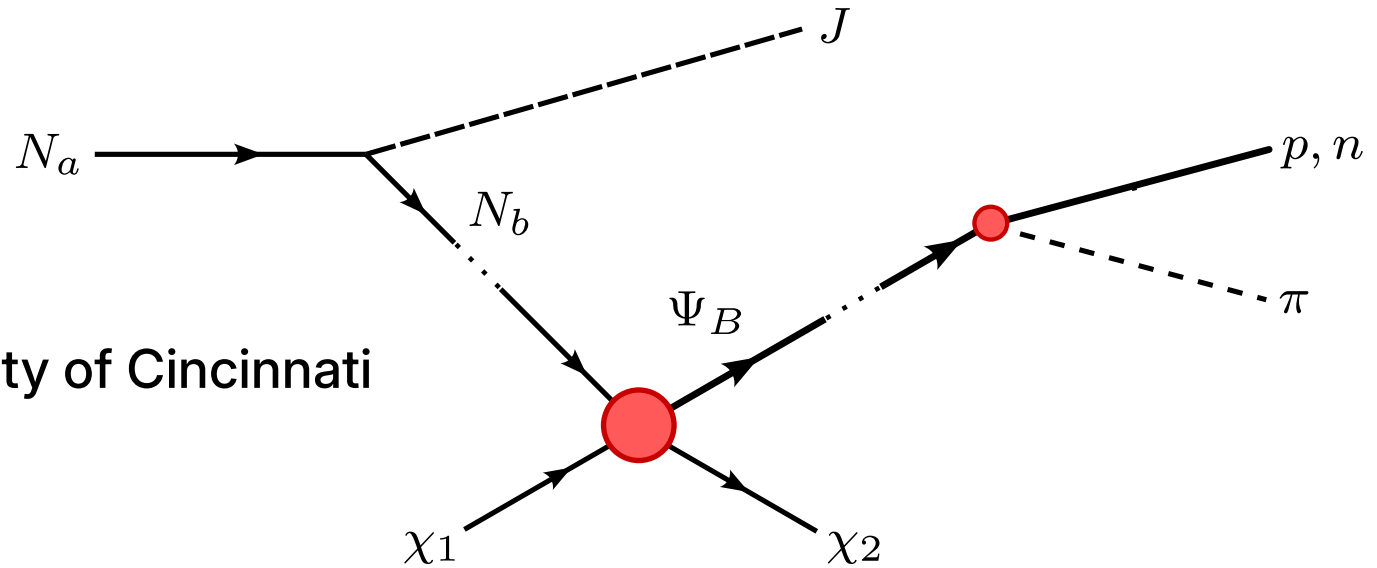


A **flavorful** and **dark** cascade for low-scale leptogenesis

NPV 2025 @ 

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In collaboration with **Julia Gehrlein** and **Jure Zupan** (25xx.xxxx)

Lore: matter-matter asymmetry

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \text{constant after BBN}$$

Measured value: $\eta = (6.12 \pm 0.04) \times 10^{-10}$

Naive estimate: Consider $\eta = 0$ and compute ratio at freeze out ($T_{\text{FO}} \sim 20$ MeV).

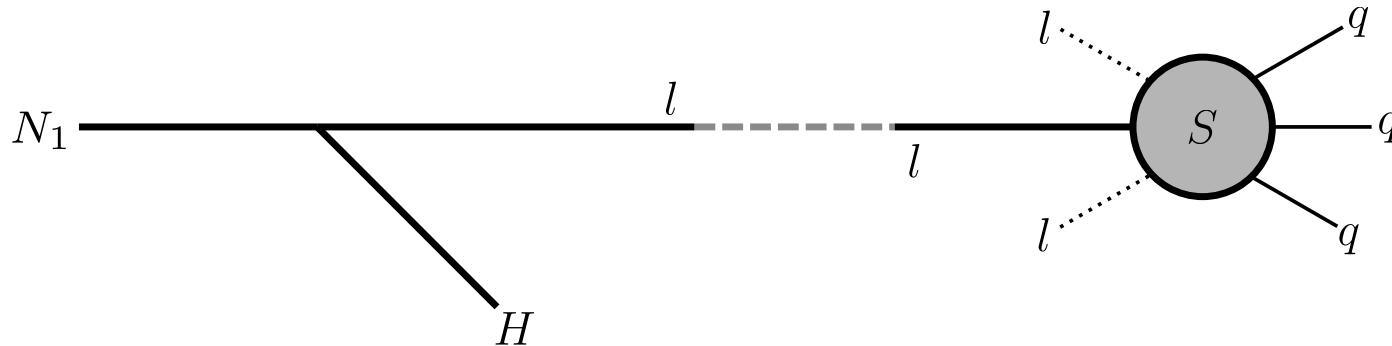
$$\frac{n_B}{n_\gamma} \simeq \frac{n_{\bar{B}}}{n_\gamma} \simeq \left(\frac{m_p}{T}\right)^{3/2} e^{-m_p/T} \simeq 10^{-18}$$

Lore: matter-matter asymmetry

What about electroweak baryogenesis with SM ingredients?
Requires strong 1st order phase transition bubbles i.e. $m_H < 72$ GeV.

BSM required!

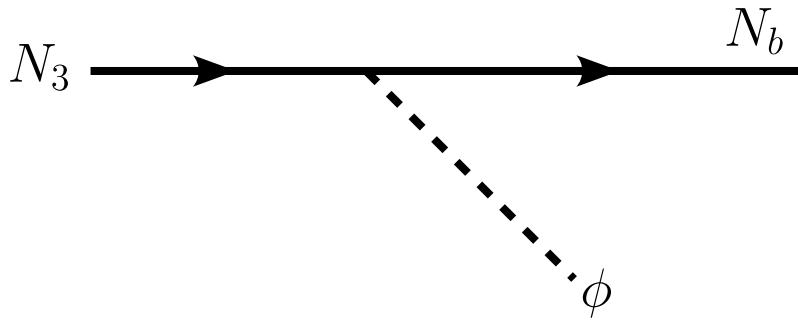
Many models... for example high scale (> 100 GeV) leptogenesis + sphalerons



