LANDAU-ZENER PRODUCTION OF STERILE NEUTRINO DM

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KIAS

Work still in progress with Kadota & Yun

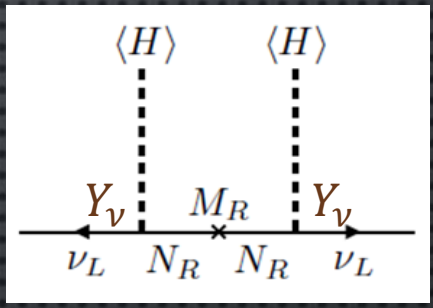
OUTLINE

- 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 non-adiabatic transition in the RHN sector.

TYPE I SEESAW

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

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

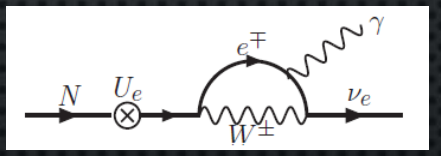


- TYPICAL SIZE OF THE YUKAWA FOR SEESAW:

$$Y_\nu \sim \frac{\sqrt{m_\nu M_N}}{\langle H \rangle} \sim 10^{-6} \sqrt{\frac{m_\nu}{0.05\text{eV}} \frac{M_N}{\text{TeV}}}$$

- TWO MASSES FOR ATMOSPHERIC AND SOLAR NEUTRINOS → ONE RHN CAN BE COSMOLOGICALLY STABLE:

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



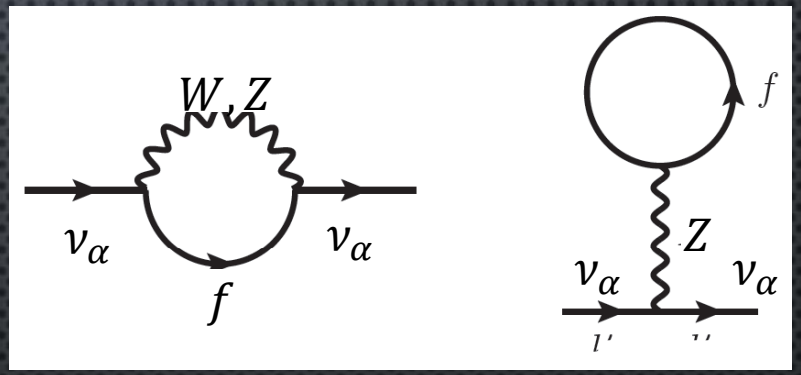
$$\Gamma_{N\to\nu\gamma} = \frac{9\alpha G_F^2}{265\pi^4} \theta^2 M_N^5 \sim \frac{1}{10^{28}\text{sec}} \left(\frac{\theta}{3\times 10^{-4}}\right)^2 \left(\frac{M_N}{\text{keV}}\right)^5 \qquad \theta = \frac{Y_\nu \langle H \rangle}{M_N}$$

DODELSON-WIDROW/SHI-FULLER MECHANISM

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

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

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

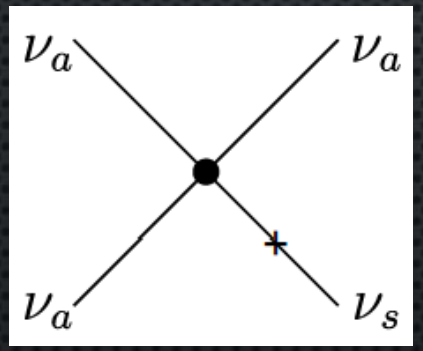


$$H_T = \left(\mathrm{p} + \frac{m_1^2 + m_2^2}{2\mathrm{p}} + \frac{V(T,\mathrm{p})}{2}\right) I + \frac{1}{2}\begin{pmatrix} V(T,\mathrm{p}) - \Delta c_{2\theta} & \Delta s_{2\theta} \\ \Delta s_{2\theta} & \Delta c_{2\theta} - V(T,\mathrm{p}) \end{pmatrix}$$

THERMAL MEDIUM EFFECT

- 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 $(\mathcal{L}_a = (n_a - n_{\bar{a}})/s)$.

