Freeze-in Cogenesis of Asymmetric Dark Matter

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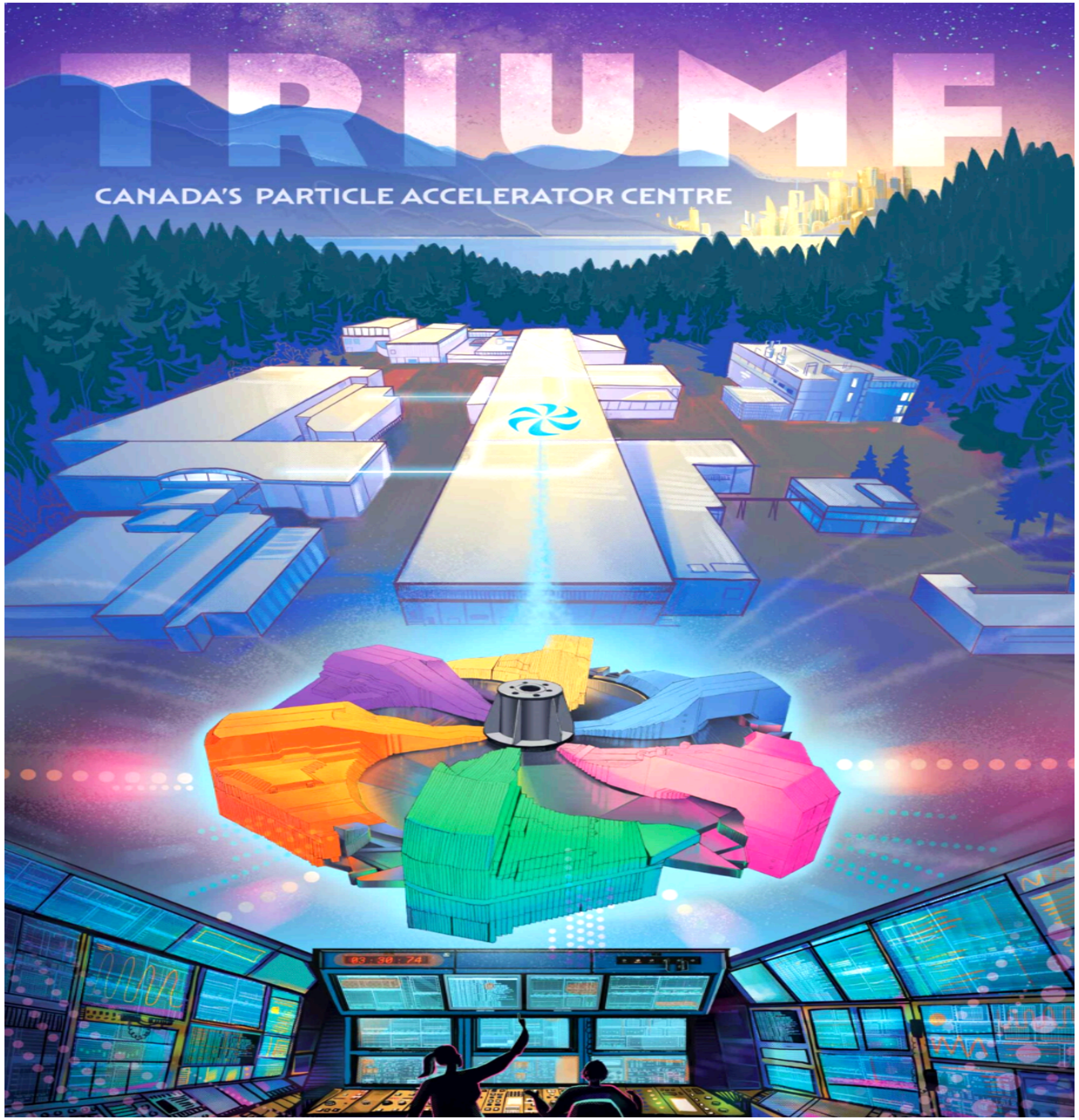
With P. Asadi (Oregon), M. Moore (MIT), D. Morrissey (TRIUMF)
hep-ph/2406.xxxxx



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Asymmetric Dark Matter

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

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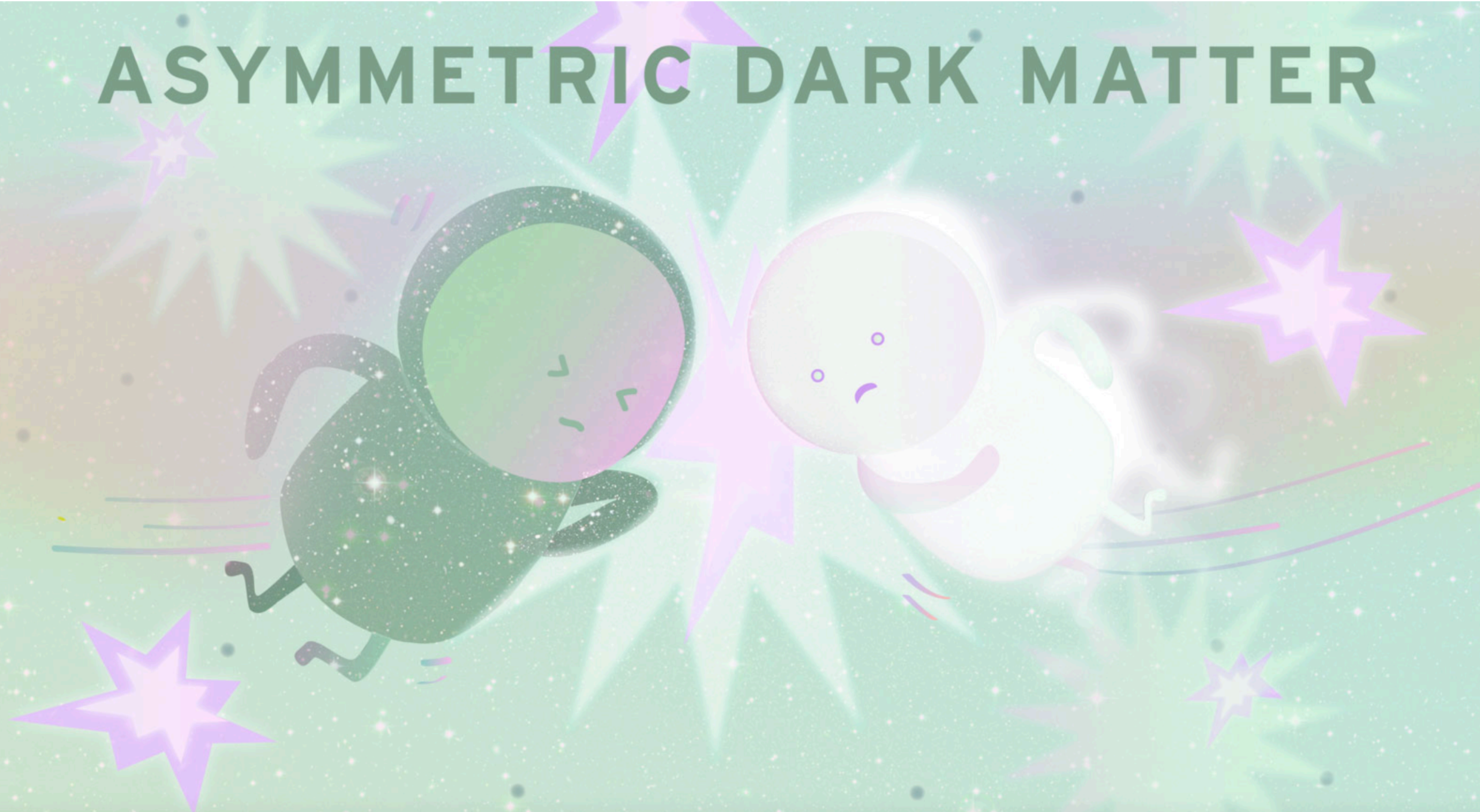

