ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Invisibles Workshop 2023

DARKNESS IN WHITE
White dwarf cooling through dark sector physics

Effect of a dark photon on plasmon decay

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Based on: Phys. Rev. D 108, 043014

HIDDeν

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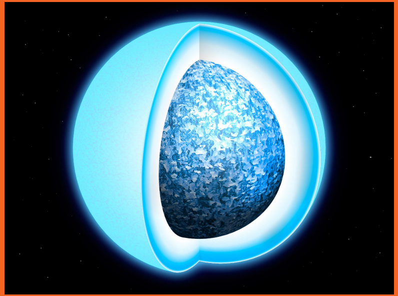
1. White dwarfs as Cosmic Laboratories



Dense star ($\sim 10^6 kg/m^3$)

Degenerate pressure from e-

Known EoS: TOV eqs. + Salpeter

Mass < $1.33 M_\odot$

Cooling

$$dT_*/dt = -L_{\gamma/\nu}/(4\pi R_* \sigma_{SB} T_*)$$

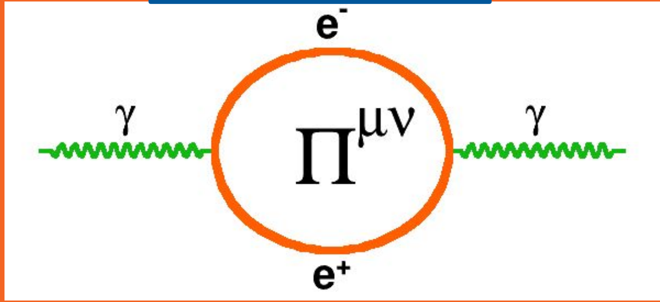
Hot WDs: neutrino emission through plasmon decay

Cold WDs: photon surface emission

2. Plasmon decay

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

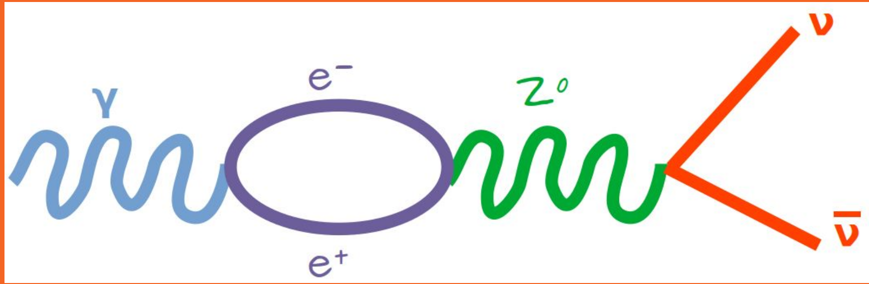
γ *self-energy*

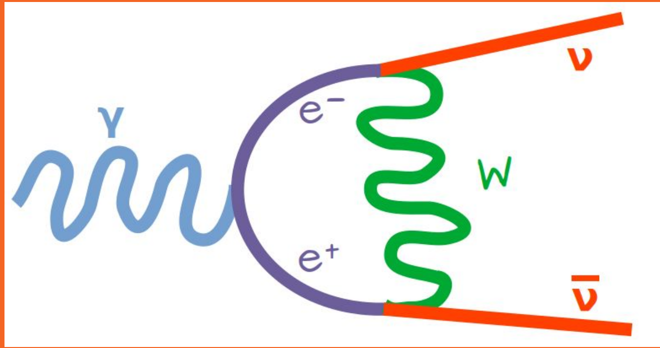


$$=4e^2 \int \frac{d^3K}{(2\pi)^3} \frac{f_e(E_K)+f_{\bar{e}}(E_K)}{2E_K} \times \frac{Q\cdot K(K^\mu Q^\nu + K^\nu Q^\mu) - Q^2 K^\mu K^\nu - (Q\cdot K)^2 g^{\mu\nu}}{(Q\cdot K)^2 - Q^4/4}$$

Alters dispersion relations for longitudinal and transverse photons: $\omega_L = \omega_L(q)$, $\omega_T = \omega_T(q)$

