Massive Vector Boson Sterile Neutrino Decay

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Sterile Neutrino Decay

- $m_N \gg 200\mathrm{GeV}$, Before EWSB. $N \leftrightarrow h\nu / h^{\pm} l^{\mp}$.
- $m_N \ll 50\mathrm{GeV}$, After EWSB, however low temperature. Thermal effects can be neglected!!
- Gap: $m_N \sim 100\mathrm{GeV}$.

Sterile Neutrino Decay

- J.Ghiglieri, M.Laine, “Full” thermal calculations of sterile neutrino production in the early universe. A series of paper.

- $\mathscr{K}^2 = 0$, only for small m_N.

- T.Hambye, D.Teresi, an approximation. When $T < T_c$, replace W_L/Z_L with $G^{0,\pm}$ of the same mass as the dressed H. (arXiv:1606.00017)

Sterile Neutrino Decay

- What about $m_N \sim 100\mathrm{GeV}$?
- Resolve the massive vector boson’s thermal emotion at first!

Massive Vector Boson

- $$\frac{i}{k^2 - m^2}\left[-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2 - \xi m^2}(1-\xi)\right]$$
- $$\frac{i}{k^2 - \xi m^2}$$

Precise cancellation of these two poles at zero temperature!

Goldstone Equivalence Gauge

- Thanks Junmou Chen.
- Physical Gauge: extend the “polarization vector” with one extra Goldstone degree of freedom:
- $\epsilon^{\mu}_{\pm,L} \rightarrow \epsilon^{M}_{\pm,L}, M = 0,1,2,3,4.$
- $\epsilon^{M}_{\pm}$ does not change.

Goldstone Equivalence Gauge

$$\epsilon^W_{L\text{out}}(p_2) = \begin{pmatrix} -\frac{\sqrt{p_2^2}}{n_2\cdot p_2} n_2^\mu \\ -i\frac{m_W(T)}{\sqrt{p_2^2}} \end{pmatrix},$$

$$p_2^\mu \mathscr{M}_{V\mu} = i m_V \mathscr{M}^{\text{GS}}$$

$$\epsilon^W_{L,R_\xi} = \epsilon^W_{L\text{in}} + \begin{pmatrix} \frac{p_2^\mu}{\sqrt{p_2^2}} \\ -i\frac{m_W(T)}{\sqrt{p_2^2}} \end{pmatrix},$$

Advantage: All the Goldstone contributions are separated out!

Finite Temperature

$$D_0^{\text{full},MN}(k) = \frac{i}{k^2 - m_A^2 - \Pi_T(k) + i\epsilon} P_T + \frac{i}{k^2 - m_A^2 - \Pi_L(k) + i\epsilon} P_L + \frac{1}{1 - \frac{\Pi_U(k)}{m_A^2}} \frac{i}{k^2 + i\epsilon} \begin{bmatrix} 0_{4\times4} & 0_{4\times1} \\ 0_{1\times4} & 1 \end{bmatrix}.$$

Transverse, Longitudinal polarizations remain unchanged. However, the Goldstone poles no longer cancel!

$$\Delta_{\textbf{GS}}^F(k) = \frac{k^2 - \Pi_L(k) + i\epsilon}{k^2 - m_A^2 - \Pi_L(k) + i\epsilon} \frac{i}{k^2 + i\epsilon}$$

Massless Goldstone with the "Renormalization Factor"

$$Z_{\text{GS}}^2 = \frac{\Pi_L(k) + i\epsilon}{m_A^2 + \Pi_L(k) + i\epsilon}!$$

Finite Temperature

- Wait!!!!!!!!!!!!!!!!
- $\Pi_L(k) = -\frac{2m_E^2 k^2}{\overrightarrow{k}^2}\left(1 - \frac{k^0}{|\overrightarrow{k}|} Q_0(\frac{k^0}{|\overrightarrow{k}|})\right)$ in HTL approximation.
- The k^2 cancels the pole in $\Delta^F_{\text{GS}}(k) = \frac{k^2 - \Pi_L(k) + i\epsilon}{k^2 - m_A^2 - \Pi_L(k) + i\epsilon} \frac{i}{k^2 + i\epsilon}$!