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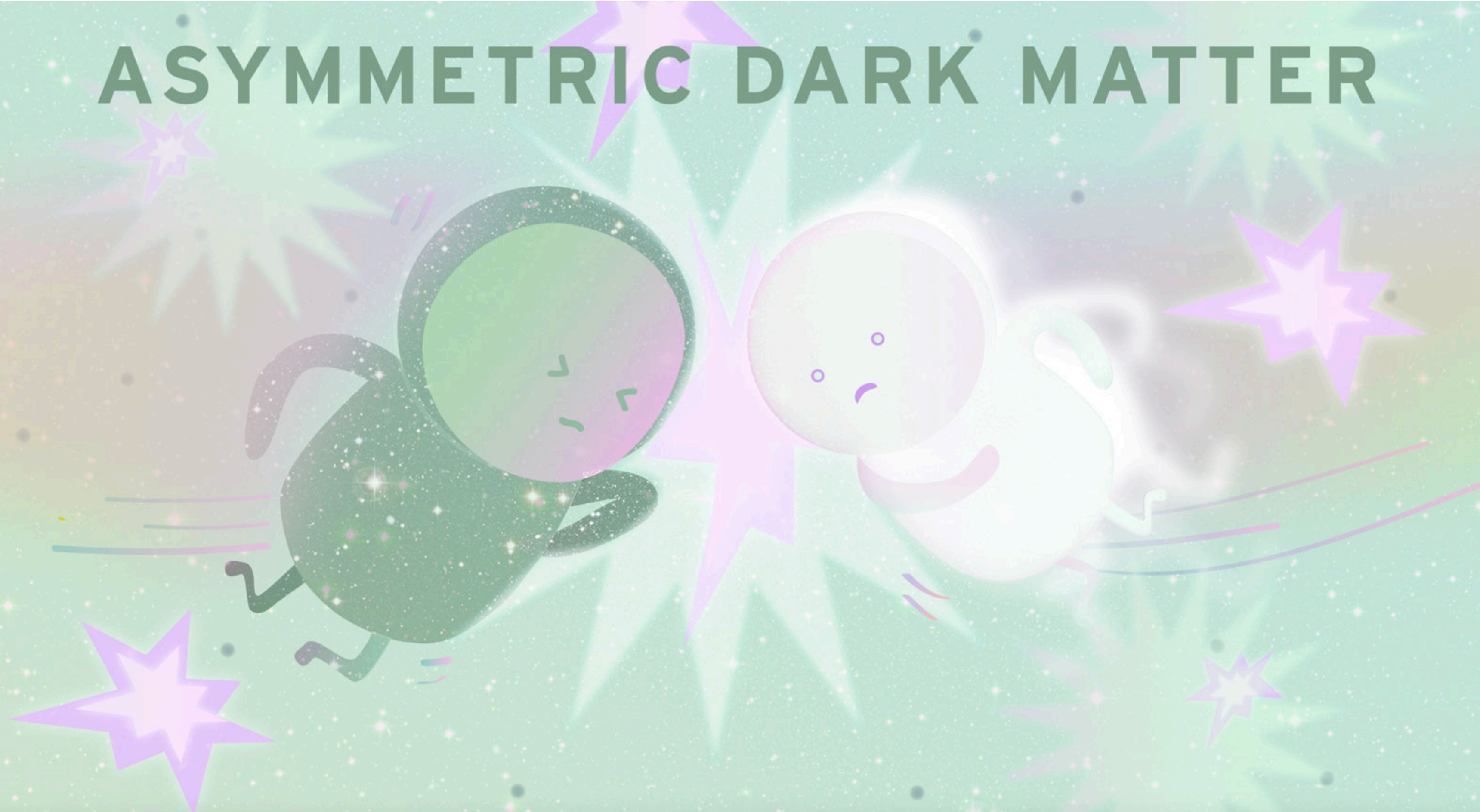

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Hall+March-Russell+West [1010.0245], Unwin [1406.3027],…

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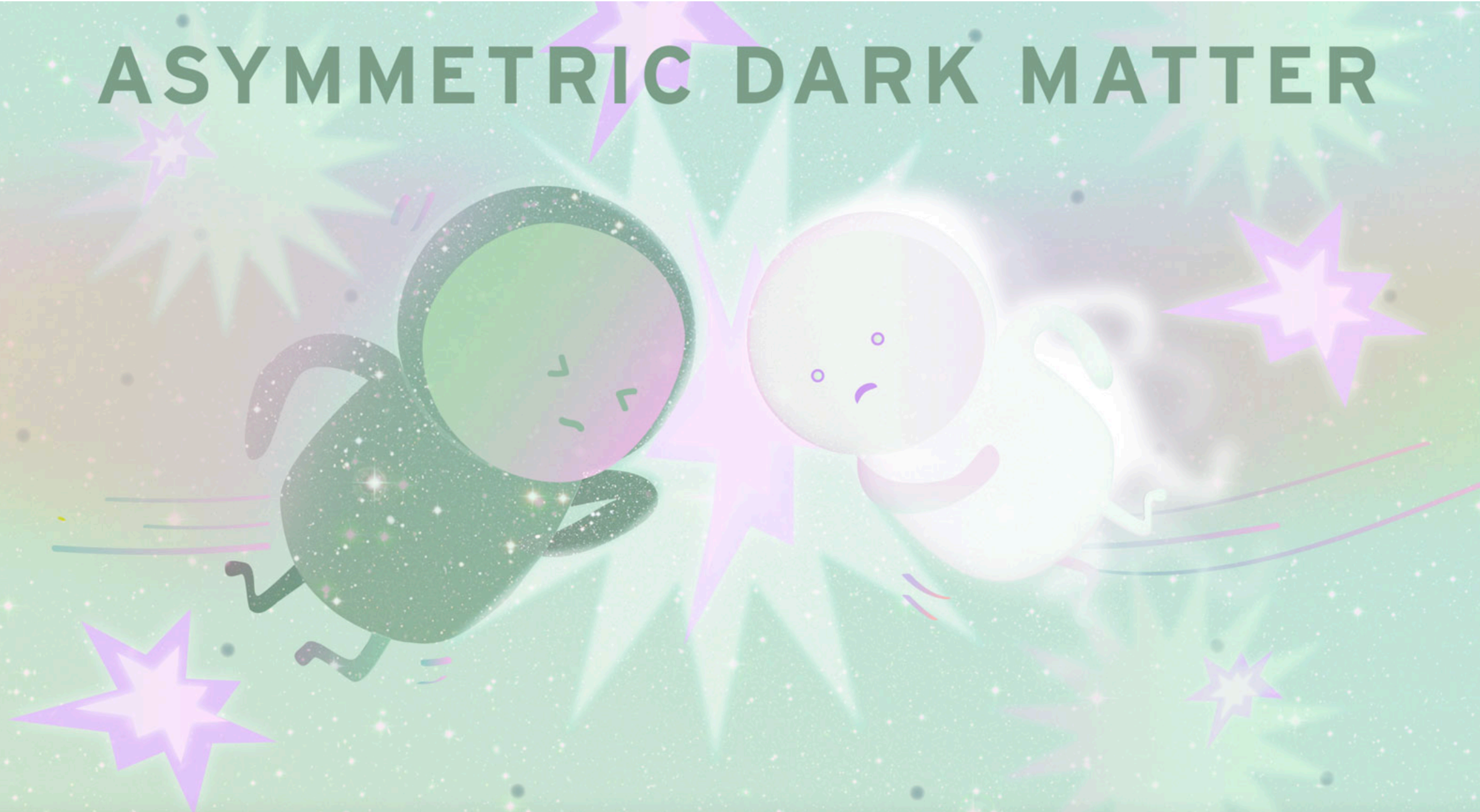

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ADM = Baryogenesis+Dark Matter

Asymmetric Freeze-in?

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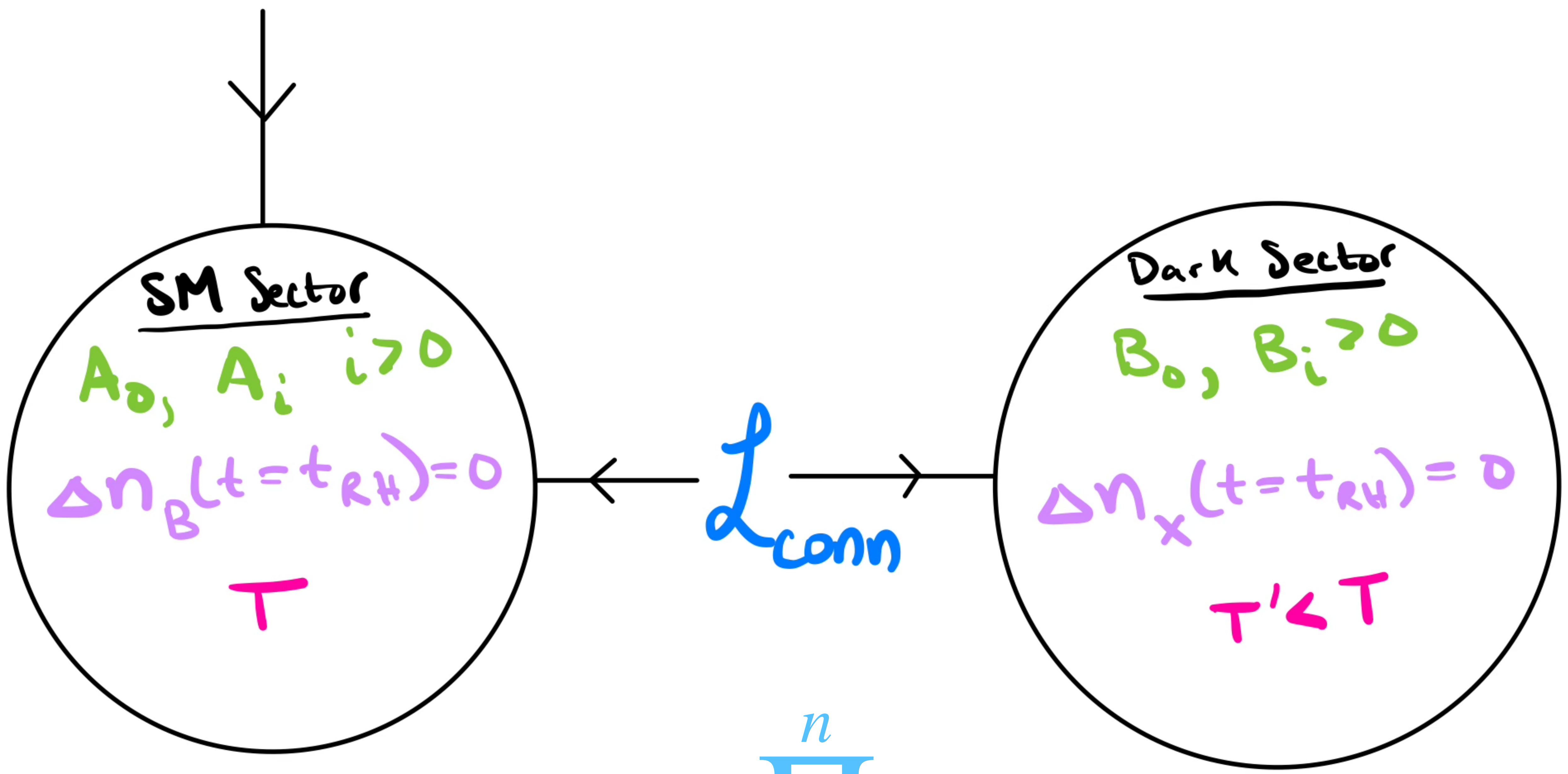
Reheating