Decay into νs





3. Emissivities

$$\mathcal{Q}_T = \left(\sum_\nu C_V^2\right)\frac{G_F^2}{48\pi^4\alpha}\int_0^\infty dq q^2 Z_t(q)\left(\omega_t(q)^2 - q^2\right)^3 n_B(\omega_t(q))$$

$$\mathcal{Q}_A = \left(\sum_\nu C_A^2\right)\frac{G_F^2}{48\pi^4\alpha}\int_0^\infty dq q^2 Z_t(q)\left(\omega_t(q)^2 - q^2\right) \times \Pi_A(\omega_t(q), q)^2 n_B(\omega_t(q))$$

$$\mathcal{Q}_L = \left(\sum_\nu C_V^2\right)\frac{G_F^2}{96\pi^4\alpha}\int_0^\infty dq q^2 Z_l(q)\left(\omega_l(q)^2 - q^2\right)^2 \times \omega_l(q)^2 n_B(\omega_l(q))$$

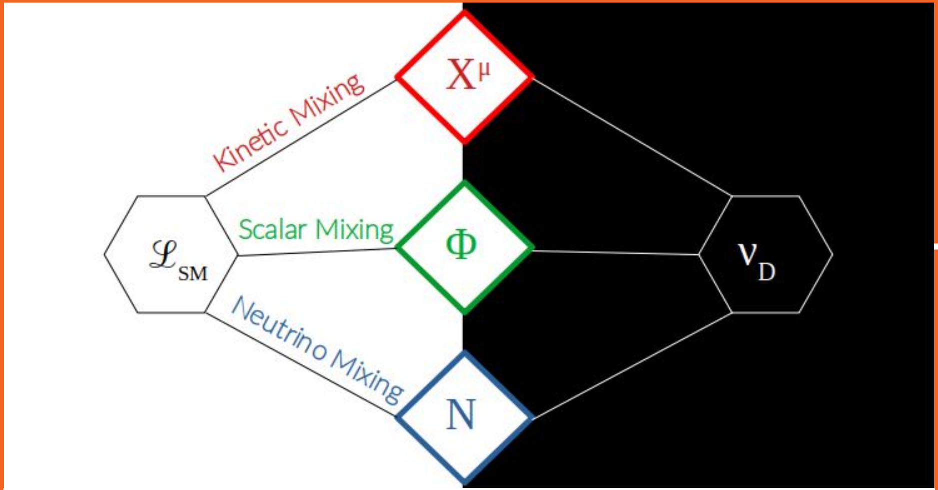
Energy per volume per time in form of neutrinos

$$\equiv \int \Gamma_\lambda \cdot \omega_\lambda \cdot n_B(\omega_\lambda)$$

$$L_\nu = 4\pi \int_0^{R_\star} \mathcal{Q}(r) r^2 dr$$

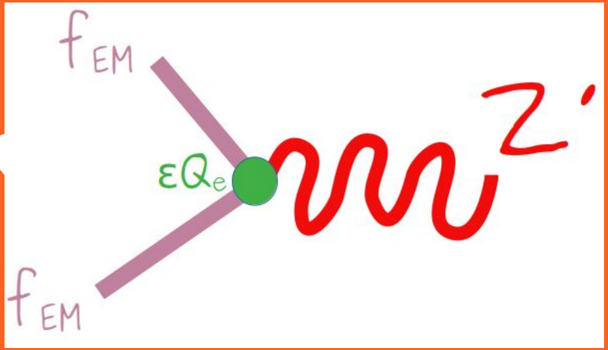
Luminosity: [erg/s] → TOV Eqs + Salpeter

4. Dark sector: dark photon



Three Portal Model: Abdullahi, A. et al., Physics Letters B, 820, 136531 -> MB LEE, $(g-2)_\mu$

SSB



Dark Photon: Z'

$10\ \text{MeV} < m_{Z'} < 10\ \text{GeV}$

5. Plasmon decay with a dark photon

$U_D \equiv U_{Di}$

$$\sum c_V^2 \to \sum_\alpha \left(c_V^{\mathrm{SM}}\right)^2 + \frac{\sqrt{8\pi\alpha}}{G_F}\frac{\epsilon g_{\mathrm{D}} \left|U_{\mathrm{D}}\right|^2}{M_{Z'}^2 - Q^2}\Re\left[\sum_{\alpha,i,j} c_{V,\alpha}^{\mathrm{SM}} U_{\alpha i}^* U_{\alpha j}\right] + \frac{18\pi\alpha}{G_F^2}\frac{\epsilon^2 g_{\mathrm{D}}^2 \left|U_{\mathrm{D}}\right|^4}{(M_{Z'}^2 - Q^2)^2}$$