Finite Temperature

- $\Pi_L(k) = -\frac{2m_E^2 k^2}{\overrightarrow{k}^2}\left(1 - \frac{k^0}{|\overrightarrow{k}|} Q_0(\frac{k^0}{|\overrightarrow{k}|})\right)$ has a branch-cut along $k^0 = (-|\overrightarrow{k}|, |\overrightarrow{k}|)$.

- $\Delta^F_{\text{GS}}(k) = \frac{k^2 - \Pi_L(k) + i\epsilon}{k^2 - m_A^2 - \Pi_L(k) + i\epsilon} \frac{i}{k^2 + i\epsilon}$ inherit this branch cut in place of the two poles.

- The branch cut peaks significantly at both $k^0 = \pm |\overrightarrow{k}|$. I call it a pair of Quasi-Pole.

Finite Temperature

- When $T > T_c$, $m_W = 0$, Goldstone and the Longitudinal polarization decouples. $\Delta^F_{\mathrm{GS}}(k) = \frac{i}{k^2 + i\epsilon}$.
- When $T < T_c$, two poles fragment into two branch cut, which is still similar to two poles. I call this a “cadaver” of a Goldstone boson. Longitudinal polarization eats the Goldstone, but could not devour once in a time.
- $T = 0$, the cadaver completely disappear.

Sterile Neutrino $1 \leftrightarrow 2$ processes

- T.Hambye, D.Teresi, an approximation. When $T < T_c$, replace W_L/Z_L with $G^{0,\pm}$ of the same mass as the dressed H. (arXiv:1606.00017)

- Fermions dispersion relations approximation according to G.Guidice et.al., 0310123

- Too rough an approximation!

Sterile Neutrino $1 \leftrightarrow 2$ processes

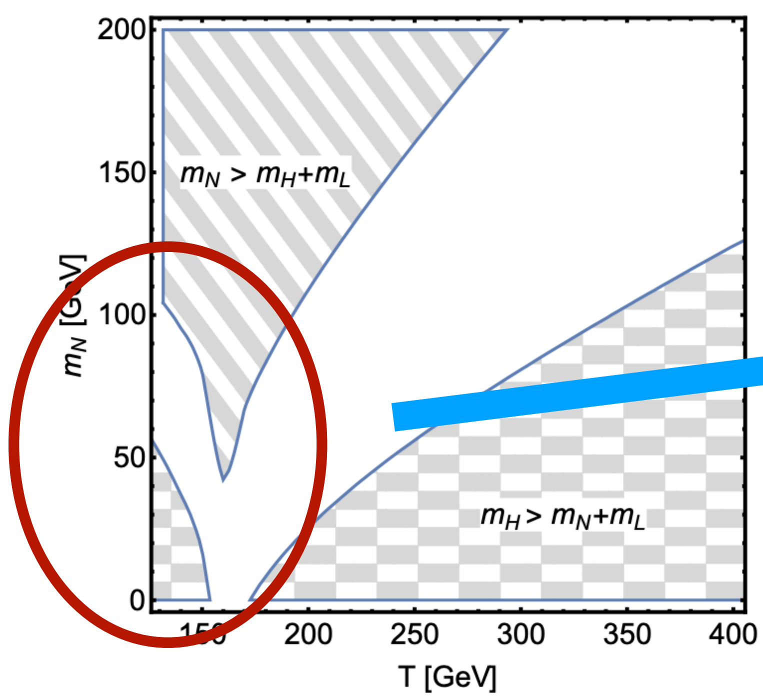


FIG. 1: Values of m_N and T for which the $N \to LH$ and $H \to LN$ decays are kinematically allowed.