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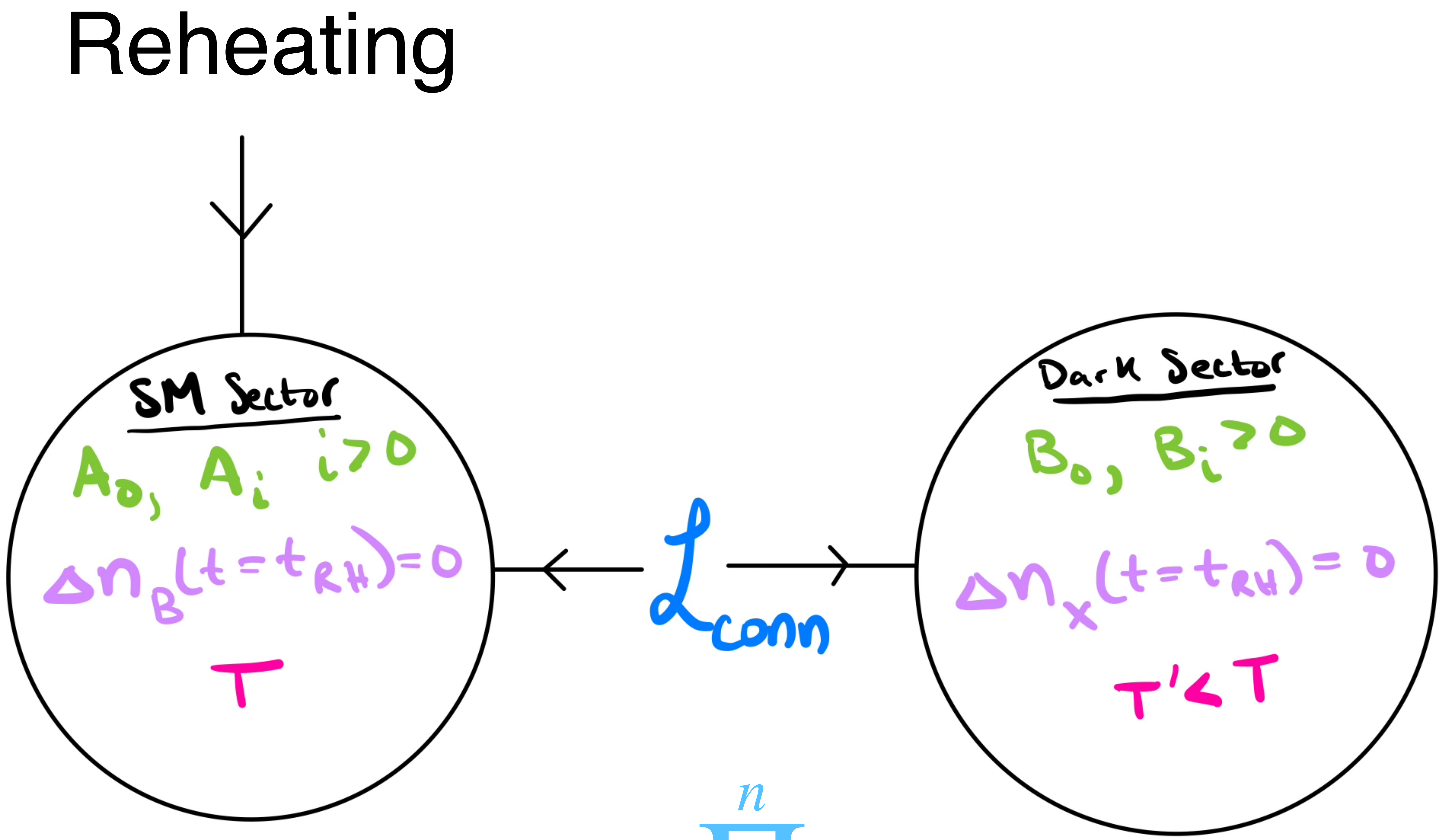
Asymmetric Freeze-in?



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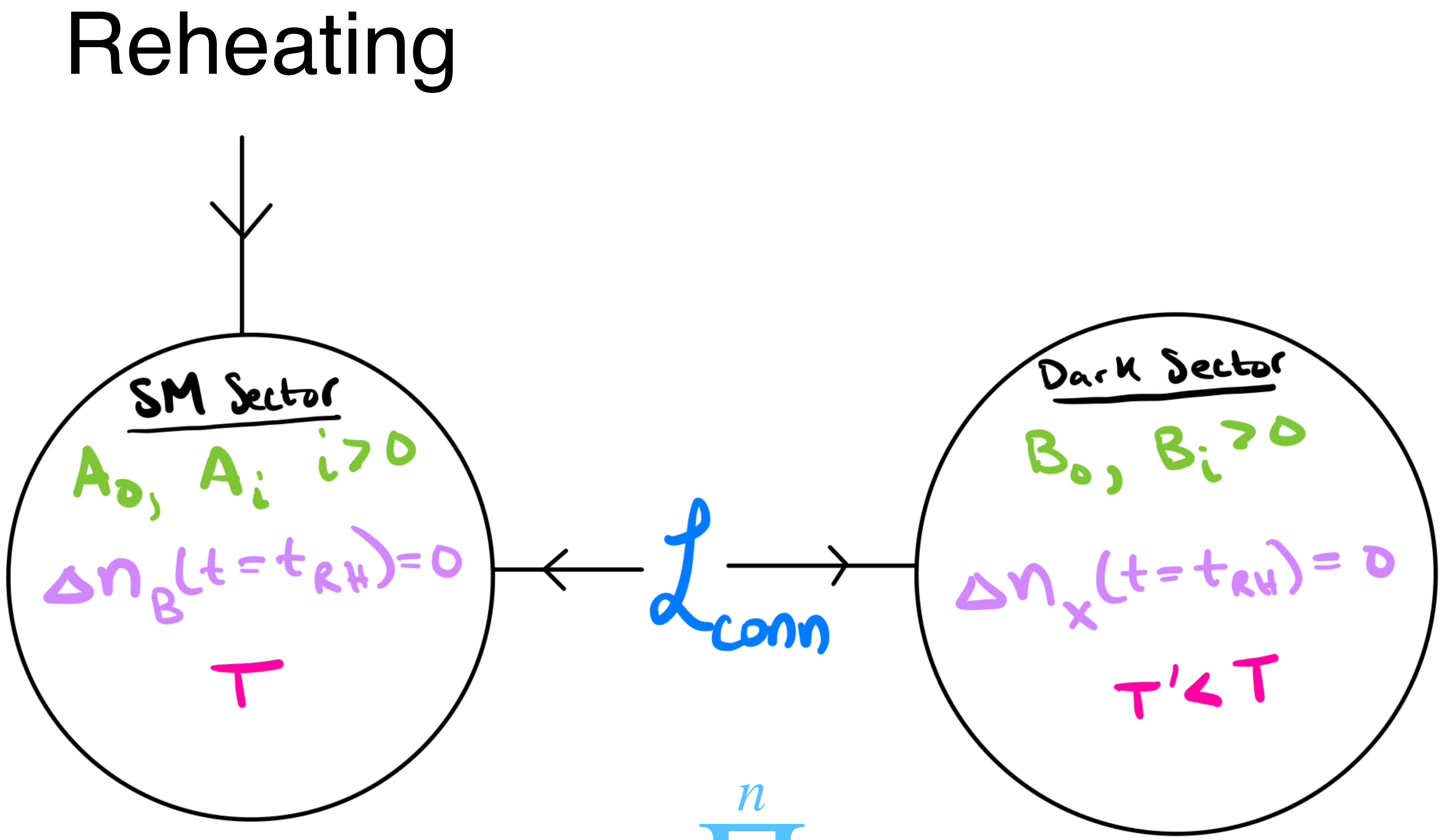

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Small λ ensures the sectors do not equilibrate with one another

Hall, March-Russell, West [1010.0245]

