

# LANDAU-ZENER PRODUCTION OF STERILE NEUTRINO DM

EUNG JIN CHUN

In collaboration with Kadota & Yun, 2609.04650



**NNU · 南京师范大学**  
NANJING NORMAL UNIVERSITY



第七届标准模型及新物理联合研讨会  
**THE 7TH JOINT WORKSHOP ON  
THE STANDARD MODEL AND BEYOND**

**OCT 28 - NOV 1, 2026**  
Nanjing Normal University · Xianlin Campus



# OUTLINE

- TYPE I SEESAW WITH THREE RHNS FOR THE GENERATION OF NEUTRINO MASS AND ITS CONNECTION TO DARK MATTER PHYSICS.
- DODELSON-WIDROW/SHI-FULLER MECHANISM FOR KEV RHN DM & ITS VARIATION.
- HEAVIER RHN DM THROUGH RESONANT PRODUCTION WITH SELF-INTERACTION IN THE RHN SECTOR.

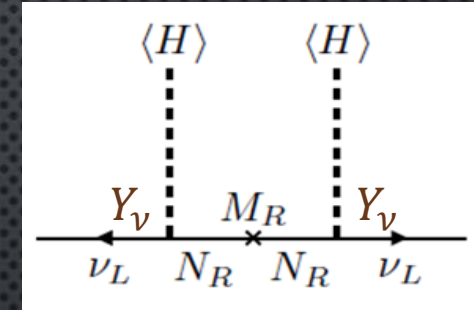
# TYPE I SEESAW

- SINGLET MAJORANA FERMION  $N$  COUPLING TO THE NEUTRINO YUKAWA TERM:

$$\mathcal{L}_\nu = Y_\nu L H N + \frac{1}{2} M_N N N + h.c. \Rightarrow m_\nu = Y_\nu \frac{\langle H \rangle^2}{M_N} Y_\nu^T$$

- TYPICAL SIZE OF THE YUKAWA OR MIXING ANGLE:

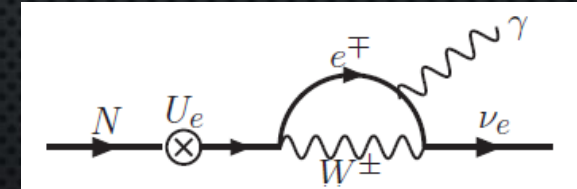
$$Y_\nu \sim \frac{\sqrt{m_\nu M_N}}{\langle H \rangle} \sim 10^{-6} \sqrt{\frac{m_\nu}{0.05 \text{eV}} \frac{M_N}{\text{TeV}}} \quad \theta = \frac{Y_\nu \langle H \rangle}{M_N} \sim 7 \times 10^{-3} \left( \frac{\text{keV}}{M_N} \right)$$



- TWO MASSES FOR ATMOSPHERIC AND SOLAR NEUTRINOS  $\rightarrow$  ONE RHN CAN BE COSMOLOGICALLY STABLE:

$$\Gamma_{N \rightarrow LH} = \frac{Y_\nu^2 M_N}{8\pi} \sim \frac{1}{10^{28} \text{sec}} \left( \frac{Y_\nu}{10^{-27}} \right)^2 \frac{M_N}{\text{TeV}}$$

$$\Gamma_{N \rightarrow \nu \gamma} = \frac{9\alpha G_F^2}{265\pi^4} \theta^2 M_N^5 \sim \frac{1}{10^{28} \text{sec}} \left( \frac{\theta}{3 \times 10^{-4}} \right)^2 \left( \frac{M_N}{\text{keV}} \right)^5$$

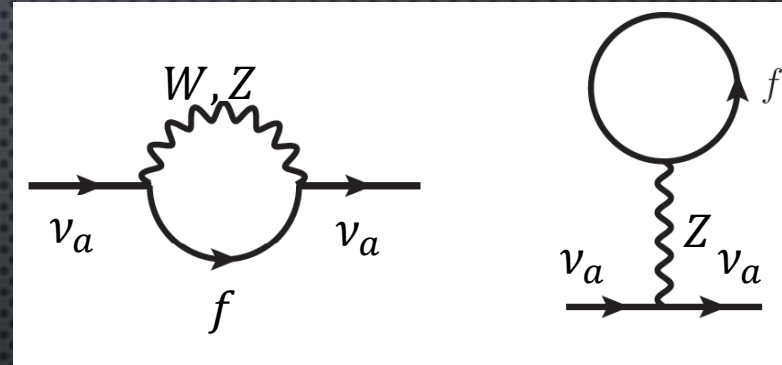


# NEUTRINO PROPAGATION IN THERMAL MEDIUM

- NEUTRINO PROPAGATION IN THERMAL BACKGROUND (MSW EFFECT) OF  $f = \alpha, \nu_\alpha, q$  WHERE  $\alpha = e, \mu, \tau$ .