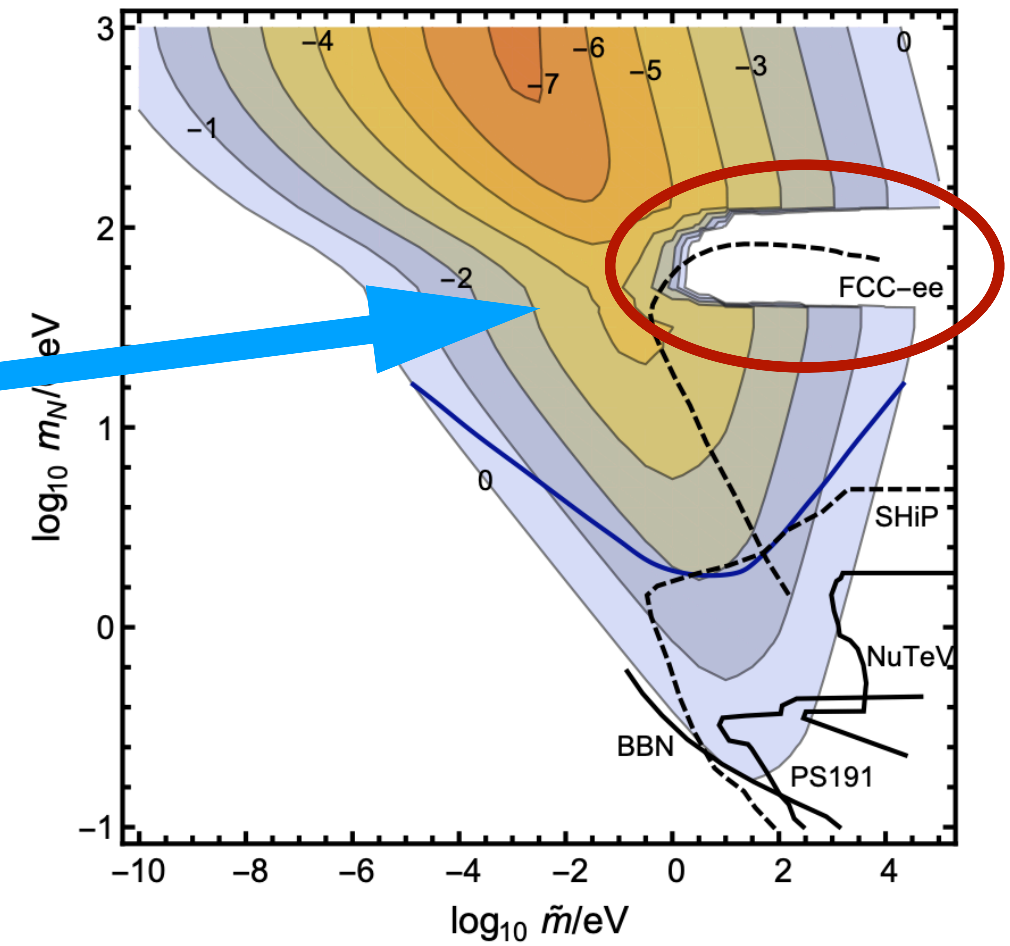
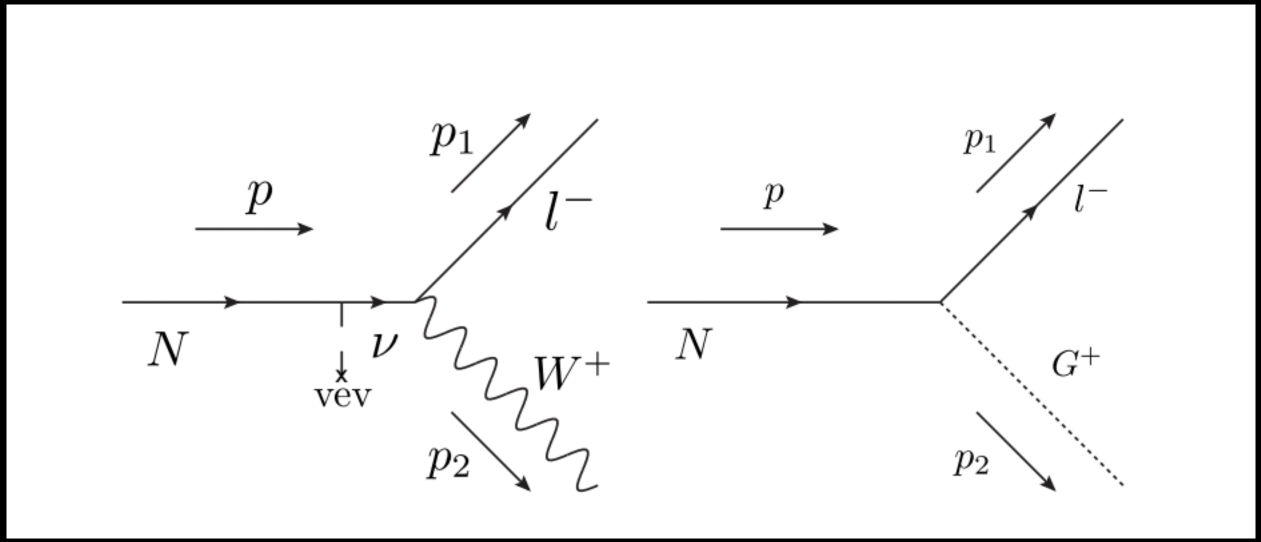