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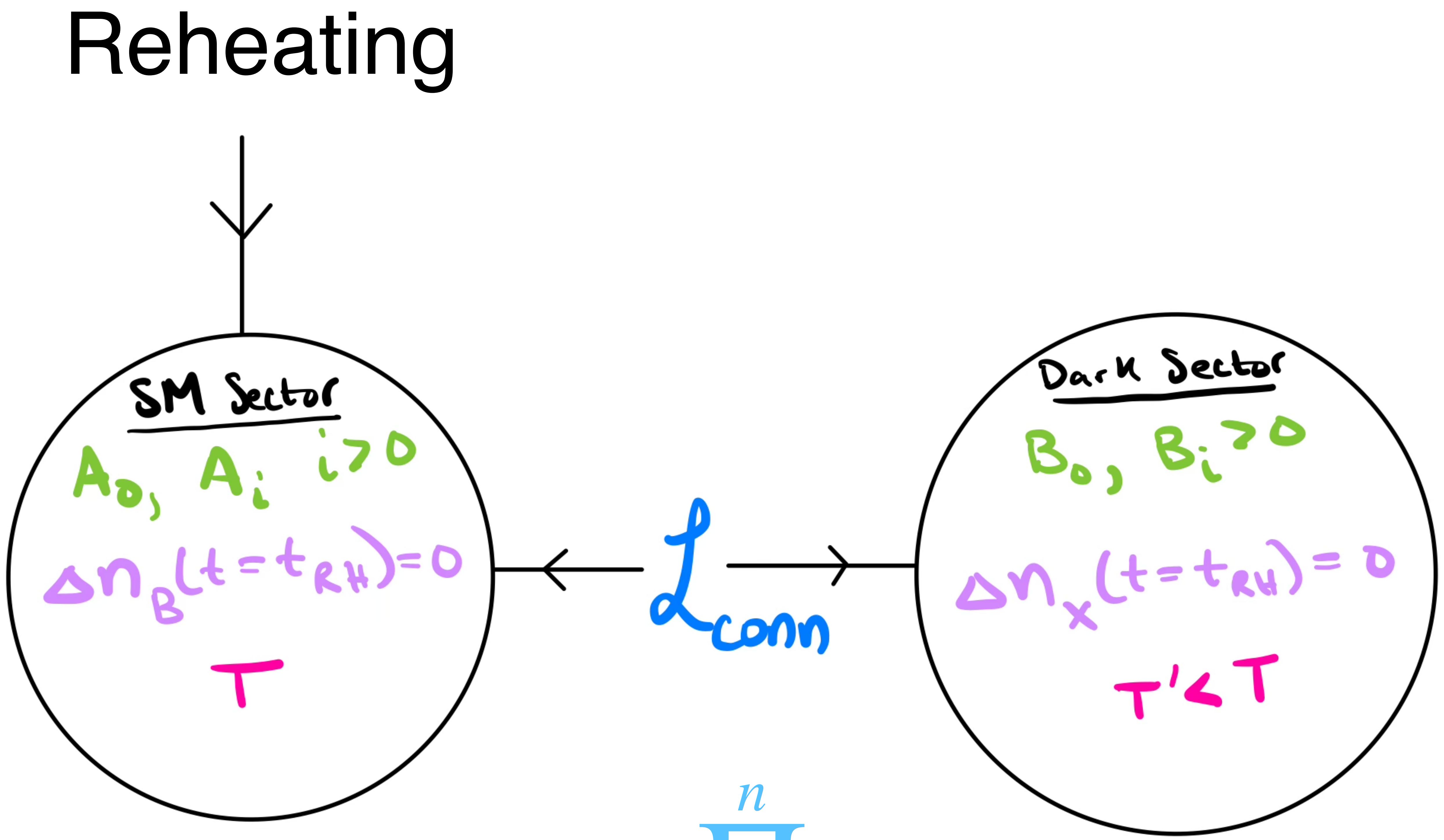

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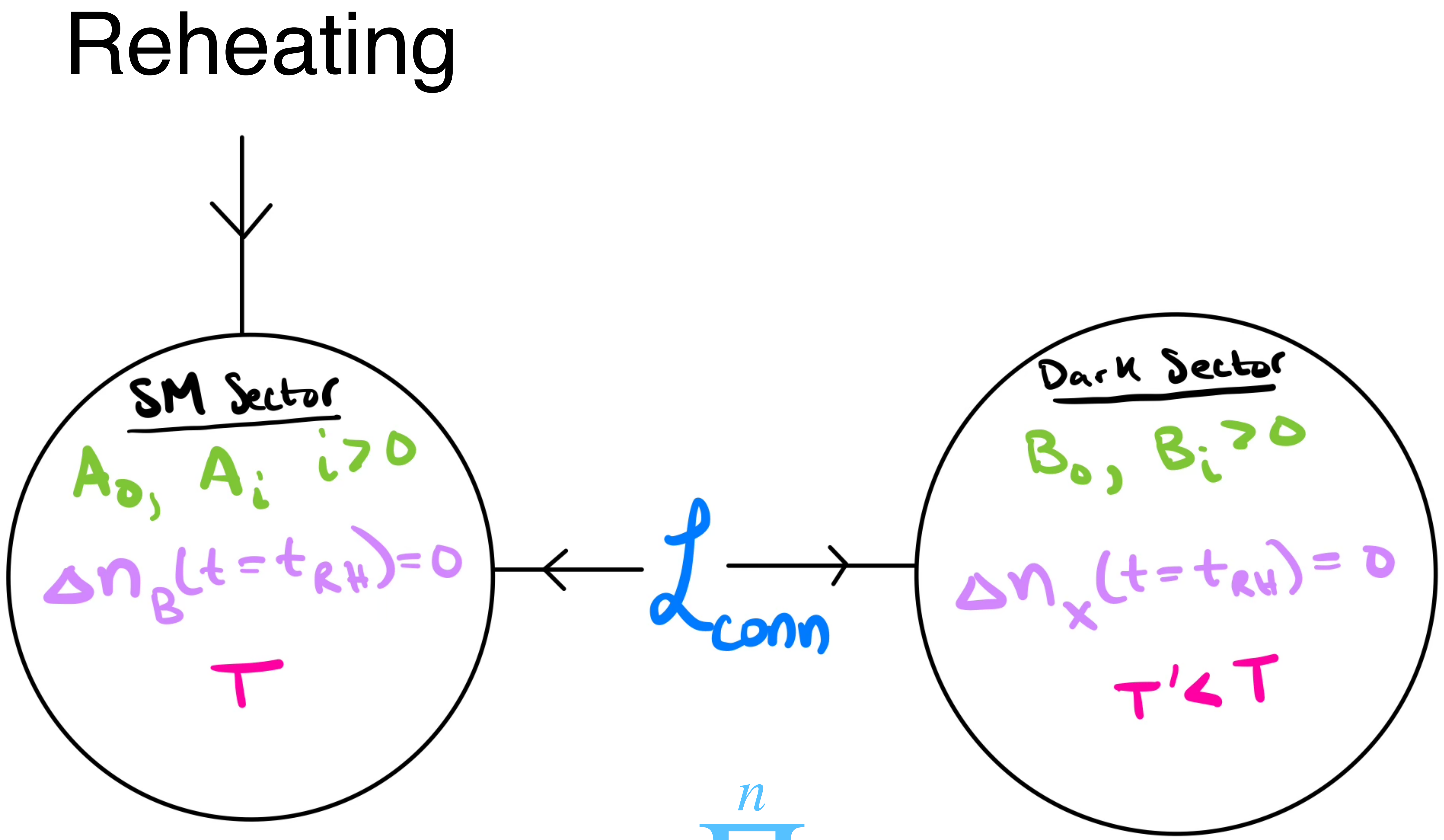

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$\lambda \ll 1 \implies$ depleting the symmetric component difficult

$\mathscr{L}_{\text{conn}}$ 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];

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];

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

Example: LHN **(single flavor)**

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

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

Additional States and Interactions

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

Model:

$$\mathscr{L} = -y_i \bar{L}\tilde{H}P_R N_i - \lambda_i \bar{\chi}\phi P_R N_i - \frac{1}{2}m_i \bar{N}_i^c N_i + \text{h.c.},\ i = 1,2$$

Field Content:

SM Fields: LH lepton L, Higgs doublet H

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

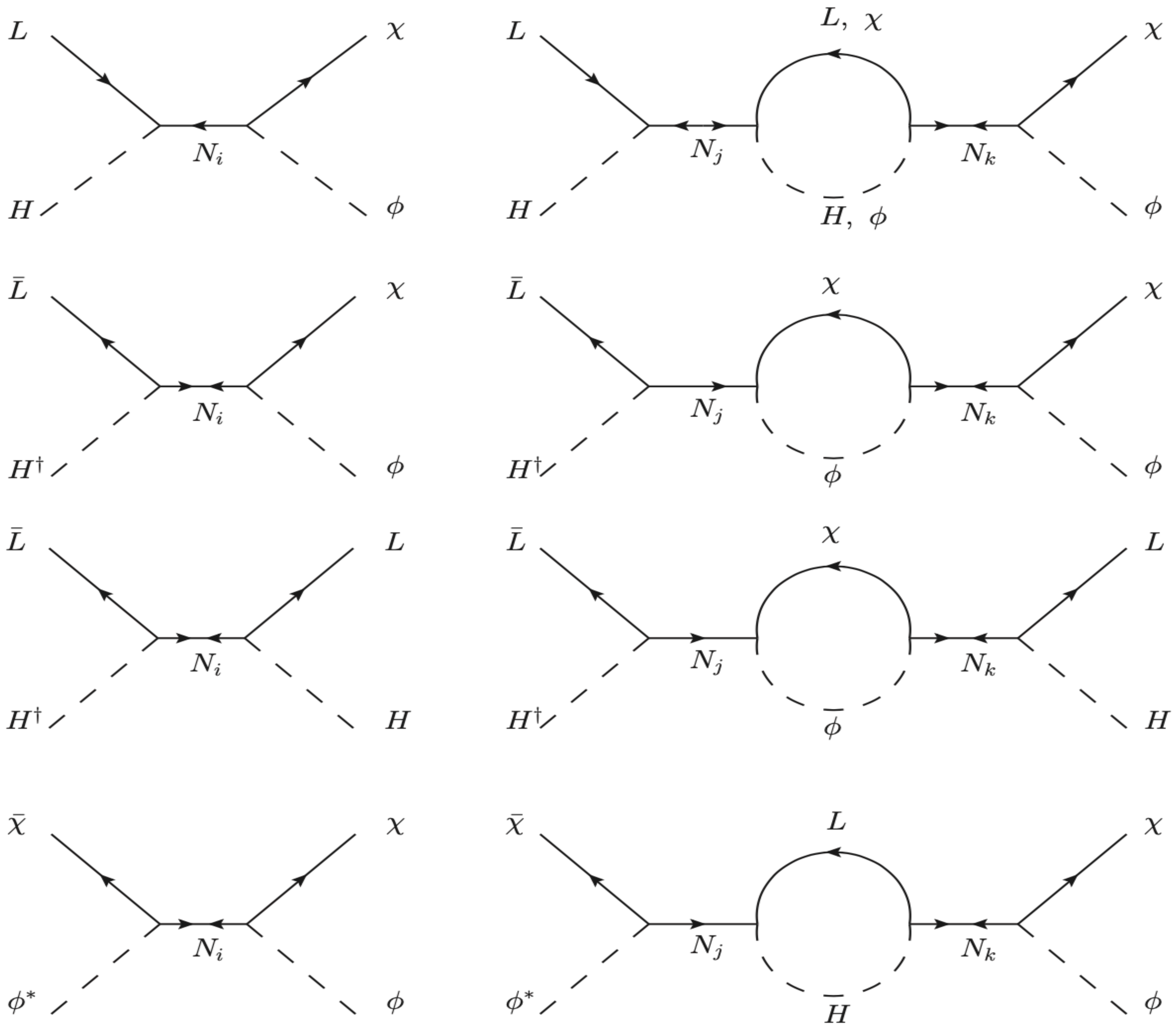
Lepton Number: $L_\phi = -(1 - L_\chi)$

Cosmology:

Assume the universe reheats to SM only and $m_{N_i} \gg T_{\text{RH}} > m_\chi, m_\phi \ldots N_i$ 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 $\Longrightarrow$

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

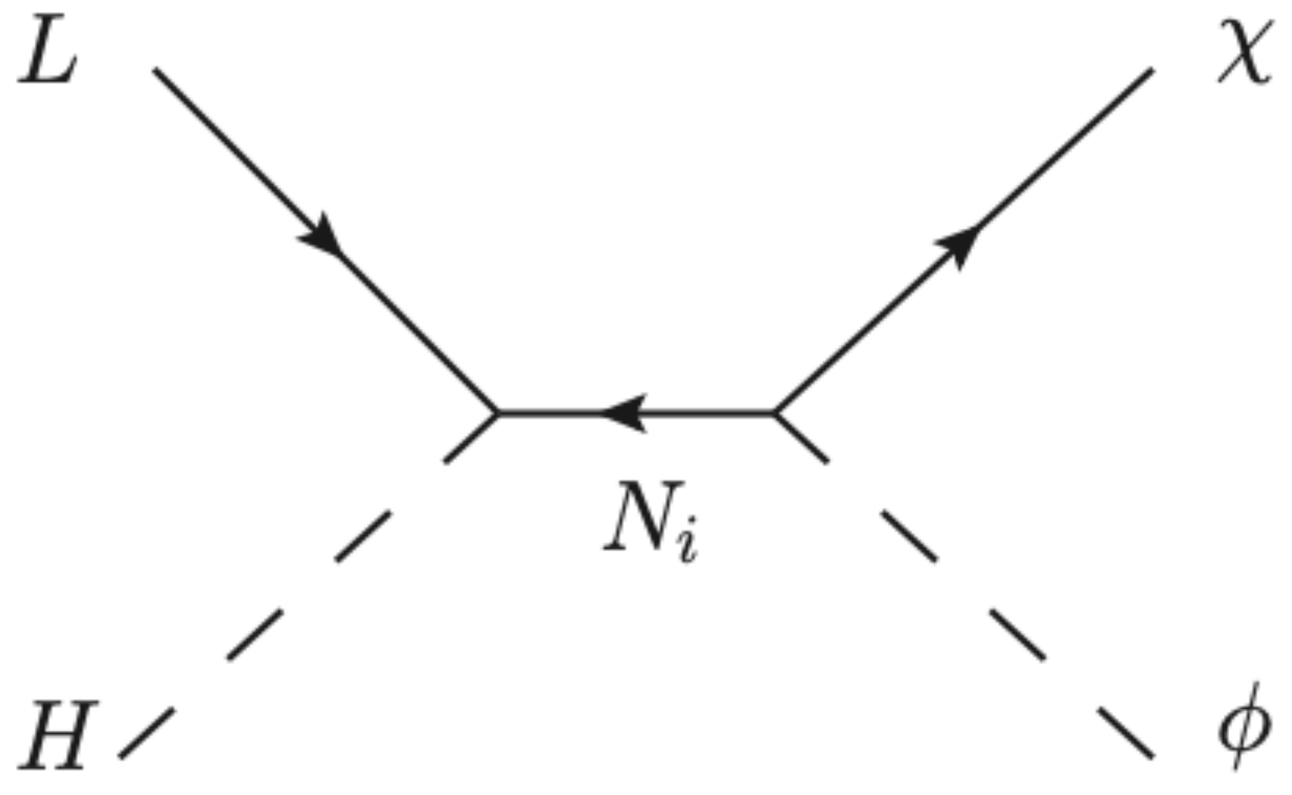
Net asymmetry can be produced!