$$\begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = \begin{pmatrix} c_{\theta_T} & s_{\theta_T} \\ -s_{\theta_T} & c_{\theta_T} \end{pmatrix} \begin{pmatrix} \nu_{T1} \\ \nu_{T2} \end{pmatrix}$$

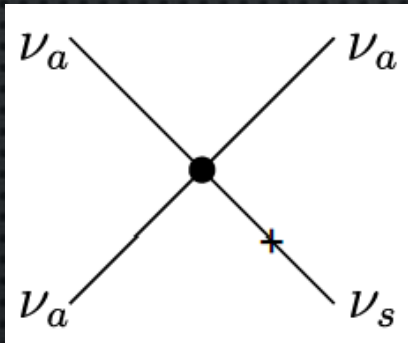
$$i \frac{d}{dt} \begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = H_T \begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix}$$



$$H_T = \left( p + \frac{m_1^2 + m_2^2}{2p} + \frac{V(T, p)}{2} \right) I + \frac{1}{2} \begin{pmatrix} V(T, p) - \Delta c_{2\theta} & \Delta s_{2\theta} \\ \Delta s_{2\theta} & \Delta c_{2\theta} - V(T, p) \end{pmatrix} \quad \Delta \equiv \frac{m_2^2 - m_1^2}{2p}$$

# DODELSON-WIDROW/SHI-FULLER MECHANISM

- STERILE NEUTRINO ( $\nu_s = N$ ) PRODUCTION THROUGH THE  $\nu_a - \nu_s$  MIXING IN THE PLASMA: THERMAL EFFECT OF THE TOTAL NUMBER DENSITY ( $n_a + n_{\bar{a}}$ ) AND LEPTON ASYMMETRY ( $\mathcal{L}_a = (n_a - n_{\bar{a}})/s$ ).



$$\Gamma(\nu_a \rightarrow \nu_s; p, T) = \frac{\Gamma_a}{2} s_{2\theta_T}^2$$

$$s_{2\theta_T}^2 = \frac{\Delta^2 s_{2\theta}^2}{\Delta^2 s_{2\theta}^2 + (\Delta c_{2\theta} - V_a(T, p))^2 + \Gamma_a^2/4}$$