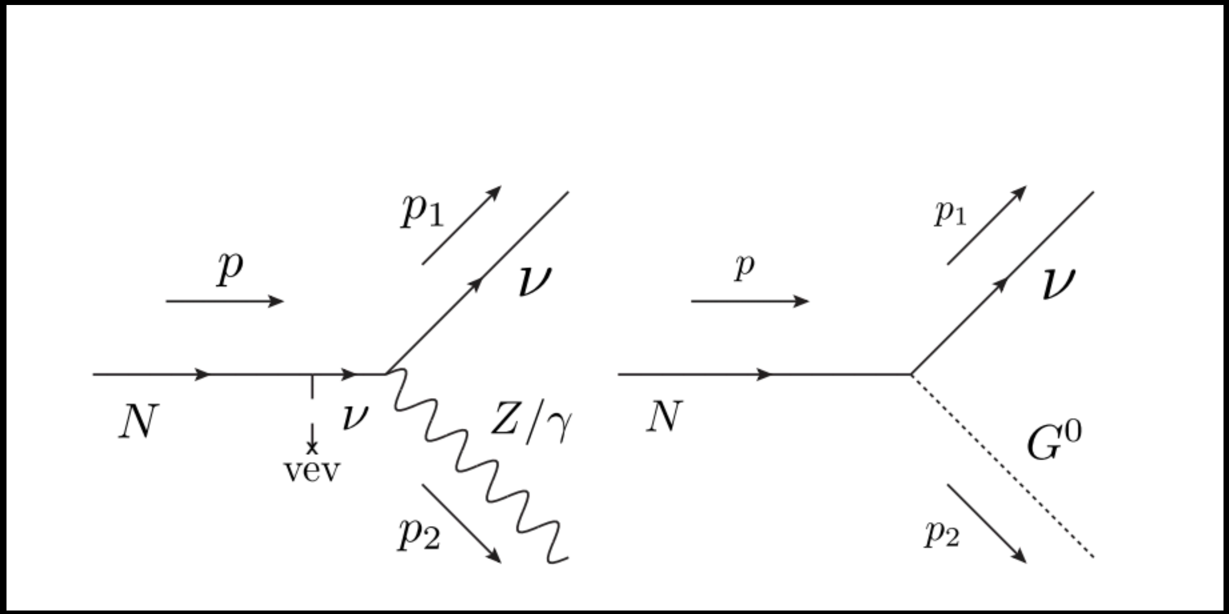
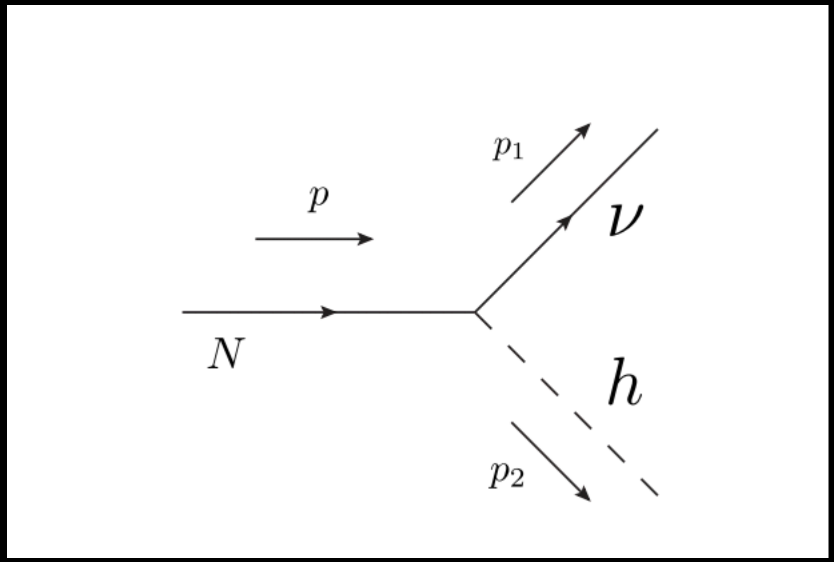