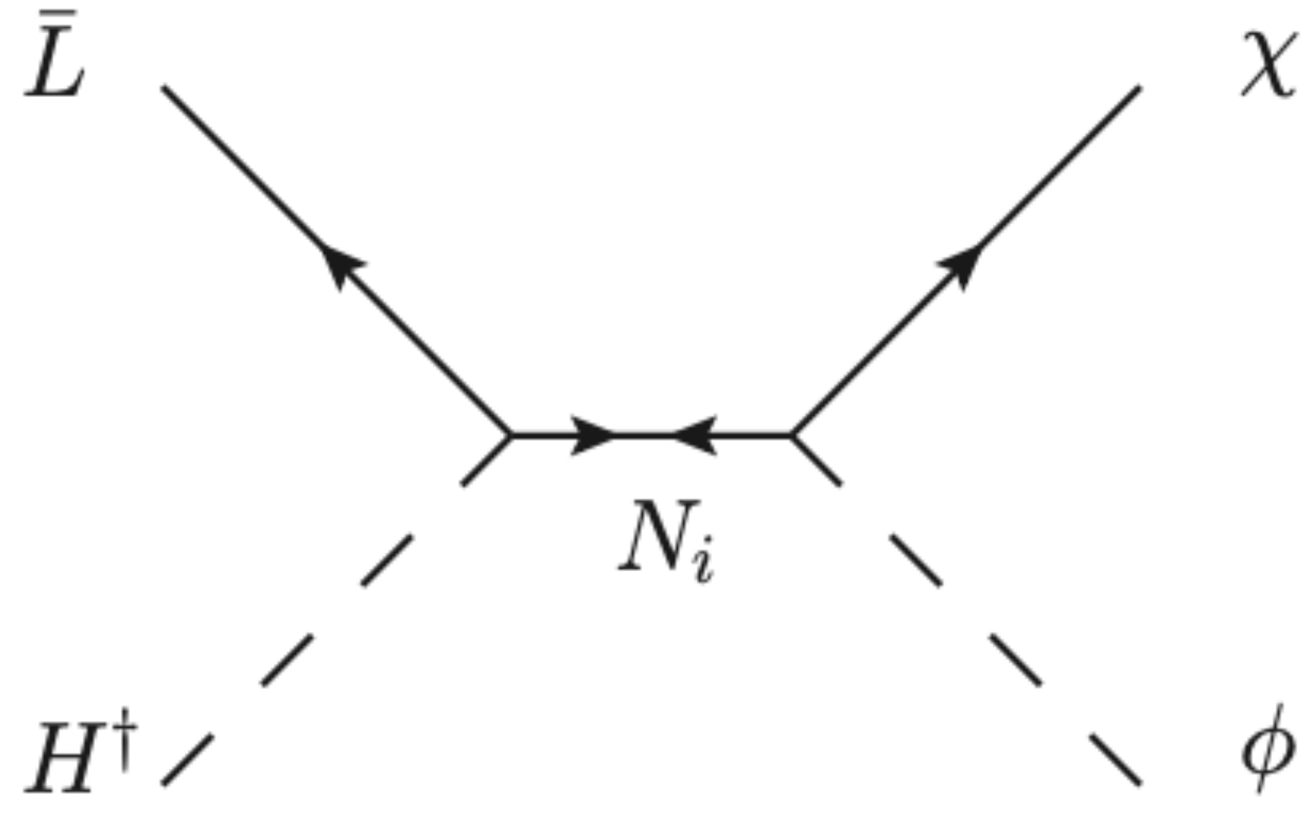
Energy Transfer

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





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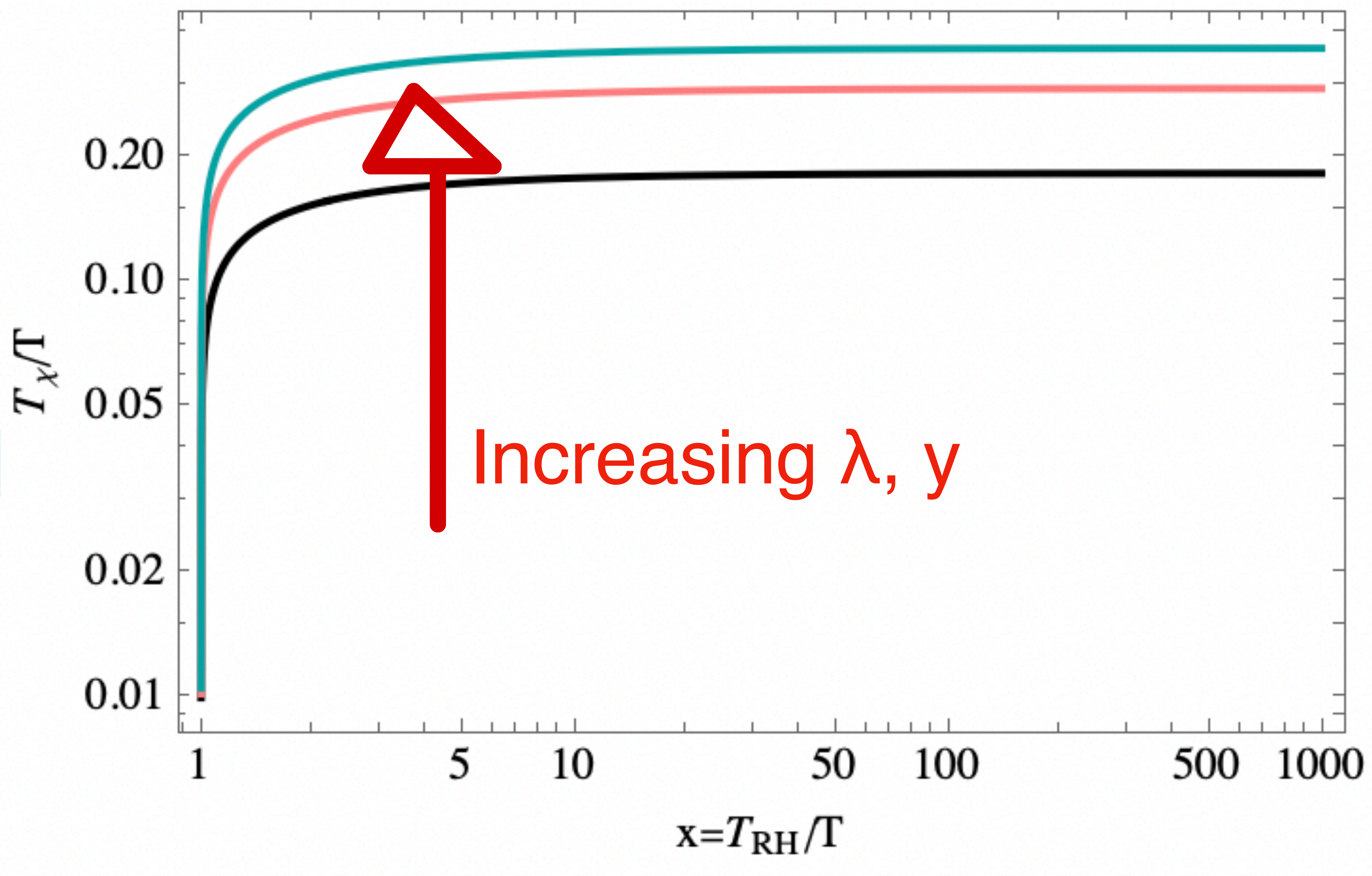