The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

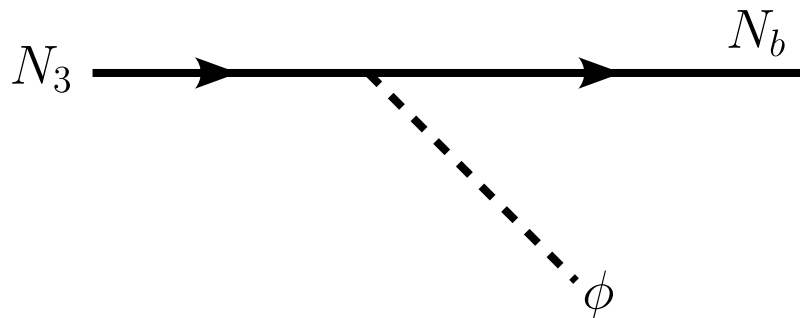
1. Production of lepton asymmetry



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1. Production of lepton asymmetry



Toy model

Consider n sterile Dirac neutrinos:

$$\mathcal{L} \supset -y_{ij} \bar{N}_i P_L N_j \phi + \text{h.c.}$$

- Lepton number is conserved
- CPT tells us:

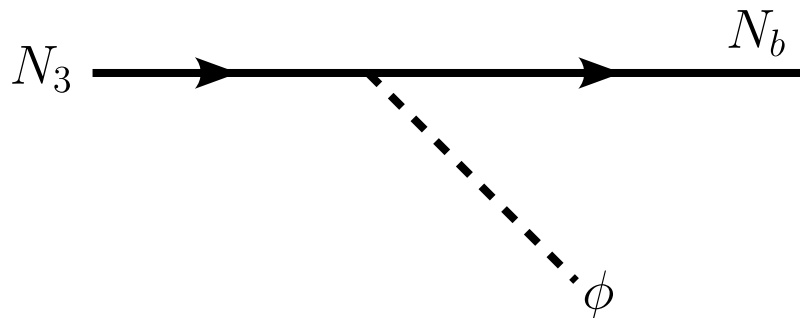
$$\Gamma_{\text{total}}(N_i) = \Gamma_{\text{total}}(\bar{N}_i)$$

→ $n \geq 3$ for non-trivial CPV

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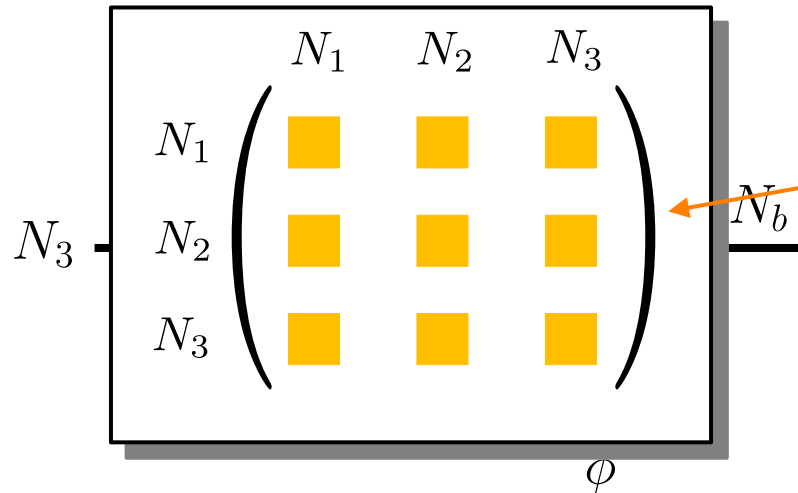
$$\Gamma_{\text{total}}(N_i) = \Gamma_{\text{total}}(\bar{N}_i)$$

$$\Delta\Gamma(N_3 \rightarrow N_2\phi) = -\Delta\Gamma(N_3 \rightarrow N_1\phi)$$

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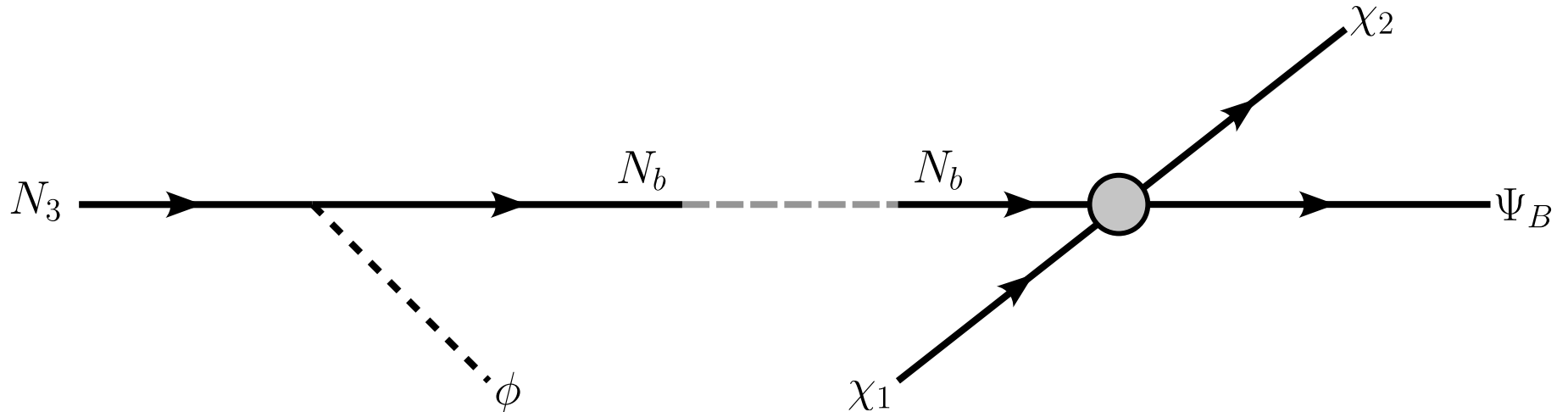
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The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