FIG. 3: Logarithm base 10 of the asymmetry ϵ_{CP} needed to obtain successful leptogenesis, with the RH neutrinos initially at thermal equilibrium. We also plot the relevant existing bounds (solid lines) and projected sensitivities of the SHiP [16] and FCC-ee [17] experiments (dashed lines). The area below the thick blue line requires values of ϵ_{CP} which are not reachable for such low m_N.

Sterile Neutrino $1 \leftrightarrow 2$ processes







Sterile Neutrino $1 \leftrightarrow 2$ processes

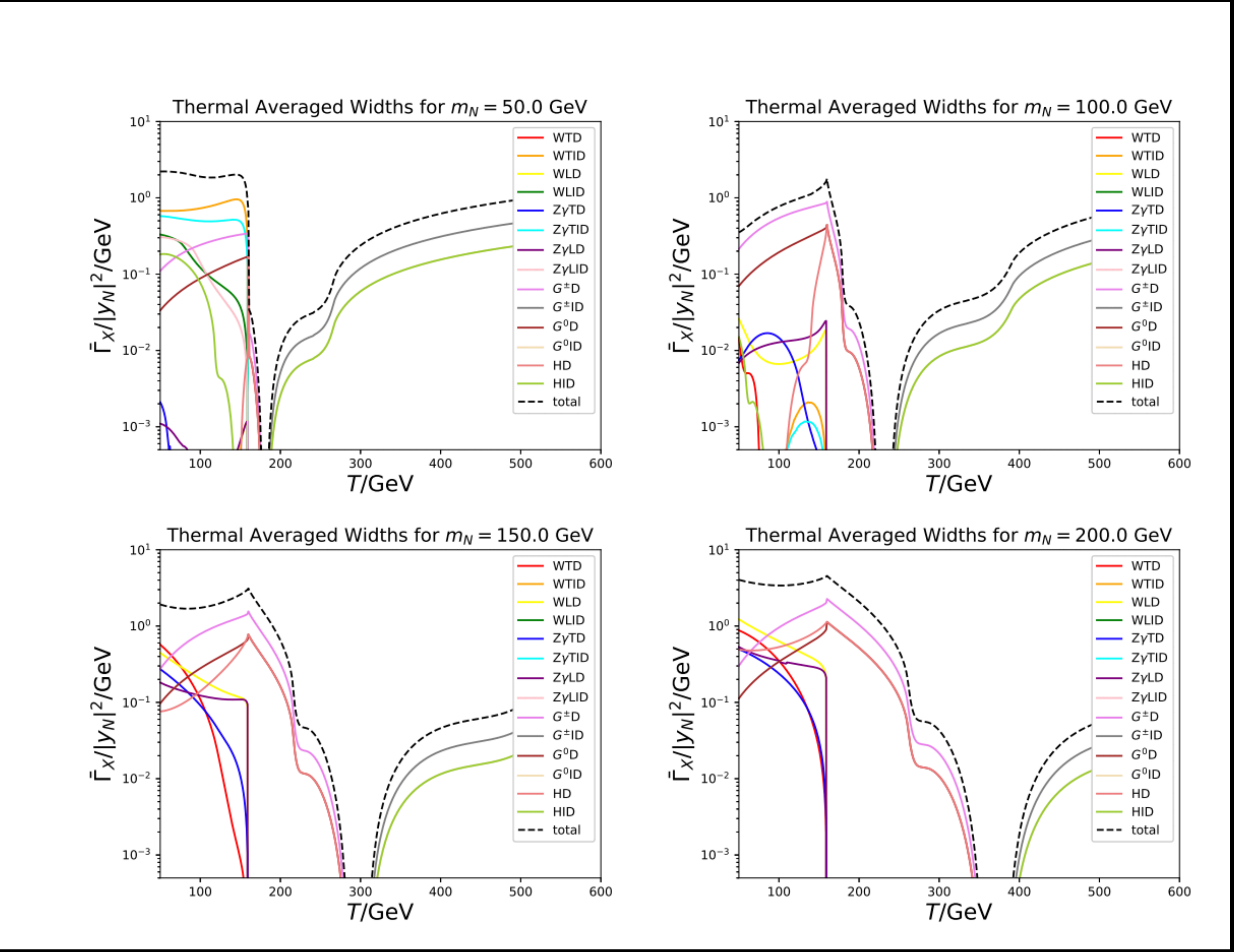
- Lepton: Particle Hole.
- Sterile Neutrino Decay, Inverse Decay of $W/Z/\gamma/h$.
- Transverse, Longitudinal, Goldstone Cadaver.
- 54 channels in total.