Dodelson-Widrow '93 + Shi-Fuller '98



$$\Gamma(\nu_a \to \nu_s : \mathrm{p}, T) = \frac{\Gamma_a}{4} s^2_{2\theta_m}$$

$$s^2_{2\theta_T} = \frac{\Delta^2 s^2_{2\theta}}{\Delta^2 s^2_{2\theta} + \left(\Delta c_{2\theta} - V_a(T, \mathrm{p})\right)^2}$$

$$\text{with } \Delta \equiv \frac{m_2^2 - m_1^2}{2\mathrm{p}}$$

$$\Gamma_a(\mathrm{p}) \approx G_F^2 \mathrm{p} T^4$$

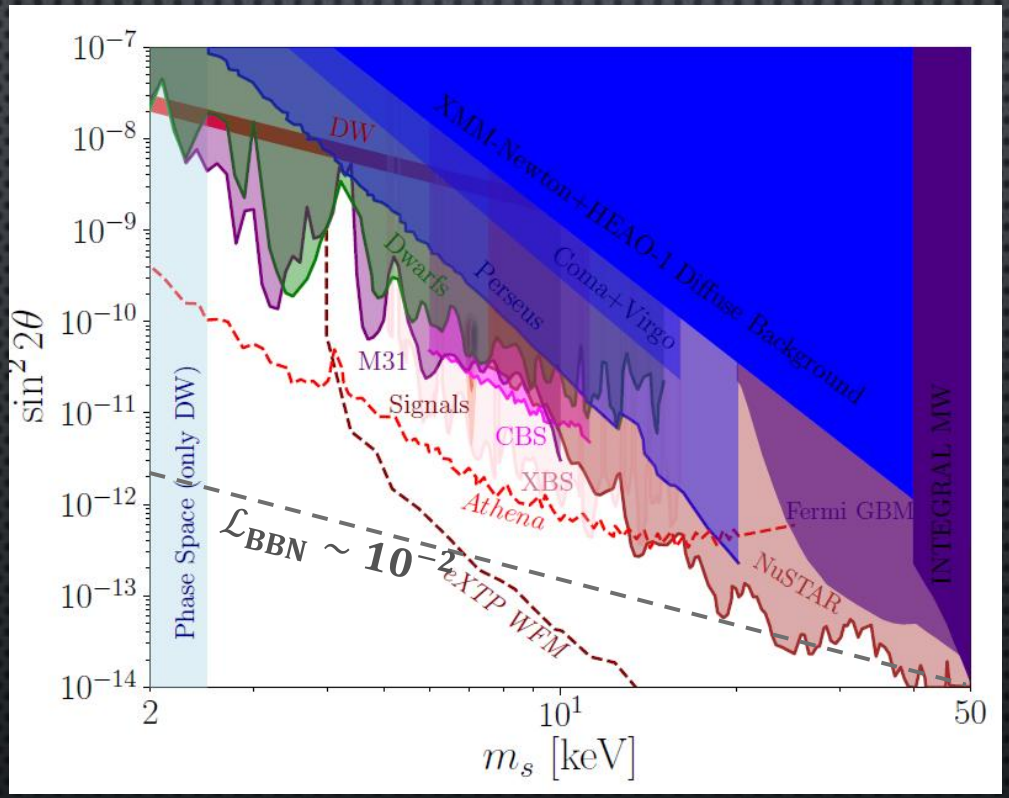
$$V_a(T, \mathrm{p}) = V_a^T + V_a^L$$

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

Resonance conversion

Abazajian, et.al, 0101524

SUMMARY PLOTS



Abazajian, 2102.10183

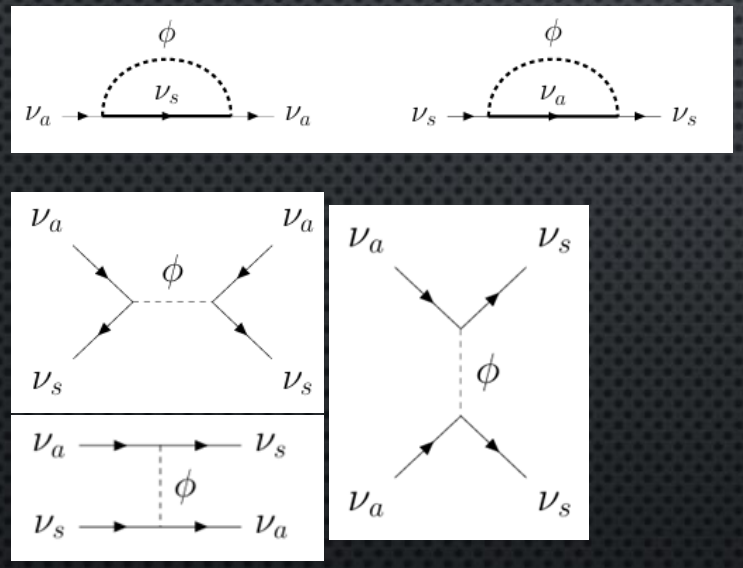
Boyarsky et.al., 1807.07938

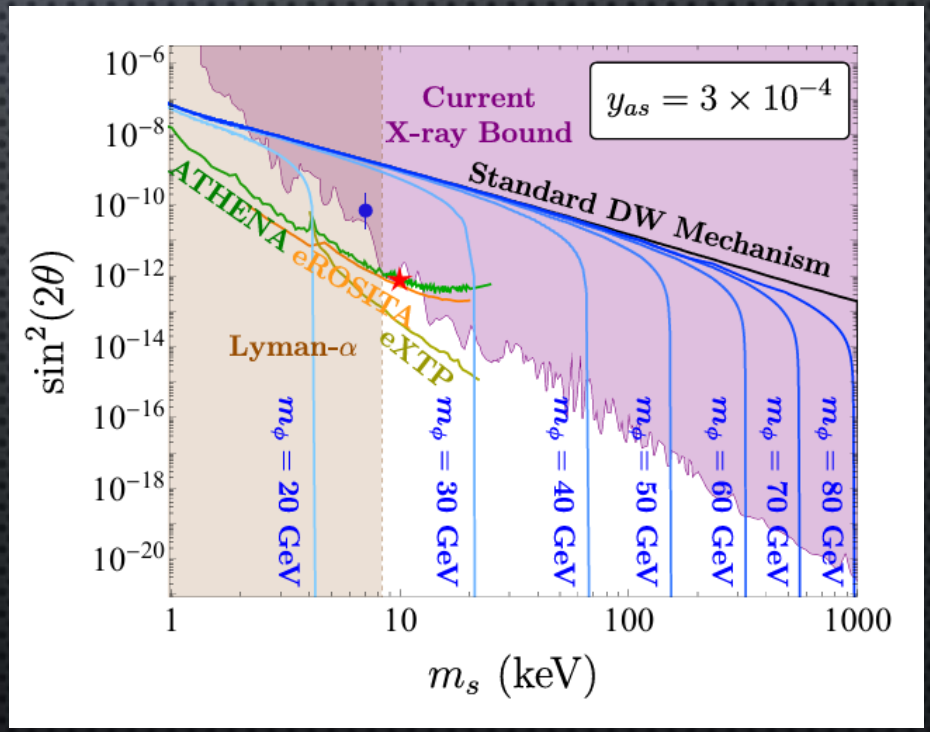
NSI TO OPEN UP NEW REGION

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

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

Bhupal Dev, et.al., 2505.22463 & refs therein





PROPAGATION IN THERMAL MEDIUM

- THE MODEL:

$$-\mathcal{L}_N = \frac{y_{ij}}{2} N_i N_j \phi + \frac{M_i}{2} N_i N_i + \frac{\lambda_{\phi H}}{2} |\phi|^2 |H|^2 + \frac{\lambda_\phi}{2} |\phi|^4 + h.c.$$

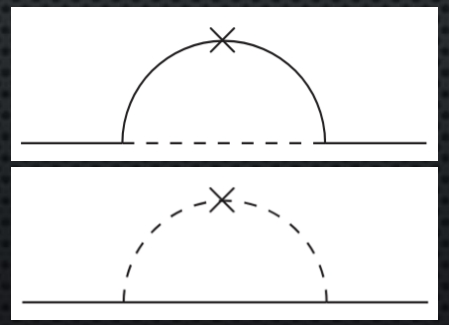
- ASSUME $y_{11} \ll y_{12} \ll y_{22}$ TO MAKE N_1 DM, AND N_2 $(\& \phi)$ IN THERMAL EQUILIBRIUM.

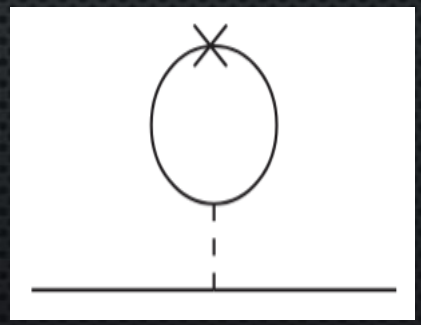
- THERMAL CORRECTION TO RHN PROPAGATION AT RELATIVISTIC LIMIT:

$$\mathcal{L}_{\text{eff}} = \bar{N}_i \{ [\gamma_\mu p^\mu (\delta_{ij} - a_{ij}) - \gamma_0 b_{ij}] + (M_i + \delta M_{ij}) \} N_j$$

$$a_{ij} \sim y_{il} y_{jl}^* \frac{T^2}{\mathrm{p}^2} \ll 1, \quad b_{ij} \sim y_{il} y_{jl}^* \frac{T^2}{\mathrm{p}}$$

$$\delta M_{ij} \sim y_{ij} y_{22}^* M_2 \frac{T^2}{m_\phi^2}$$





THERMAL HAMILTONIAN

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

$$\delta m_{ij}^2 \approx \frac{1}{8} y_{i2} y_{j2}^* T^2 \qquad M_l \delta M_{ij} \approx \frac{1}{6} y_{ij} y_{22}^* \frac{M_2 M_l}{m_\phi^2} T^2$$