1. Production of lepton asymmetry

2. Transfer to baryon asymmetry



The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

1. Introduce dark sector:

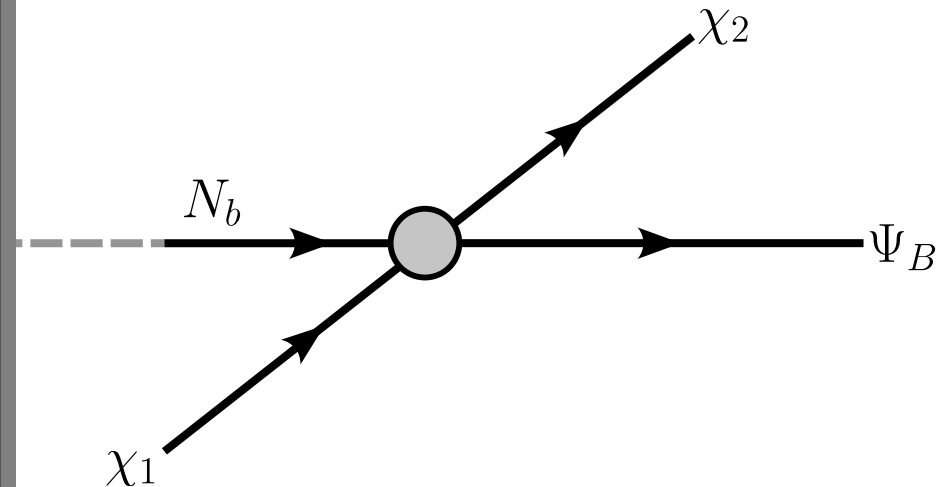
$$\mathcal{L} \supset -\lambda \bar{N}_1 \Psi_B X - \lambda' \bar{\chi}_1 \chi_2 X + \text{h.c.}$$

Need to preferentially scatter on $N_{1,2}$ – either kinematically forbid

$$m_{N_1} + m_{\chi_1} < m_{N_2} + m_{\chi_2}$$

or introduce generation-philic flavor structure.

2. Transfer to baryon asymmetry



The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

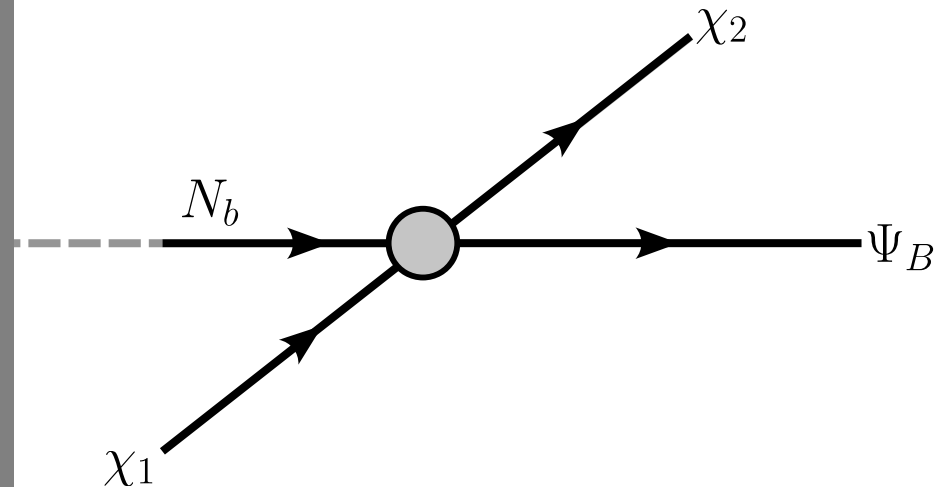
1. Introduce dark sector:

$$\mathcal{L} \supset -\lambda \bar{N}_1 \Psi_B X - \lambda' \bar{\chi}_1 \chi_2 X + \text{h.c.}$$

- Note we can arrange for baryon and lepton number conserved

	X	Ψ_B	χ_1	χ_2
L	1	0	2	1
B	-1	1	1	2
spin	0	1/2	1/2	1/2

2. Transfer to baryon asymmetry

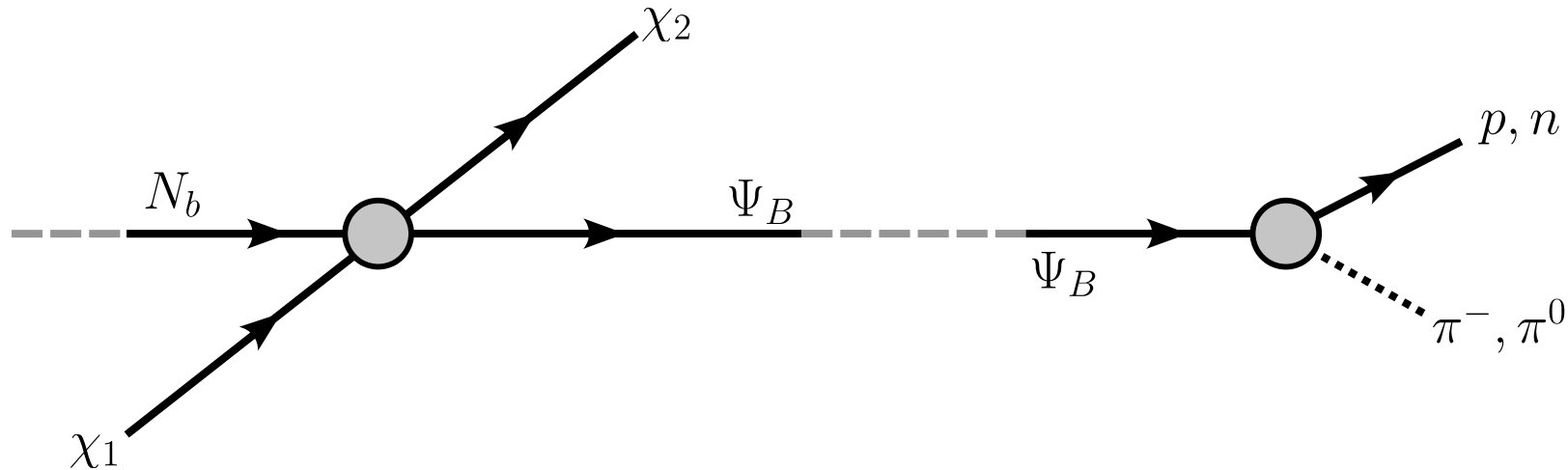


The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

2. Transfer to baryon asymmetry

3. Heavy dark baryon decay



The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering

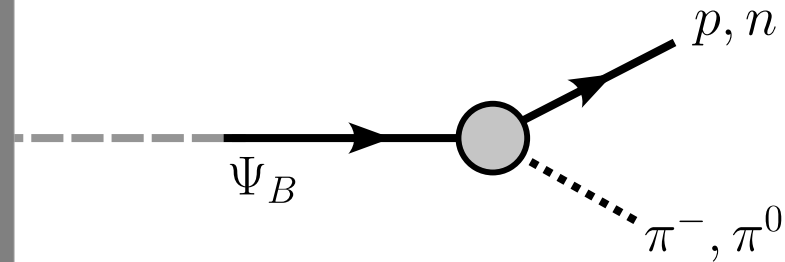
2 Neutron portal:

$$\mathcal{L} \supset -\frac{1}{\Lambda^2} \bar{\Psi}_B P_R d \bar{u}^c P_R d + \text{h.c.}$$