Sterile Neutrino $1 \leftrightarrow 2$ processes

Combine all the channels into 14 channels

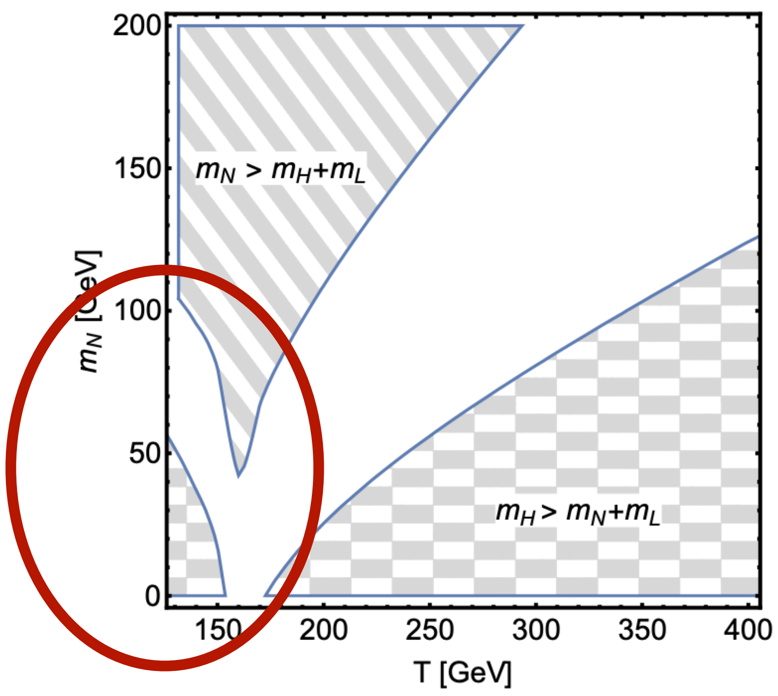
Alias	Meaning	Alias	Meaning
WTD	$N \leftrightarrow W_T^+ l^-$	ZγLID	$N\bar{\nu} \leftrightarrow Z_L/\gamma_L$
WTID	$Nl^+ \leftrightarrow W_T^+$	$G^\pm$D	$N \leftrightarrow G^+ l^-$
WLD	$N \leftrightarrow W_L^+ l^-$	$G^\pm$ID	$NG^- \leftrightarrow l^-$, $Nl^+ \leftrightarrow G^+$
WLID	$Nl^+ \leftrightarrow W_L^+$	G^0D	$NG^0 \leftrightarrow \nu$, $N\bar{\nu} \leftrightarrow G^0$
ZγTD	$N \leftrightarrow Z_T/\gamma_T \nu$	G^0ID	$NG^0 \leftrightarrow \nu$, $N\bar{\nu} \leftrightarrow G^0$
ZγTID	$N\bar{\nu} \leftrightarrow Z_T/\gamma_T$	HD	$N \leftrightarrow h\nu$
ZγLD	$N \leftrightarrow Z_L/\gamma_L \nu$	HID	$Nh \leftrightarrow \nu$, $N\bar{\nu} \leftrightarrow h$