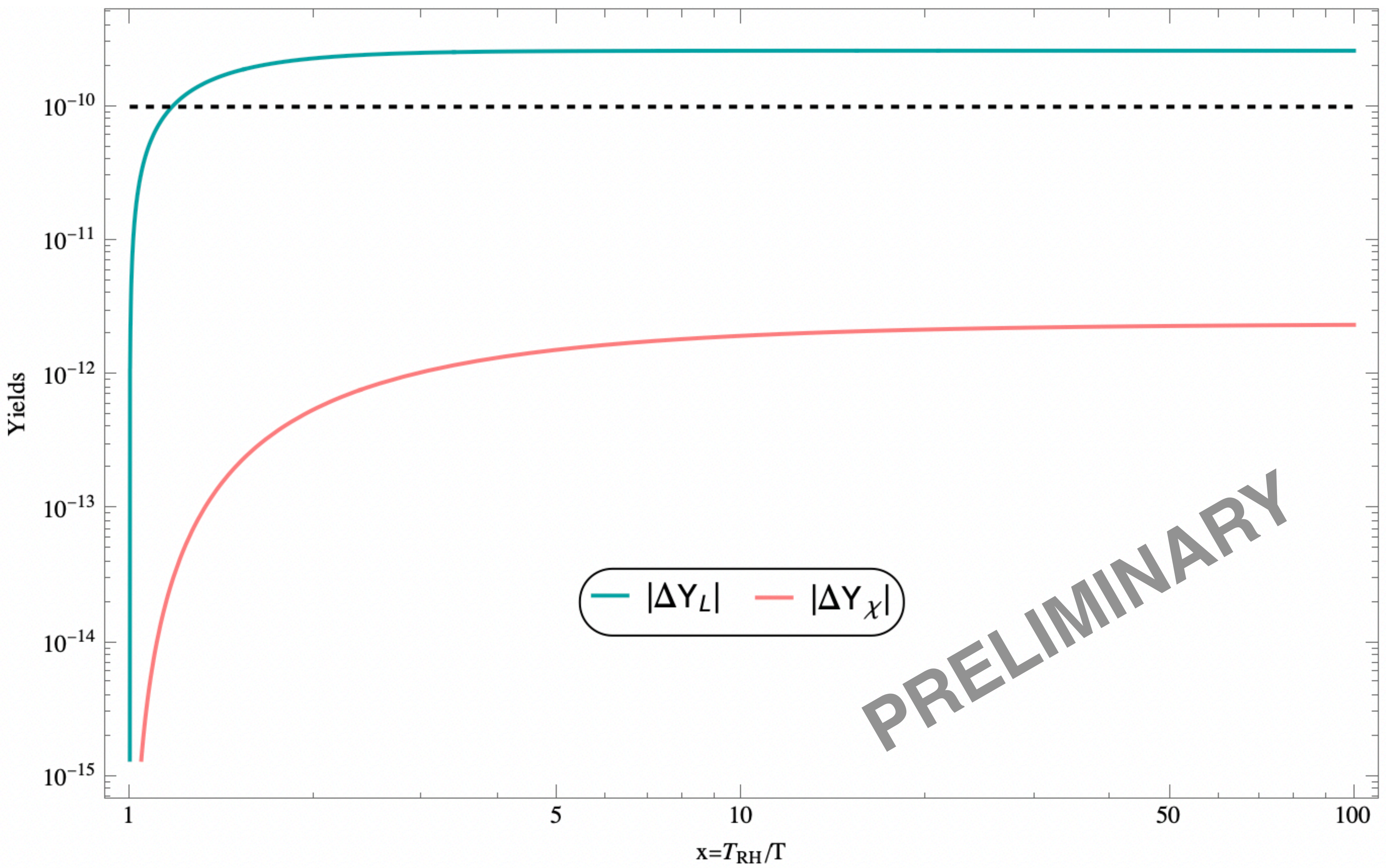
Freeze-in Cogenesis of Heavy ADM

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

$\alpha_{21} = \pi/4,\ \beta_{21} = \pi/2$



$m_1 = 4\times10^3$ TeV, $m_2 = 15\times10^3$ TeV, $T_{RH} = 50$ TeV

ADM mass: fixed by the asymmetries

Sphalerons convert lepton asymmetry to baryon asymmetry

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

$$m_\chi \approx 5c_s(\Delta Y_L/\Delta Y_\chi)m_p \approx 200\text{ GeV}$$

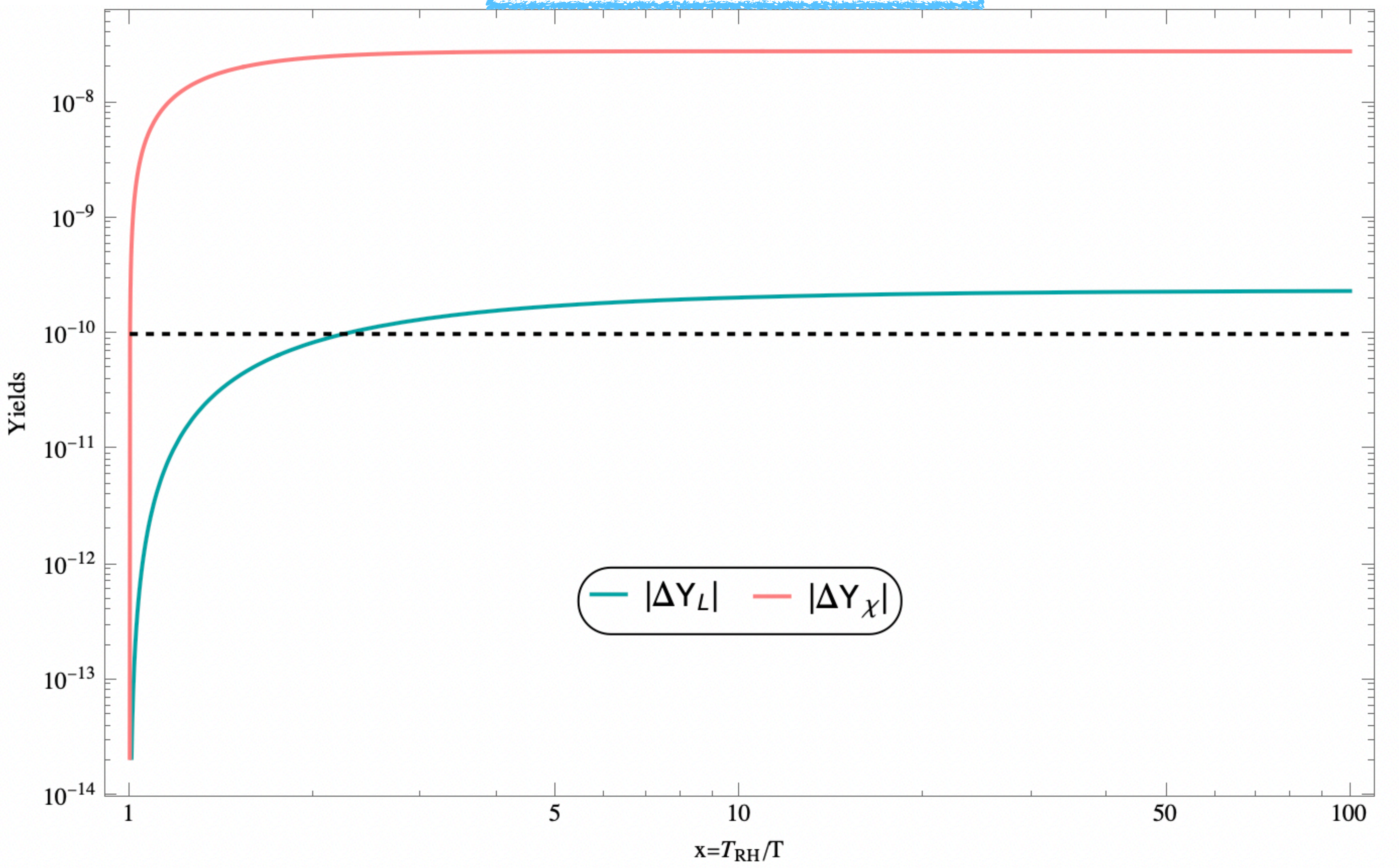
Freeze-in Cogenesis of ~~Heavy~~ ADM

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

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

Stronger phase in visible or dark sector!

$\alpha_{21} = \pi/2,\ \beta_{21} = \pi/4$



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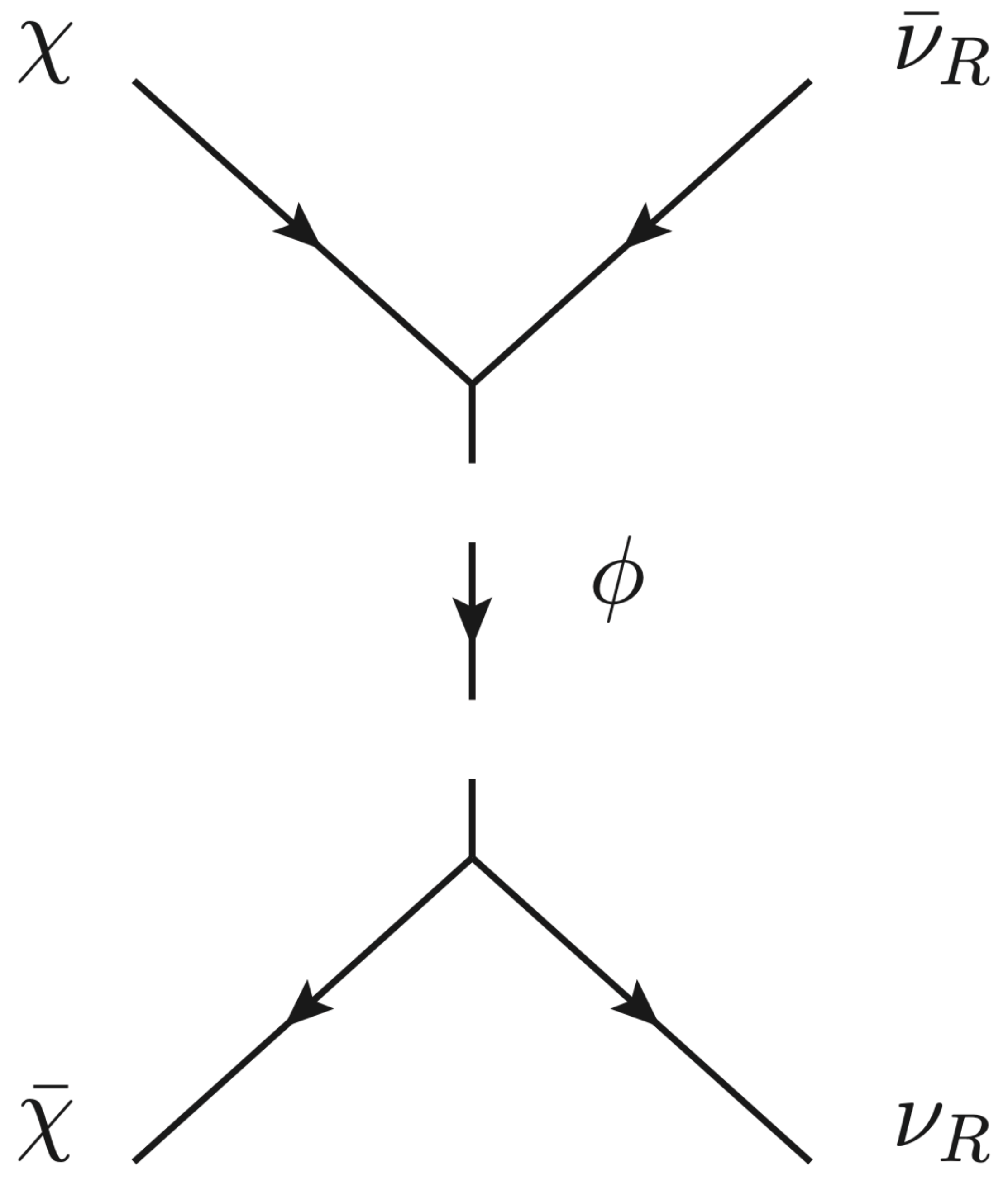
ADM mass: Leads to larger asymmetry in respective sector

$$m_\chi \approx 5c_s(\Delta Y_L/\Delta Y_\chi)m_p \approx 15 \text{ MeV}$$

Symmetric Component?

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

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

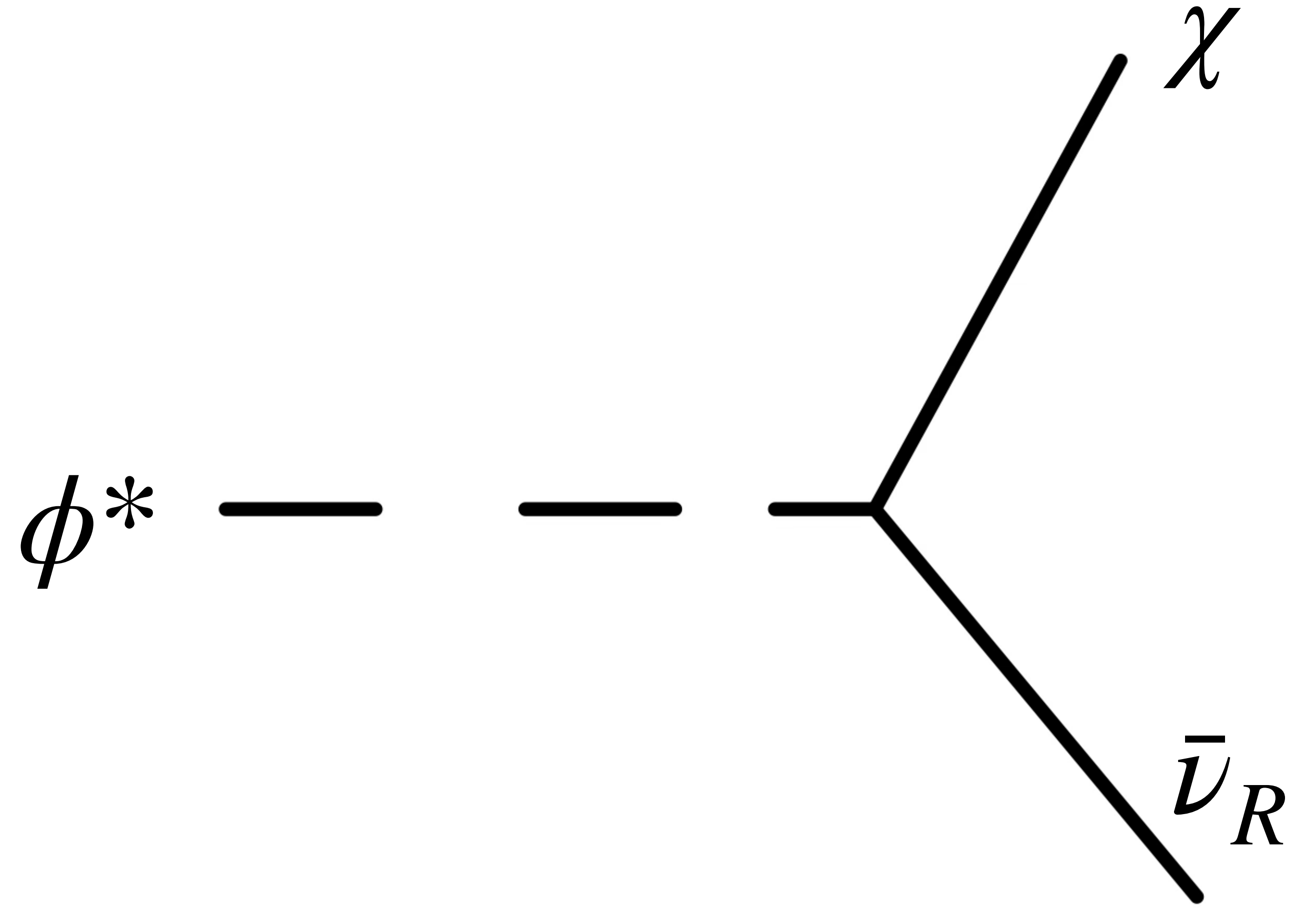


Depletion: Transfer symmetric component into a dark sink

Bhattiprolu et. al. [2312.43152]