↓ Match

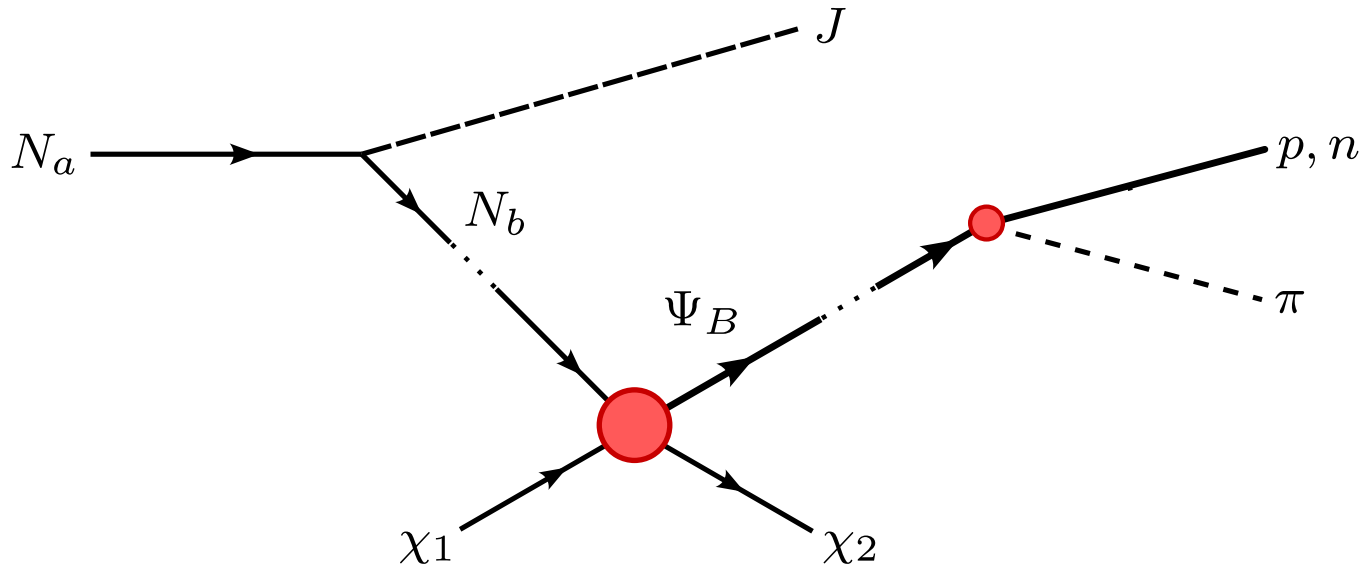
$$\mathcal{L} \supset -\frac{C\Lambda_{\text{QCD}}^3}{f_\pi\Lambda^2} \bar{\Psi}_B p \pi^- + \text{h.c.} + \dots$$

3. Heavy dark baryon decay



The mechanism

Our mechanism: low-scale (< 100 GeV) leptogenesis + DM scattering



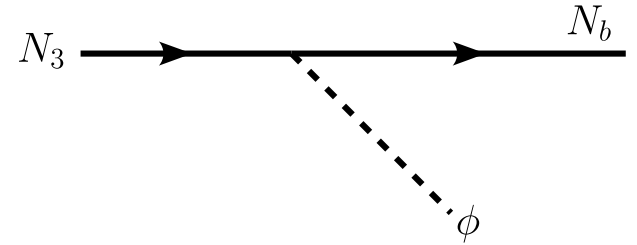
- Baryon and lepton number are conserved, **visible** baryon number is violated

Constraints

- Out of equilibrium after EWPT, but before BBN

$$H = \frac{\dot{a}}{a} \simeq 1.66\sqrt{g_*} \frac{T^2}{M_{\text{Pl}}}$$

$$H_{\text{BBN}} < \Gamma_{N_3} < H_{\text{EWPT}}$$



Constraints

- Out of equilibrium after EWPT, but before BBN

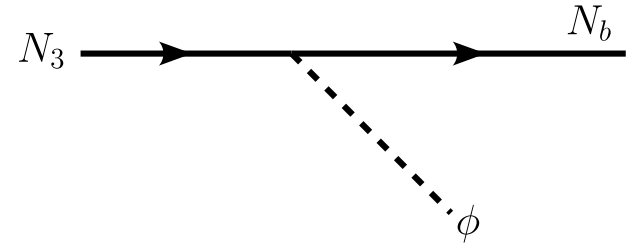
$$H = \frac{\dot{a}}{a} \simeq 1.66\sqrt{g_*} \frac{T^2}{M_{\text{Pl}}}$$

$$10^{-25} \text{ GeV} \lesssim \Gamma_{N_3} \lesssim 10^{-14} \text{ GeV}$$

$T \sim 1 \text{ MeV}$

$T \sim 100 \text{ GeV}$

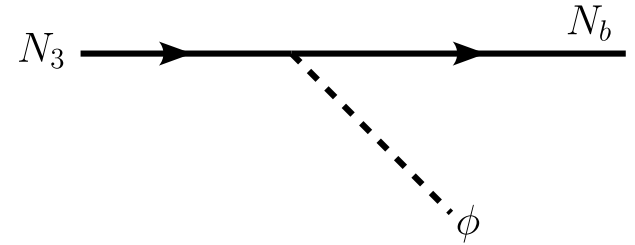
$$\Gamma(N_3 \rightarrow N_b \phi) \simeq \frac{|y_{b3}|^2}{8\pi} m_{N_3}$$