Sterile Neutrino $1 \leftrightarrow 2$ processes



Sterile Neutrino $1 \leftrightarrow 2$ processes

Threshold Effect



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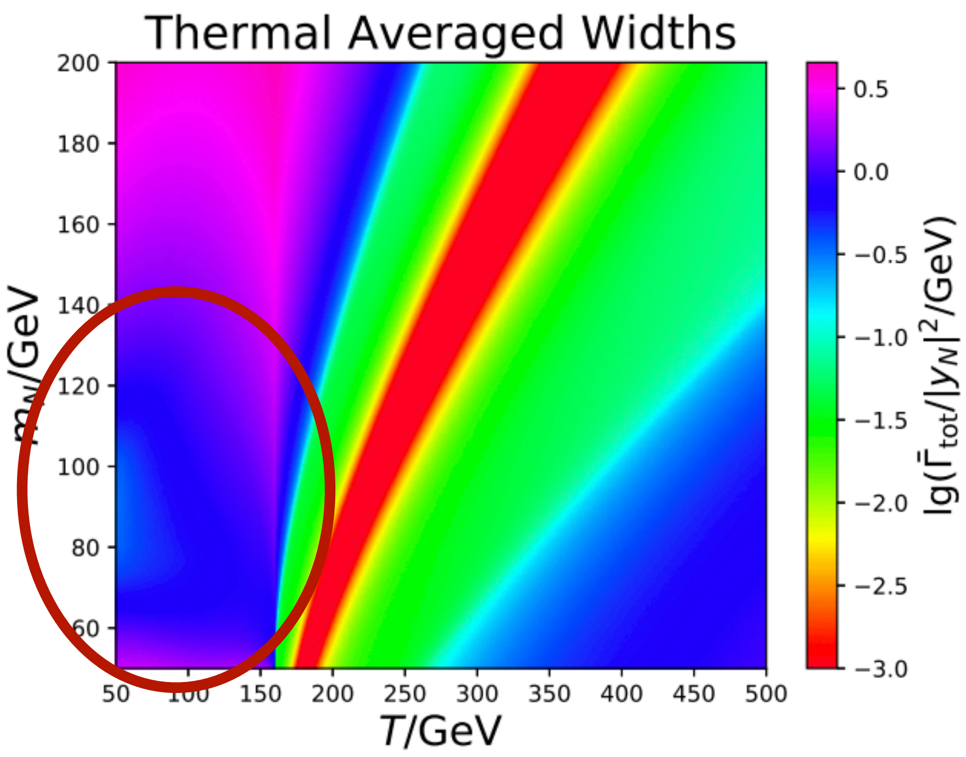
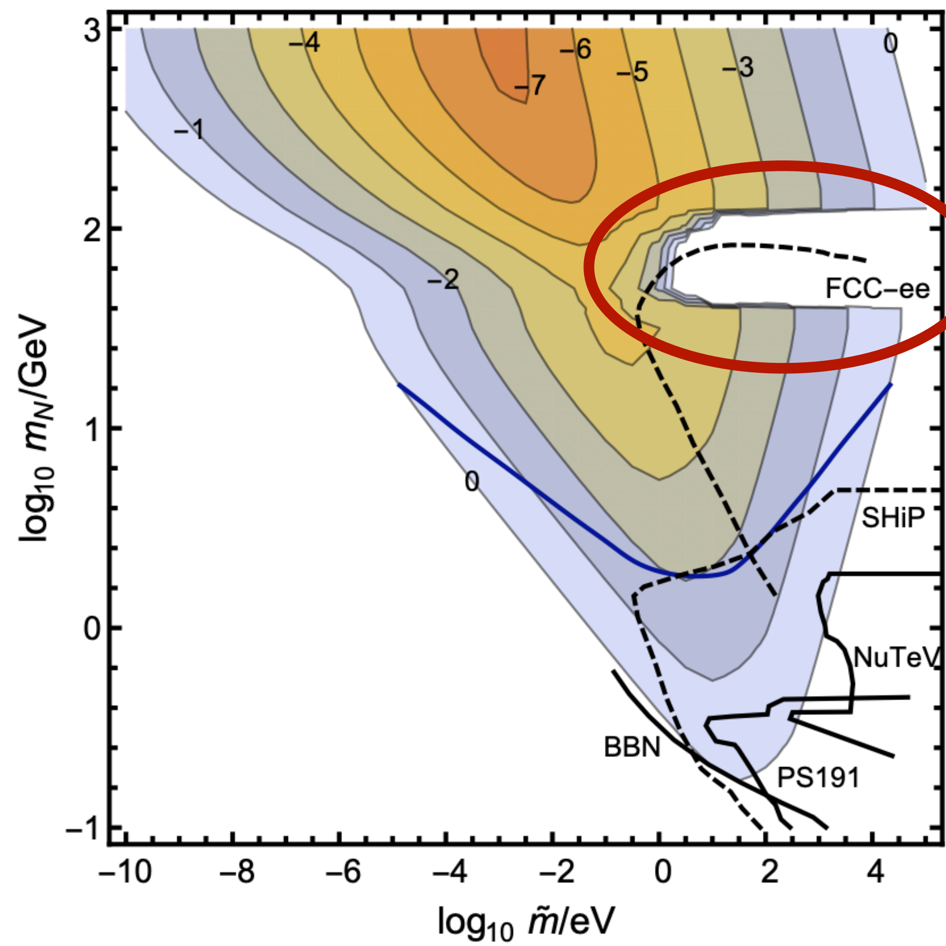
No Threshold Effect