Dodelson-Widrow '93 + Shi-Fuller '98

$$\Gamma_a(p) \sim G_F^2 p T^4$$

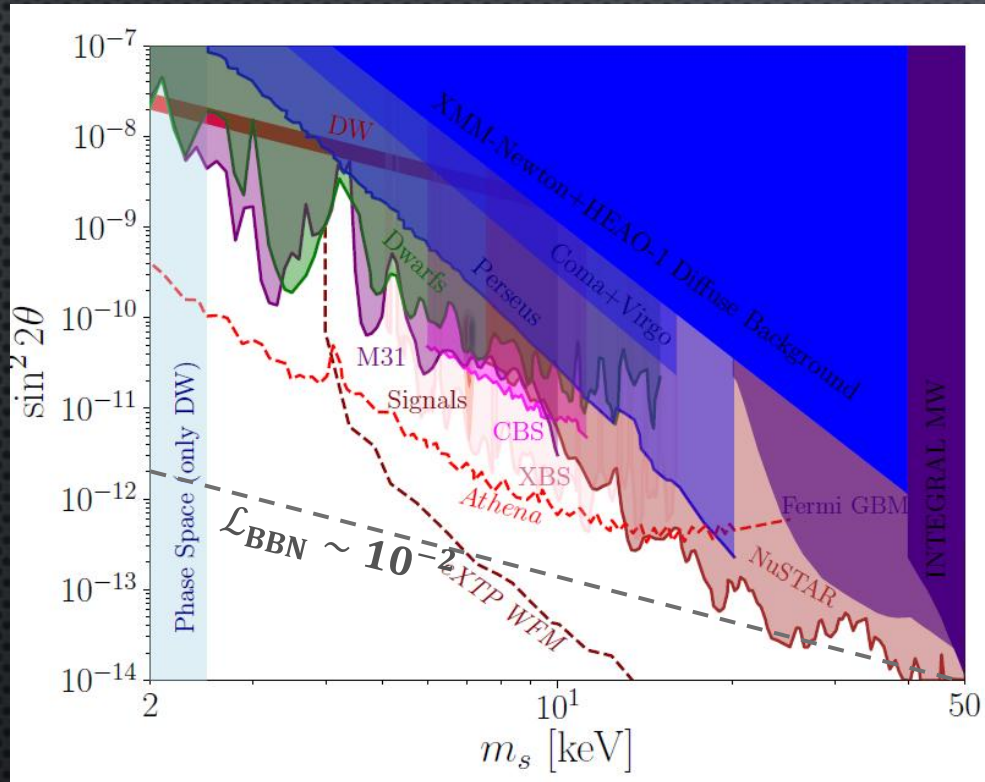
$$V_a(T, p) = V_a^T + V_a^L$$

$$\sim -G_F^2 p T^4 + G_F \mathcal{L}_a T^3$$

Resonance  
conversion

Abazajian, 2102.10183

# EXCLUSION PLOT



NSI to go below the excluded region.

Ex)  $\phi \nu_a \nu_a$ ;  $\phi \nu_s \nu_s$ ;  $\phi \nu_a \nu_s$

$X_\mu \bar{\nu}_a \gamma^\mu \nu_a$ ;  $X_\mu \bar{\nu}_s \gamma^\mu \nu_s$ ;  $X_\mu \bar{\nu}_a \gamma^\mu \nu_s$

→ Heavier RHN DM via  
a new resonance mechanism

Abazajian, 2102.10183 Boyarsky et.al., 1807.07938

# SELF-INTERACTION FOR RESONANT PRODUCTION

- THE MODEL:

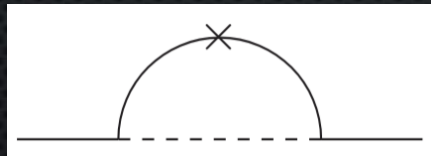
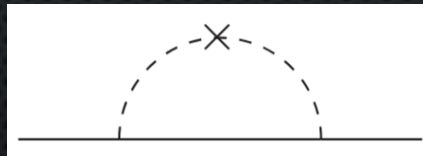
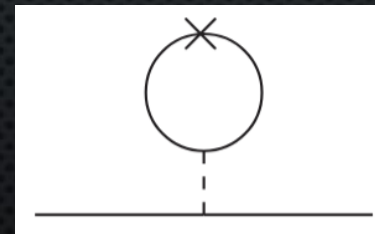
$$-\mathcal{L}_N = \frac{g_{ij}}{2} N_i N_j \phi + \frac{M_i}{2} N_i N_i + h.c.$$

- ASSUME  $g_{11} \ll g_{12} \ll g_{22}$  TO MAKE  $N_1$  DM, AND  $N_2$  IN THERMAL EQUILIBRIUM.

- THERMALIZE  $\phi$  THROUGH HIGGS PORTAL INTERACTION  $\frac{\lambda_{\phi H}}{2} |\phi|^2 |H|^2$  WITH  $\lambda_{\phi H} \lesssim 0.01$

- BELOW  $T < v_H$ , THERMALIZATION VIA  $\frac{\lambda_{\phi H} m_f}{2 m_h^2} \phi^2 \bar{f} f$  FOR  $m_\phi \gtrsim m_\mu$