Constraints

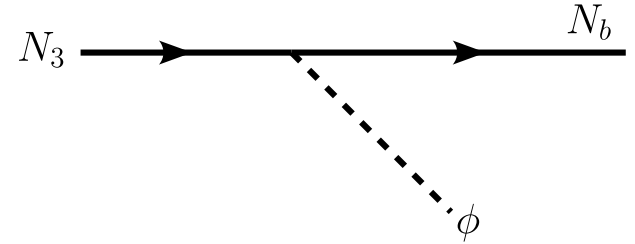
- Out of equilibrium after EWPT, but before BBN

$$10^{-12} \lesssim |y_{b3}| \left(\frac{m_{N_3}}{10 \text{ GeV}} \right)^{1/2} \lesssim 2 \times 10^{-7}$$



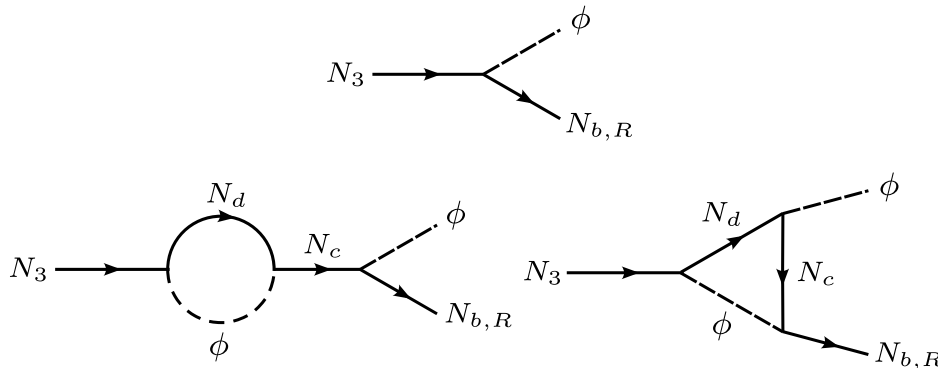
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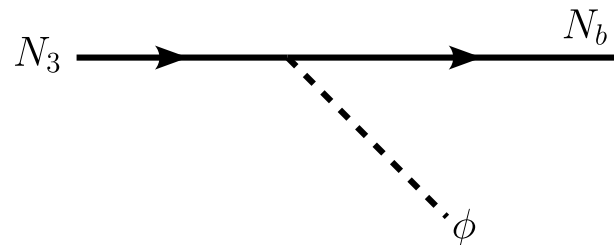
- CP asymmetry need to be large enough: $Y_L \gtrsim Y_B \approx 10^{-10}$



$$\epsilon = \frac{\Delta\Gamma}{\Gamma_{N_3}} \approx \sum_{c,d} \frac{1}{16\pi^2} \frac{\text{Im}(y_{cd}y_{d3}^*y_{2c}^*y_{23})}{|y_{23}|^2 + |y_{13}|^2}$$

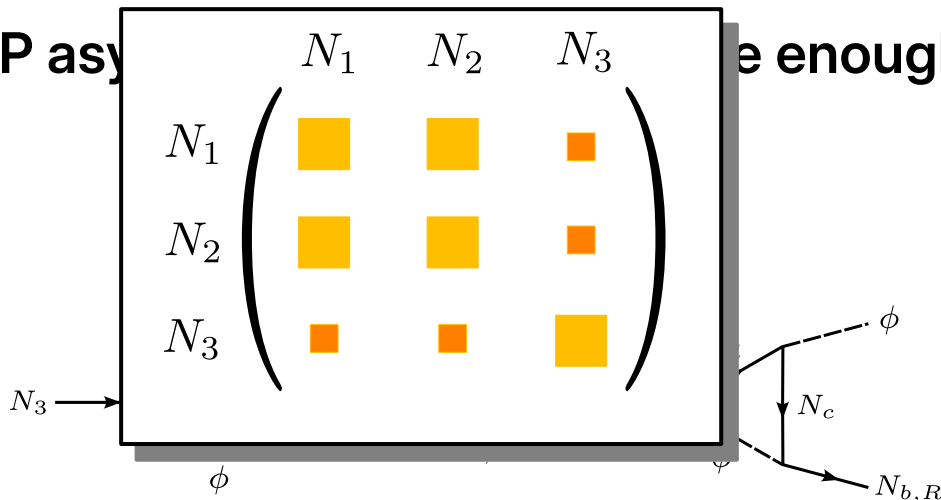
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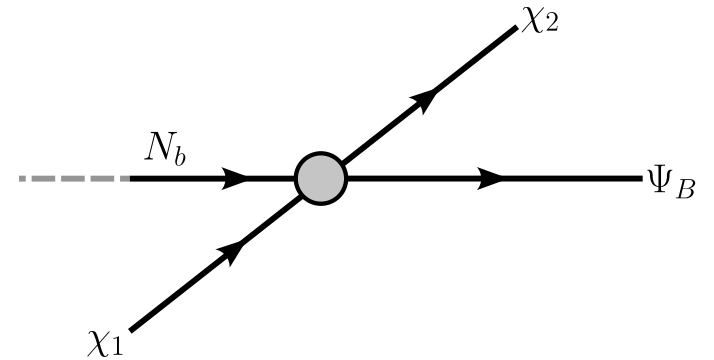
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Constraints