$$H_T \Rightarrow \frac{1}{4\mathrm{p}}\begin{pmatrix} \Delta M^2 - \delta M_{22}^2 & \delta M_{12}^2 \\ \delta M_{12}^2 & -\Delta M^2 + \delta M_{22}^2 \end{pmatrix} \qquad \Delta M^2 \equiv M_1^2 - M_2^2$$

$$\delta M_{22}^2 = c_{22} y_{22}^2 T^2$$

$$\delta M_{12}^2 = c_{12} y_{12} y_{22} T^2$$

- THERMAL MIXING $\quad \tan 2\theta_m \approx \dfrac{\delta M_{12}^2}{\Delta M^2 - \delta M_{22}^2} \Rightarrow$ Resonace at $T_{\rm res} = \dfrac{\sqrt{\Delta M^2}}{\sqrt{c_{22}} y_{22}}$
- THERMAL EIGENVALUES $\quad H_{T1,2} = \pm \dfrac{1}{4\mathrm{p}} \sqrt{(\Delta M^2 - \delta M_{22}^2)^2 + (\delta M_{12}^2)^2}$

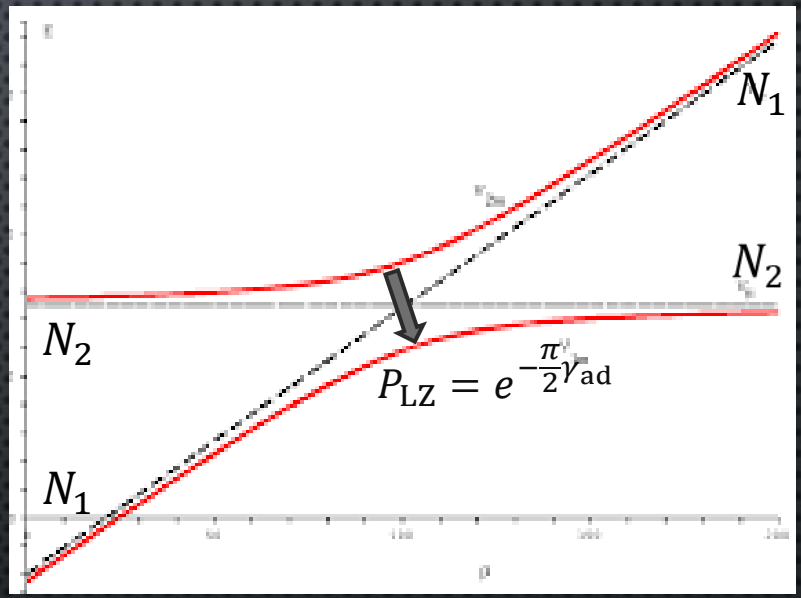
NONADIABATIC TRANSITION

- ADIABATICITY PARAMETER:

$$\gamma_{\rm ad} \equiv \left|\frac{\Delta H_T}{d\theta_T/dt}\right| \Rightarrow \left(\frac{(\delta M_{12}^2)^2}{HTM_1^2}\right)_{\rm res} \ll 1$$

- NON-ADIABATIC $N_2 \to N_1$ TRANSITION:

$$P(N_2 \to N_1) = 1 - e^{-\frac{\pi}{2}\gamma_{\rm ad}} \approx \frac{\pi}{2}\gamma_{\rm ad}$$



LANDAU-ZENER PRODUCTION

- N_1 DM NUMBER DENSITY

$$n_{N_1} = P(N_2 \to N_1) n_{N_2}^{\rm eq} \approx \frac{\pi}{2} \gamma_{\rm ad}\, n_2^{\rm eq}$$

$$M_1 \frac{n_{N_1}}{s} \approx 0.44\ {\rm eV} \Rightarrow y_{12}^2 y_{22} \approx 10^{-23}$$ independently of M_1

- RESONANCE & STABILITY REQUIREMENT

$$M_2 < M_1 < m_\phi$$

- NON-THERMALIZATION OF N_1

$$N_1 N_2 \not\leftrightarrows N_2 N_2$$

$$y_{12} y_{22} < 4 \times 10^{-9} \left(\frac{\rm M_1}{\rm GeV} \right)^{1/4}$$

- APPLICABLE DOWN TO MEV

$$\frac{\lambda_{\phi H} m_f}{m_h^2} \phi^2 \bar{f} f$$ equilibrated for $T > \frac{5}{\lambda_{\phi H}^2} \frac{m_e}{m_f}$ MeV $\quad T_{\rm res} \sim \frac{M_1}{y_{22}}$

Conclusion

- Connecting origins of neutrino mass and dark matter.
- 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 non-adiabatic process, which works for any mass scale above MeV.