- THERMAL DISTRIBUTION OF  $N_2$  &  $\phi$  PRODUCES (OFF-DIAGONAL) THERMAL MASS CORRECTIONS



# THERMAL HAMILTONIAN

$$\hat{H}_T \approx p I + \frac{1}{2p} \begin{pmatrix} 0 & \delta m_{12}^2 \\ \delta m_{12}^2 & \delta m_{22}^2 \end{pmatrix} + \frac{1}{2p} \begin{pmatrix} M_1^2 & (M_1 + M_2)\delta M_{12} \\ (M_1 + M_2)\delta M_{12} & M_2^2 + 2M_2\delta M_{22} \end{pmatrix}$$

$$\delta m_{ij}^2 \approx \frac{1}{8} g_{i2} g_{j2}^* T^2 \quad \delta M_{ij} \approx \frac{1}{6} g_{ij} g_{22} \frac{M_2}{m_\phi^2(T)} T^2 \quad m_\phi^2(T) = m_\phi^2 + \frac{1}{3} g_{22}^2 T^2$$

$$\hat{H}_T \Rightarrow \frac{1}{4p} \begin{pmatrix} \Delta M^2 - \delta M_{22}^2 & \delta M_{12}^2 \\ \delta M_{12}^2 & -\Delta M^2 + \delta M_{22}^2 \end{pmatrix} \quad \Delta M^2 \equiv M_1^2 - M_2^2 > 0 \quad \begin{aligned} \delta M_{22}^2 &= c_{22} g_{22}^2 T^2 \\ \delta M_{12}^2 &= c_{12} g_{12} g_{22} T^2 \end{aligned}$$

• THERMAL MIXING  $\tan 2\theta_m \approx \frac{\delta M_{12}^2}{\Delta M^2 - \delta M_{22}^2} \Rightarrow \text{Resonance at } T_{\text{res}} = \frac{\sqrt{\Delta M^2}}{\sqrt{c_{22} g_{22}}} \sim \sqrt{8} \frac{M_1}{g_{22}}$

• THERMAL EIGENVALUES  $\hat{H}_{T1,2} = \pm \frac{1}{4p} \sqrt{(\Delta M^2 - \delta M_{22}^2)^2 + (\delta M_{12}^2)^2}$

# QUANTUM KINETIC EQUATION

- LINDBALD FORM: 
$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}, \hat{\rho}] - \frac{1}{2}\{\hat{\Gamma}_A, \hat{\rho}\} + \frac{1}{2}\{\hat{\Gamma}_P, I - \hat{\rho}\}$$

$$\hat{\Gamma}_A = \delta_{22}A_2 \quad \hat{\Gamma}_P = \delta_{22}P_2 \quad A_2 = P_2 e^{+\omega/T} \quad P_2 \approx \frac{g_{22}^4}{32\pi} T$$

$$\omega \sim p$$

- NOTATION: 
$$z = \frac{M_1}{T} \quad H = \frac{1}{z} \frac{dz}{dt} \quad x = \frac{p}{T} \quad f_{\text{eq}} = \frac{1}{1 + e^x}$$

$$\delta = \frac{\hat{H}_{12}}{H} \quad \Delta = \frac{\hat{H}_{11} - \hat{H}_{22}}{H} \quad 2D = \frac{P_2 + A_2}{H} = \frac{P_2}{H} f_{\text{eq}}^{-1}$$

# QUANTUM KINETIC EQUATION

- REDUCED FORM:
 
$$z \frac{d\rho_{11}}{dz} = +i\delta(\rho_{12} - \rho_{21}) \quad z \frac{d\rho_{11}}{dz} \approx -\frac{\delta^2}{D^2 + \Delta^2}(\rho_{11} - \rho_{22})$$

$$z \frac{d\rho_{12}}{dz} = -(D + i\Delta)\rho_{12} + i\delta(\rho_{11} - \rho_{22}) \quad \rho_{12} \approx \rho_{12}^{qs} = \frac{i\delta}{D + i\Delta}(\rho_{11} - \rho_{22})$$

$$z \frac{d\rho_{22}}{dz} = -i\delta(\rho_{12} - \rho_{21}) + 2D(\rho_{22} - f_{eq}) \quad \rho_{22} \approx f_{eq}$$
- OUR PARAMETERS
 
$$(\delta, \Delta, D) \sim \frac{1}{64} \sqrt{\frac{45}{2\pi^3 g_*}} \frac{m_{pl}}{M_1} \left( g_{12} g_{22}^2 \frac{z}{z_{res}}, \quad 2g_{22}^3 \left( \frac{z}{z_{res}} - 1 \right), \quad \frac{g_{22}^5}{32\pi} \frac{z}{z_{res}} \right)$$

$$\delta \ll D \ll \Delta \quad \text{with} \quad g_{12} \ll g_{22} < 1$$
- SOLUTION
 
$$\rho_{11} \approx (1 - e^{-I(x)}) f_{eq}(x) \quad \text{with} \quad I(x) = \int \frac{2\delta^2 D}{D^2 + \Delta^2} \frac{dz}{z}$$