- $N_{2/1}$ need to live long enough to scatter

$$\Gamma_{N_{1,2}} \ll \Gamma_{\text{scatter}}$$



Constraints

- $N_{2/1}$ need to live long enough to scatter

$$\Gamma_{N_{1,2}} \ll \Gamma_{\text{scatter}}$$

- No inverse scattering

$$m_{N_2} + m_{\Psi_B} > m_{\chi_2} + m_{\chi_1}$$

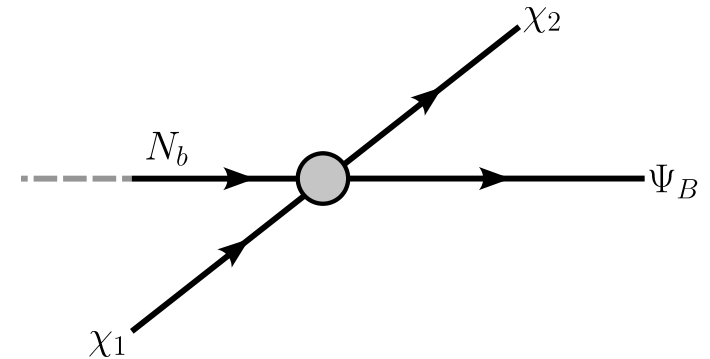
- No new decay channels

$$m_X + m_{\Psi_B} > m_{N_2}$$

$$m_X + m_{N_2} > m_{\Psi_B}$$

- Stable DM

$$m_{\chi_1} + m_X > m_{\chi_2}$$



- Correct relic abundance

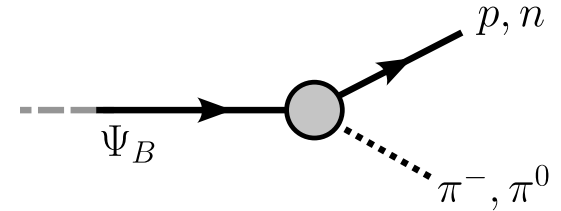
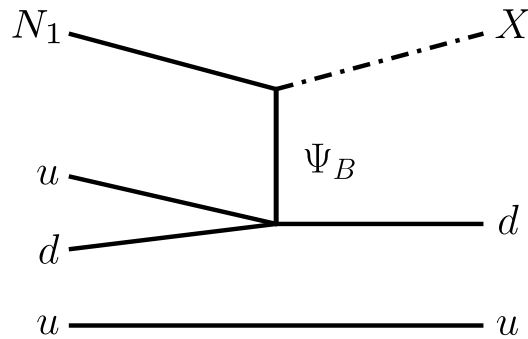
$$m_{\chi_1} + m_{\chi_2} \sim 5m_p$$

- Evolution of DM abundance

$$\frac{s_{\text{late}}}{s_{\text{early}}} \left(\frac{\Omega_{1,\text{early}}}{m_{\chi_1}} + \frac{\Omega_{2,\text{early}}}{m_{\chi_2}} \right) = \frac{\Omega_{1,\text{late}}}{m_{\chi_1}} + \frac{\Omega_{2,\text{late}}}{m_{\chi_2}}$$

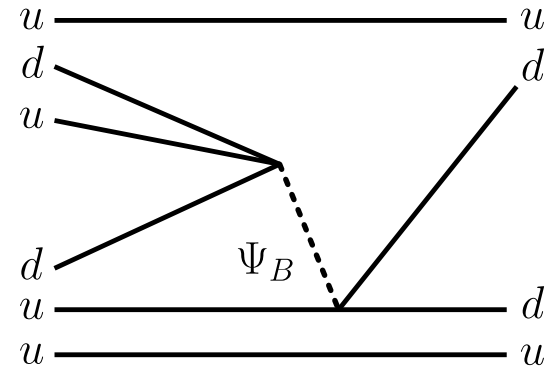
Constraints

- Induced nucleon decay $p \rightarrow \pi^+ + \cancel{E}$



- Dinucleon decay $pp \rightarrow \pi^+ \pi^+$

- LHC constraints $\frac{\lambda_{udd}}{\Lambda^2} \lesssim 0.07 \text{ TeV}^{-2}$

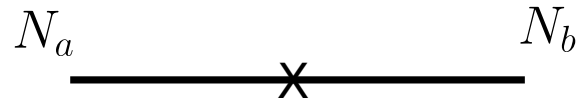


- Neutron stars $m_{\Psi_B} \gtrsim 1.2 \text{ GeV}$

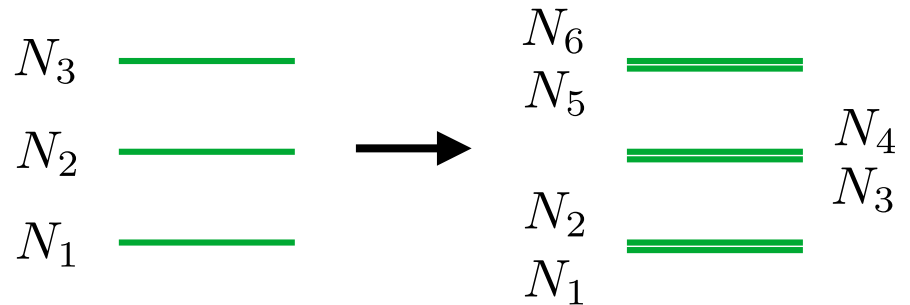
Majorana neutrinos?

Connect lepton asymmetry to smallness of neutrino masses

$$\mathcal{L} \supset -\mu_{ab} N_a N_b$$



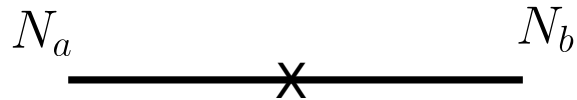
- Need psuedo-Dirac states:



Majorana neutrinos?

Connect lepton asymmetry to smallness of neutrino masses

$$\mathcal{L} \supset -\mu_{ab} N_a N_b$$



- Oscillation period needs to be slower than the relevant time-scales in the problem

$$\Delta m_{N_3} \ll \Gamma(N_3 \rightarrow N_b \phi)$$

$$\Delta m_{N_1} \ll \Gamma_{\text{scatter}}(N_1 \chi_1 \rightarrow \Psi_B \chi_2)$$

Inverse seesaw

Neutrino sector (extended inverse seesaw): $\lambda f \ll m_D \ll m$,

$$\mathcal{L}_M = -\frac{1}{2} \begin{pmatrix} \overline{\nu_R^C} & \overline{\mathcal{N}_R} & \overline{\mathcal{N}'_R} \end{pmatrix} \begin{pmatrix} 0 & m_D^\top & 0 \\ m_D & \lambda\sigma^* & m^\top \\ 0 & m & \lambda'\sigma \end{pmatrix} \begin{pmatrix} \nu_L \\ \mathcal{N}_L^C \\ \mathcal{N}'_L^C \end{pmatrix} + \text{h.c.}$$

