)^4 \{f_{i_1} \ldots f_{i_n} |\mathscr{M}(i \to f)|^2 - f_{f_1} \ldots f_{f_m} |\mathscr{M}(f \to i)|^2\}$$

Equilibrium$\Longrightarrow$ $f_{i_1} \ldots f_{i_n} = f_{f_1} \ldots f_{f_m}$

Cancellation in equilibrium as required by the third Sakharov condition

Unitarity and CPT

Unitarity$\Longrightarrow$

$$\sum_f |\mathcal{M}(i \to f)|^2 = \sum_f |\mathcal{M}(f \to i)|^2$$ Hook [1105.3728]; Unwin [1406.3027]; Baldes, et. al. [1407.4566];

Equilibrium$\Longrightarrow f_{i_1} \ldots f_{i_n} = f_{f_1} \ldots f_{f_m}$

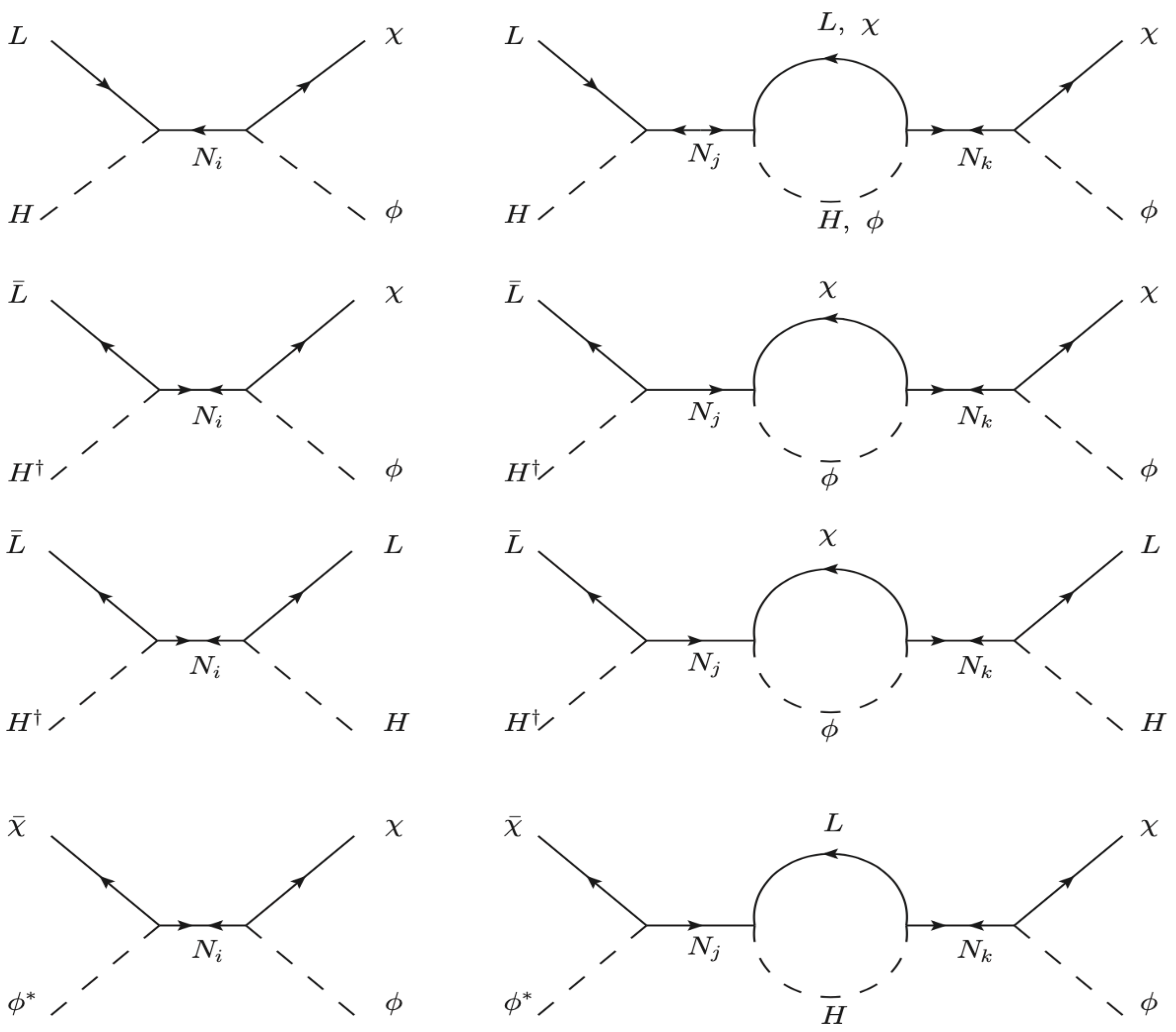
Example: LHN **(single flavor)**

Unitarity$\Longrightarrow$ $|\mathcal{M}(LH \to \bar{L}H^\dagger)|^2 - |\mathcal{M}(\bar{L}H^\dagger \to LH)|^2 = 0$

Equilibrium$\Longrightarrow$ $f_L f_H = f_{\bar{L}} f_{H^\dagger}$

To violate CP and produce asymmetry, need: more on-shell states+departure from equilibrium

Freeze-in Cogenesis of ADM



Freeze-in: Dark sector frozen in and establishes (minimum) dark temperature

$$\xi_\chi \equiv T_\chi / T$$

CP Violation: CP Asymmetries ensured through the introduction of χ, ϕ and m_N

CPT+Unitarity:

$$\epsilon(\chi\phi^* \to \bar{\chi}\phi) \equiv \epsilon_\chi = -\left[\epsilon(LH^\dagger \to \chi\phi^*) + \epsilon(\bar{L}H \to \chi\phi^*)\right]$$

$$\epsilon(LH^\dagger \to \bar{L}H) \equiv \epsilon_L = \left[\epsilon(LH^\dagger \to \chi\phi^*) - \epsilon(\bar{L}H \to \chi\phi^*)\right]$$

Unitarity and CPT

Unitarity $\Longrightarrow$

$$|\mathscr{M}(\chi\phi \to \bar{\chi}\phi^*)|^2 - |\mathscr{M}(\bar{\chi}\phi^* \to \chi\phi)|^2$$
$$+|\mathscr{M}(\chi\phi \to LH)|^2 - |\mathscr{M}(\bar{\chi}\phi^* \to \bar{L}H^\dagger)|^2$$
$$+|\mathscr{M}(\chi\phi \to \bar{L}H^\dagger)|^2 - |\mathscr{M}(\bar{\chi}\phi^* \to LH)|^2 = 0$$

Collision terms $\Longrightarrow$

$$\mathscr{C}_{\Delta\chi} \supset \int d\Pi_L d\Pi_H d\Pi_\chi d\Pi_\phi \delta^4(p_L + p_H - p_\chi - p_\phi)(2\pi)^4$$
$$\times \left[\left(f_L^{\text{eq}} f_H^{\text{eq}} - f_\chi^{\text{eq}} f_\phi^{\text{eq}} \right) \left(|\mathscr{M}(LH \to \chi\phi)|^2 - |\mathscr{M}(\bar{L}H^\dagger \to \bar{\chi}\phi^*)|^2 + |\mathscr{M}(LH \to \bar{\chi}\phi^*)|^2 - |\mathscr{M}(\bar{L}H^\dagger \to \chi\phi)|^2 \right) \right] + \ldots$$

$\chi,\ \phi$ sector out of equilibrium $\Longrightarrow f_L f_H \neq f_\chi f_\phi$ **Net asymmetry can be produced!**