# RESONANCE PRODUCTION AND LANDAU-ZENER

- NARROW WIDTH:

$$\left[ \frac{D}{\Delta'} \right]_{\text{res}} \sim \frac{g_{22}^2}{64\pi} \ll 1 \Rightarrow I(x) \approx I_{\text{res}} = 2\pi \left[ \frac{\delta^2}{\Delta'} \right]_{\text{res}}$$

$$\Rightarrow \rho_{11} \approx (1 - e^{-I_{\text{res}}}) f_{\text{eq}} \quad I_{\text{res}} = \frac{\pi}{2} \gamma_{\text{ad}}$$

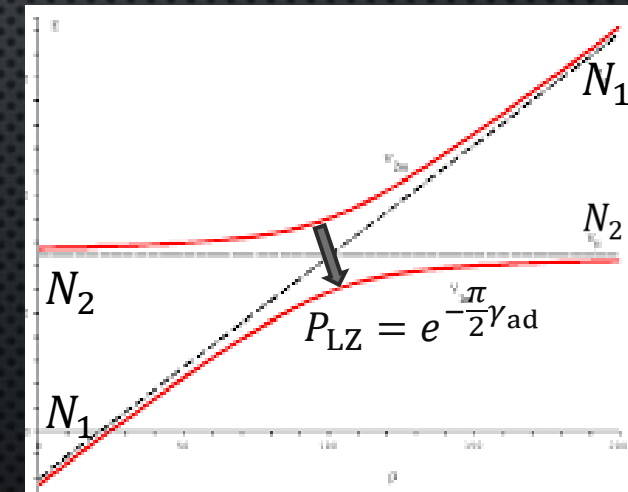
- FINAL YIELD:  $I_{\text{res}} \sim \frac{1}{\sqrt{g_*}} g_{12}^2 g_{22} \frac{m_{\text{pl}}}{M_1} \ll 1$

$$\rho_{11} \approx I_{\text{res}} f_{\text{eq}} \Rightarrow \frac{n_1}{s} \sim \frac{0.1}{g_*^{3/2}} g_{12}^2 g_{22} \frac{m_{\text{pl}}}{M_1}$$

- LANDAU-ZENER:

$$P(N_2 \rightarrow N_1) = 1 - e^{-\frac{\pi}{2} \gamma_{\text{ad}}}$$

$$\gamma_{\text{ad}} \equiv \left| \frac{\Delta H_T}{d\theta_T/dt} \right| = \left( \frac{(\delta M_{12}^2)^2}{H T M_1^2} \right)_{\text{res}}$$



# CONDITIONS

- $N_1$  DM NUMBER DENSITY  $M_1 \frac{n_1}{s} \approx 0.44 \text{ eV} \Rightarrow g_{12}^2 g_{22} \approx 5 \times 10^{-24}$   
independently of  $M_1$  (\*)  $I_{\text{res}} \lesssim \frac{\text{keV}}{M_1} \ll 1$
- RESONANCE & STABILITY REQUIREMENT  $0 < M_1 - M_2 < m_\phi < M_1 + M_2$
- WIDE RANGE OF DM MASS  $m_\mu \lesssim M_1 \lesssim 10^{14} g_{22}^5 \text{ GeV}$

# CONCLUSION

- STERILE (RH) NEUTRINO CAN BE COSMOLOGICALLY STABLE TO BECOME A DM CANDIDATE.
- ORIGINAL MECHANISM OF DW PREDICTING KEV DM HAS BEEN STUDIED AND EXTENDED IN MANY WAYS ASSUMING VARIOUS NSI.
- WE SUGGEST A NEW SCENARIO WITH THERMAL EFFECT IN THE RHN SECTOR REALIZING DM PRODUCTION THROUGH RESONANT PROCESS, WHICH WORKS FOR WIDE RANGE OF MASS SCALE ABOVE 0.1 GeV.
- THE VIABLE PARAMETER REGION EXHIBITS THE LANDAU-ZENER TRANSITION WITH  $\gamma_{ad} \ll 1$ .