Spontaneous symmetry breaking of $U(1)_L$ at the scale f

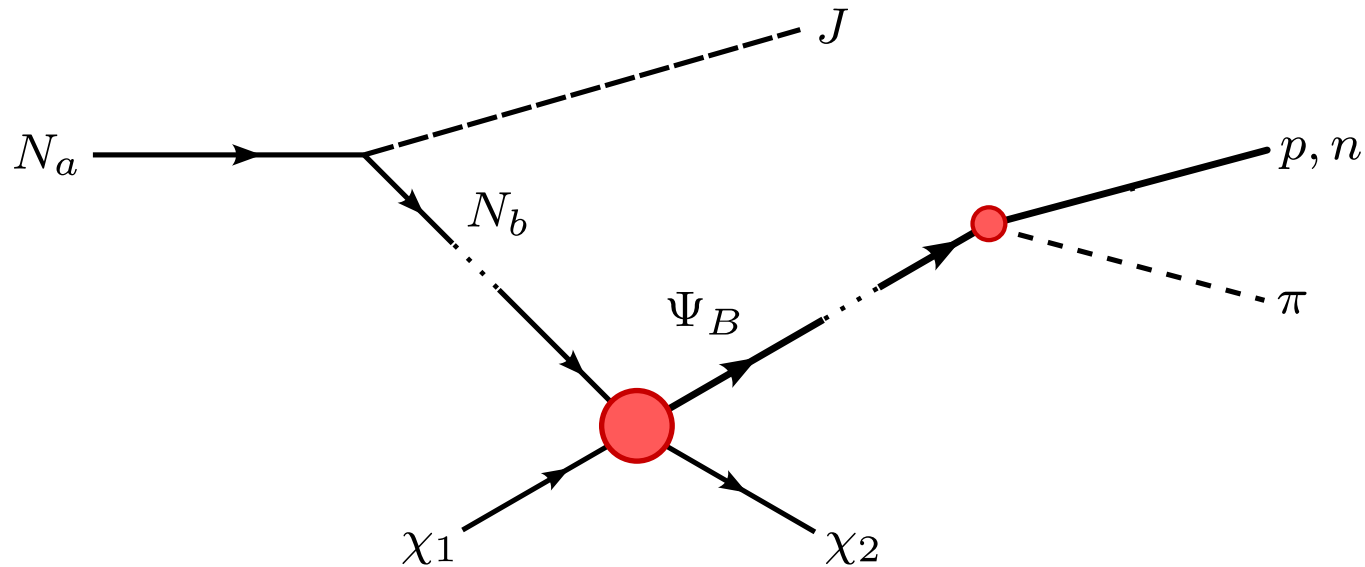
$$\sigma \rightarrow \frac{1}{\sqrt{2}}(f + \sigma_0 + iJ)$$

Neutrinos acquire hierarchical masses:

$$m_\nu \simeq \frac{\mu m_D^2}{m^2}, \quad m_{N_1, N_2} \simeq m \mp \frac{\mu}{2}$$

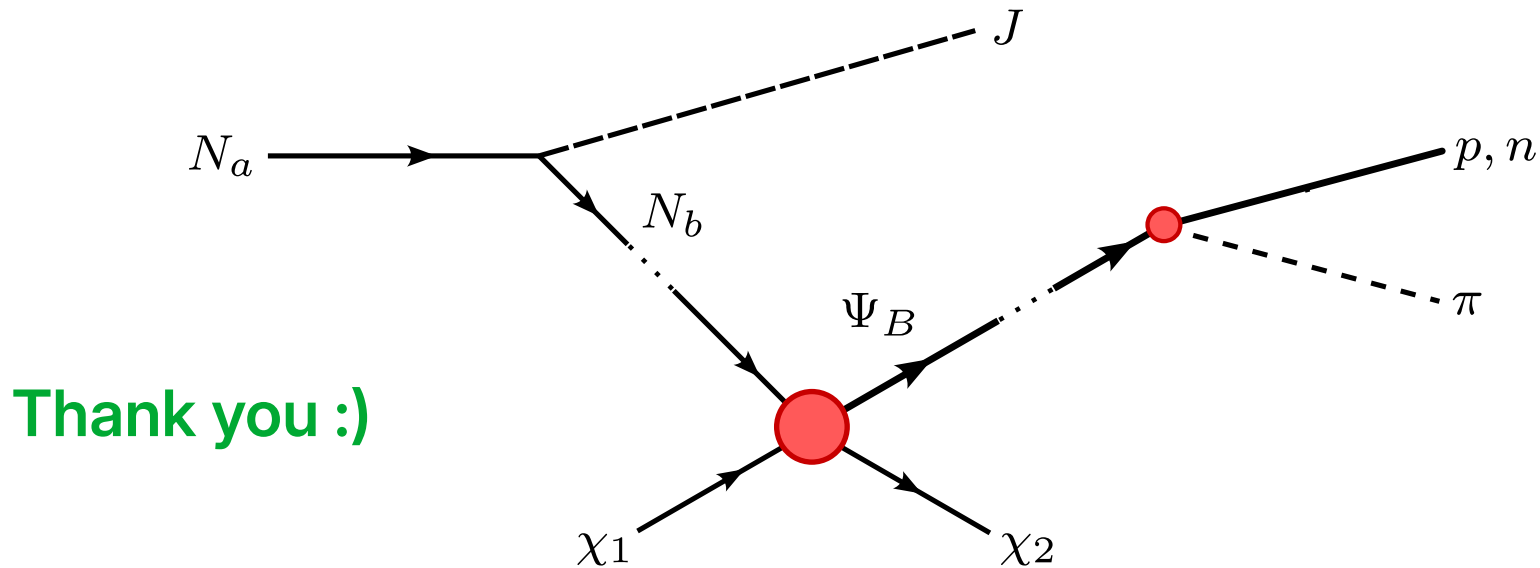
Conclusion

Phenomenologically promising model of low-scale leptogenesis.