Leptogenesis

Void existing



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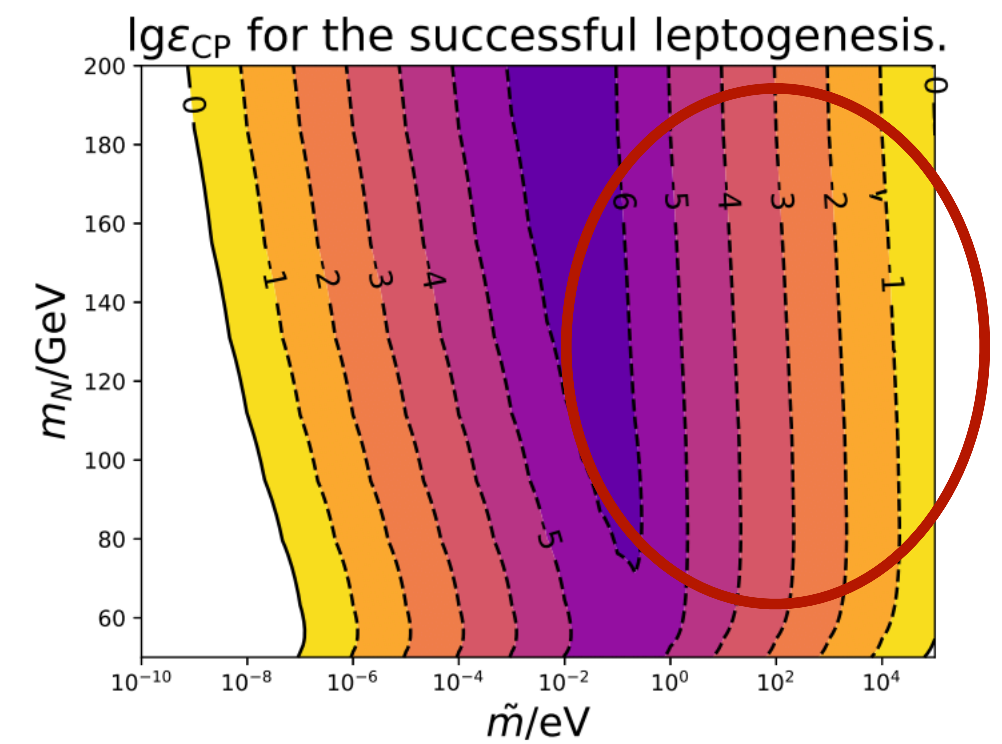
Void disappearing



Future Prospect

- Full calculation of $2 \leftrightarrow 2$ processes. (Thus only initial thermal equilibrium situation)

- LPM resumption.

- Calculation of ϵ_{CP}.

- Dark matter freeze-in involving the massive vector boson.

Thanks!