Introduce a single flavor of RH Dirac neutrinos

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



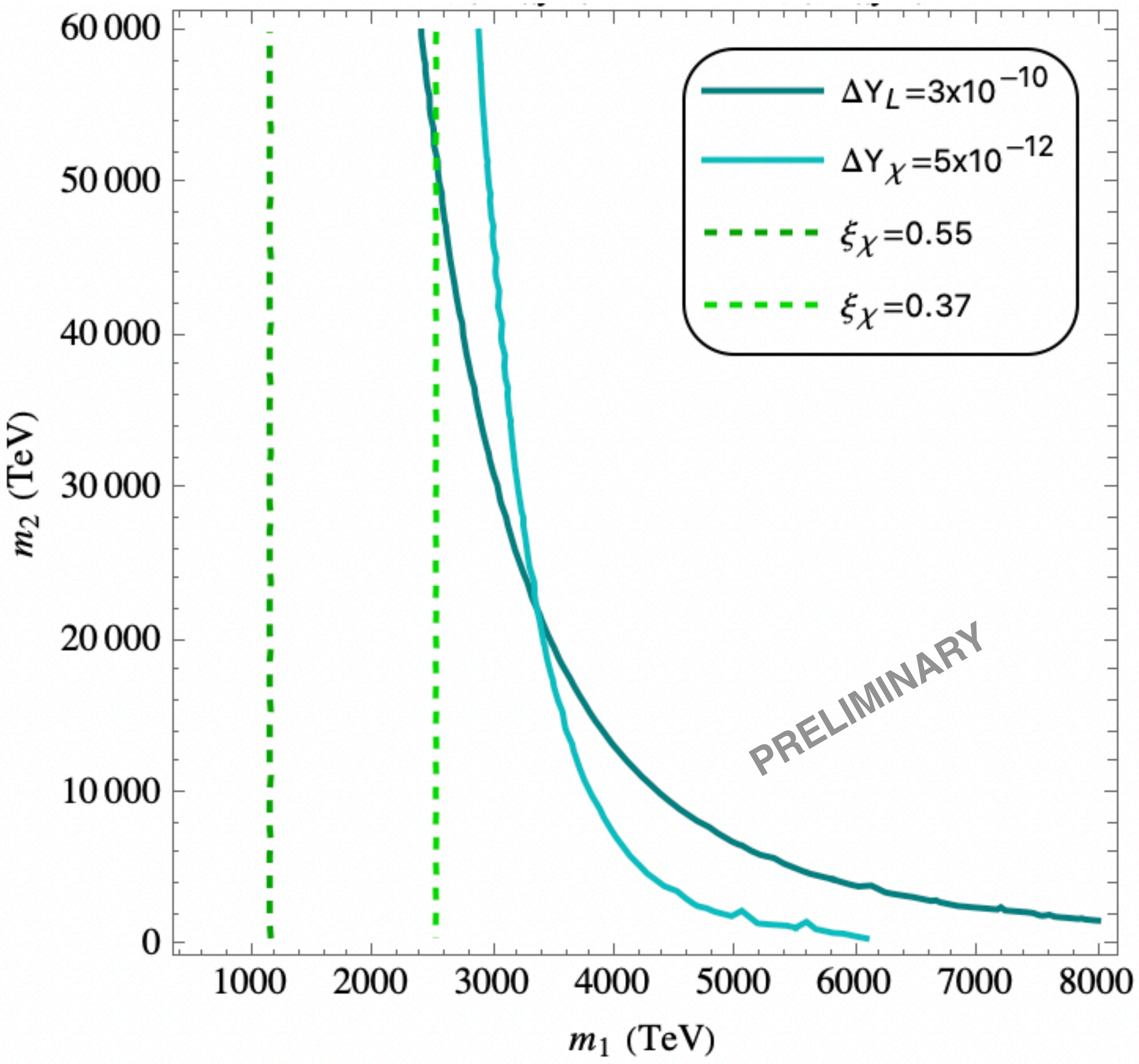
Thermalization and N_{eff}

Thermalization: Light ν_R provides thermal bath which ensures the dark sector remains in thermal equilibrium with T_χ

$\Longrightarrow$ Constraints on ξ_χ from $\Delta N_{\text{eff}} = \rho_{\nu_R}/\rho_\nu < 0.3$

$$\Longrightarrow \quad \xi_{\chi,i} \lesssim 0.67 \times \left[\frac{g^\chi_{*S}(T_i)}{g^\chi_{*S}(T_f)}\frac{g_{*S}(T_f)}{g_{*S}(T_i)}\right]^{-1/3}$$

$$\Delta N_{\text{eff}} = \rho_{\nu_R}/\rho_\nu < 0.06 \Longrightarrow \xi_{\chi,i} \lesssim 0.45 \times \left[\frac{g^\chi_{*S}(T_i)}{g^\chi_{*S}(T_f)}\frac{g_{*S}(T_f)}{g_{*S}(T_i)}\right]^{-1/3}$$



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 $T_{\mathrm{RH}} < m_N$

Phase dependence allows both $\Delta Y_L \gg \Delta Y_\chi$, $\Delta Y_L \ll \Delta Y_\chi$ and $m_{\mathrm{ADM}} \gg m_p$, $m_{\mathrm{ADM}} \ll m_p$

Future work: Neutrino masses? Generalize the model, direct baryogenesis?

Thank You!

Backup

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 $\Longrightarrow$

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

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$\Longrightarrow$

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

Collision terms$\Longrightarrow$

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

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

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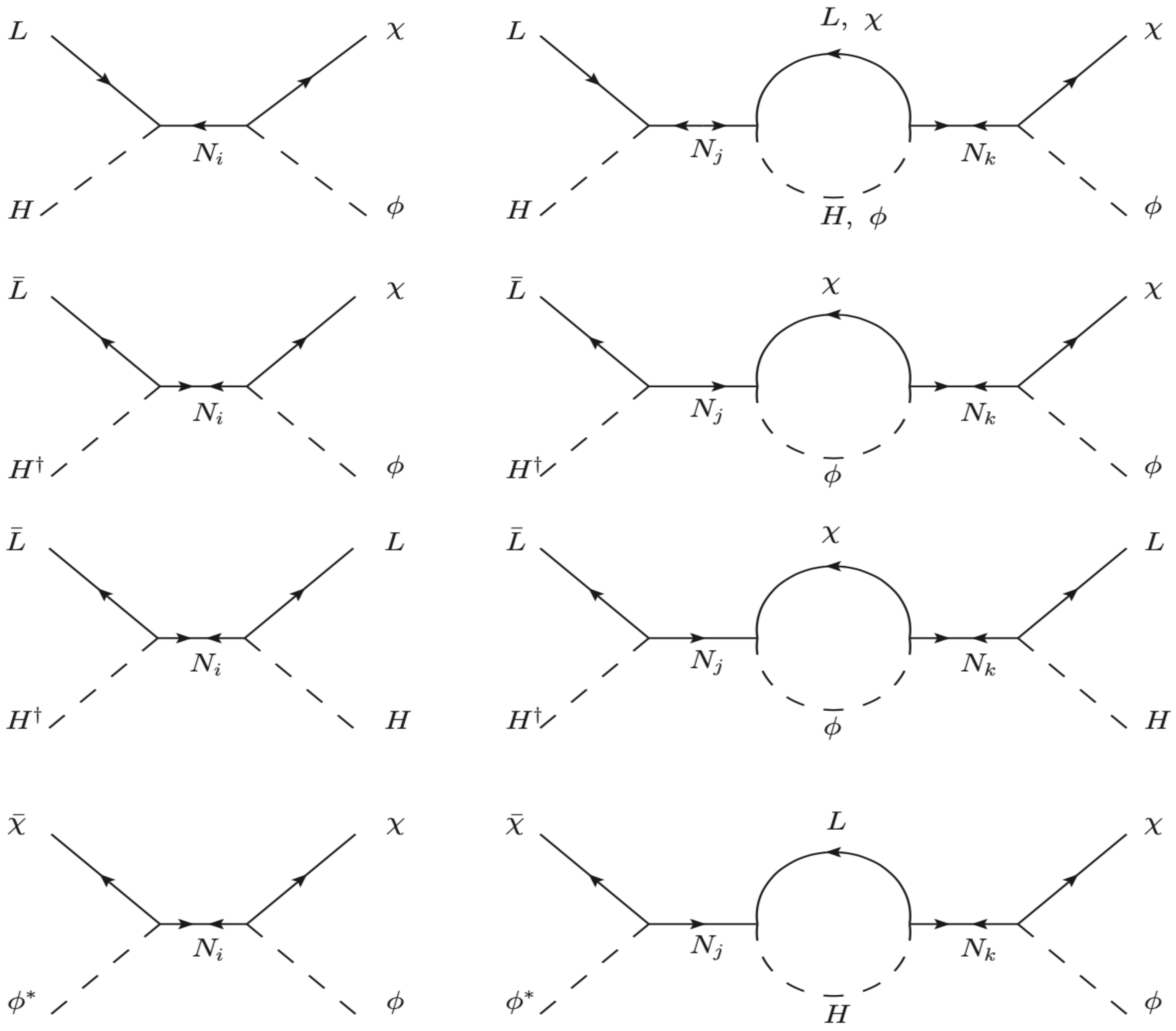

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CP Violation: CP Asymmetries ensured through the introduction of χ, ϕ and m_N

CPT+Unitarity:

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

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