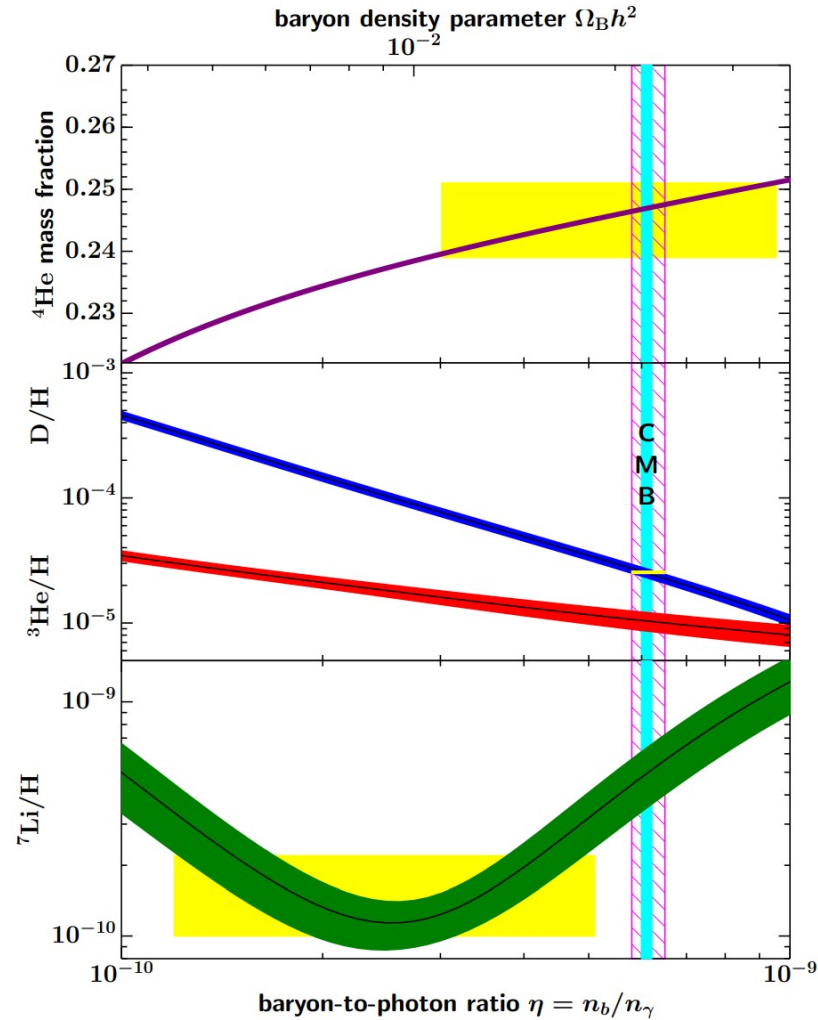
Conclusion

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BACK-UPS

Primordial abundances
as predicted by the standard
model of BBN (1912.01132)



The mechanism - details

1. Lepton asymmetry

Introduce SM singlets:

	\mathcal{N}_i	\mathcal{N}'_i	σ
L	1	-1	2
spin	1/2	1/2	0

Neutrino sector (extended inverse seesaw):

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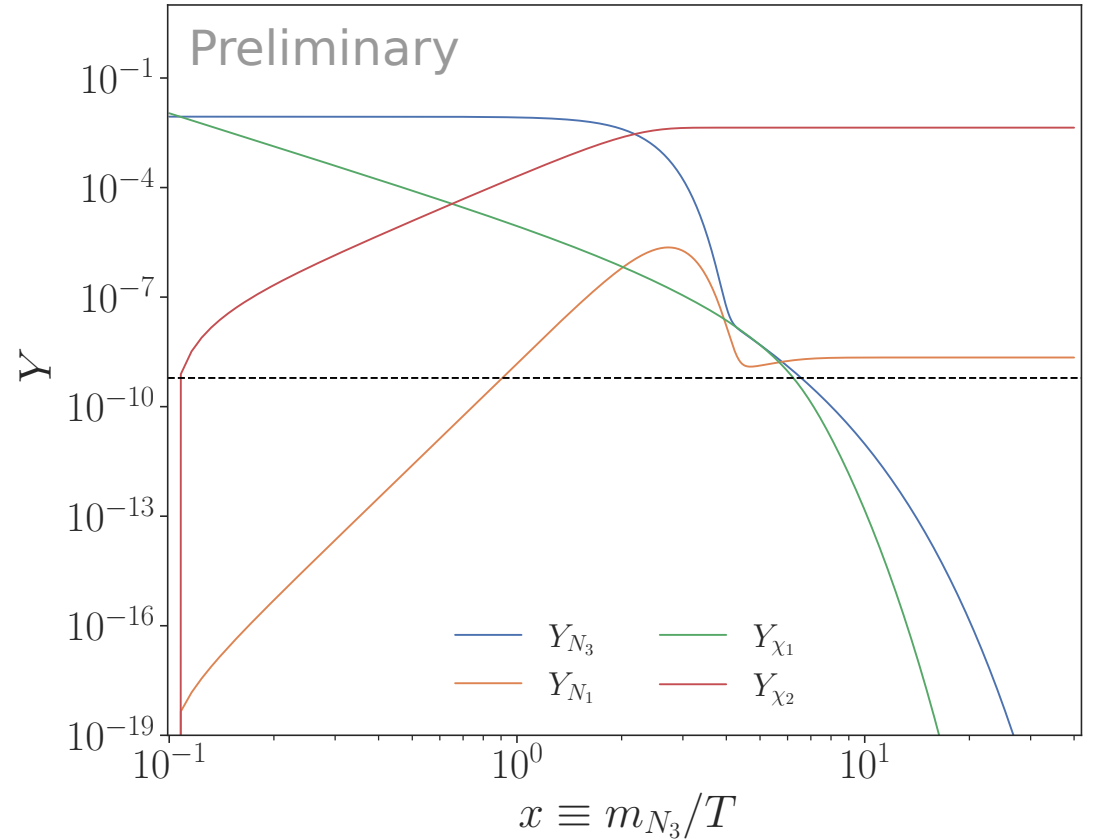
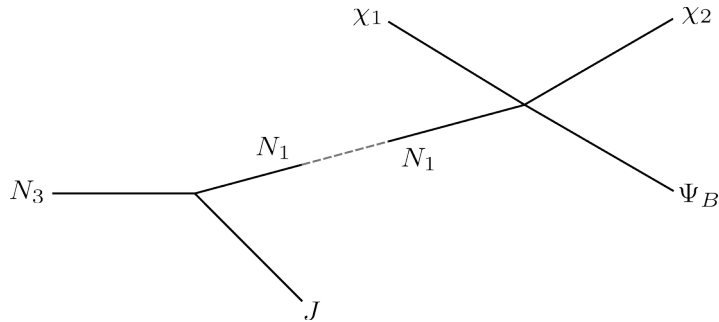
Evolution

$$m_{N_3} = 20 \text{ GeV}$$

$$m_{\chi_1} = 0.5 \text{ GeV}$$

$$m_{\chi_2} = 0.3 \text{ GeV}$$

$$m_{\Psi_B} = 1.2 \text{ GeV}$$



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