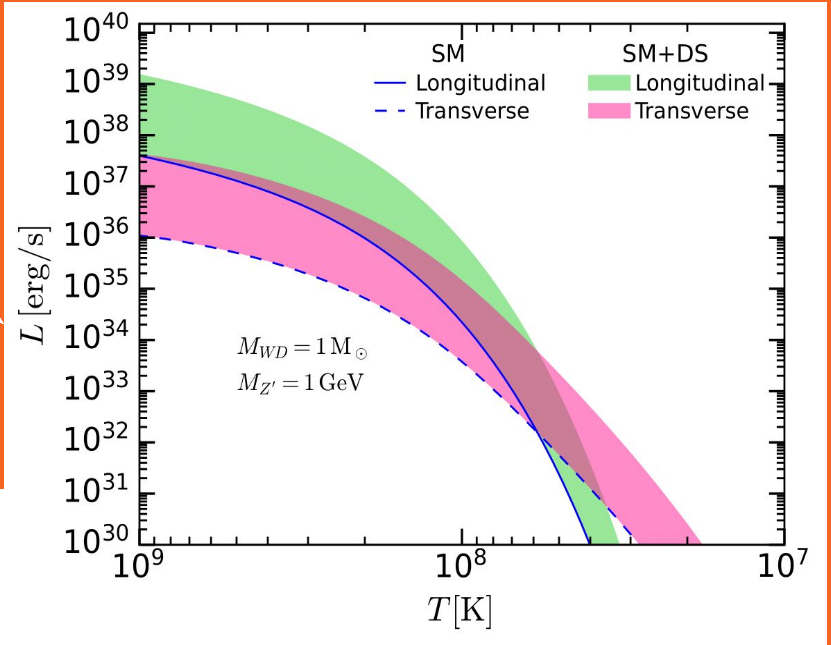
SM contribution

Interference term

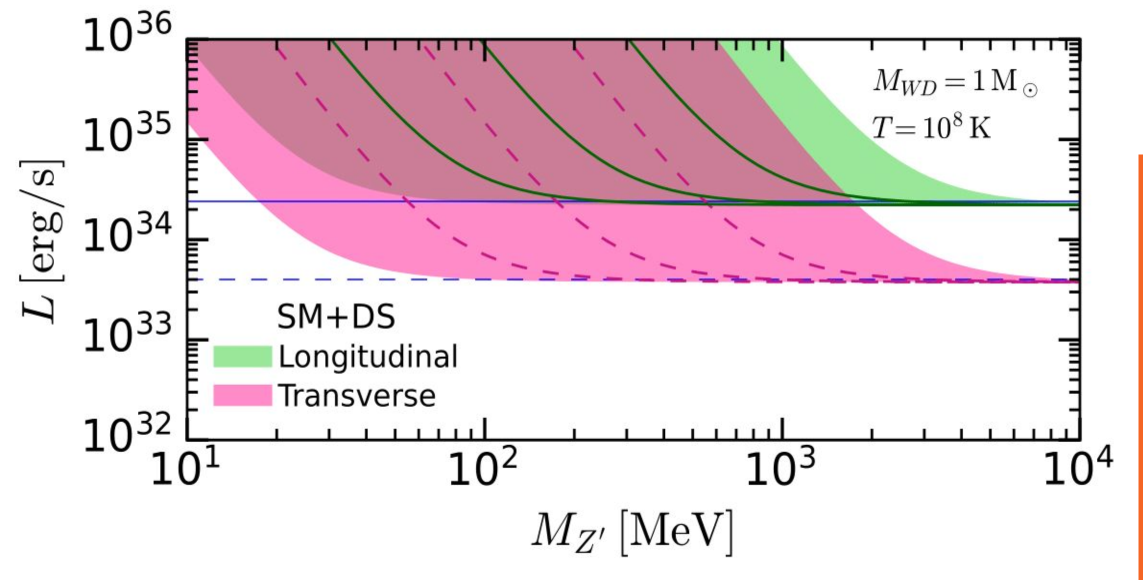
Dark contribution

6. Results

$M_{Z'}=1GeV$



$T=10^8 K$



$M_{WD}=1M_\odot$

$10^{-8}<\varepsilon g_D|U_D|^2<10^{-4}$

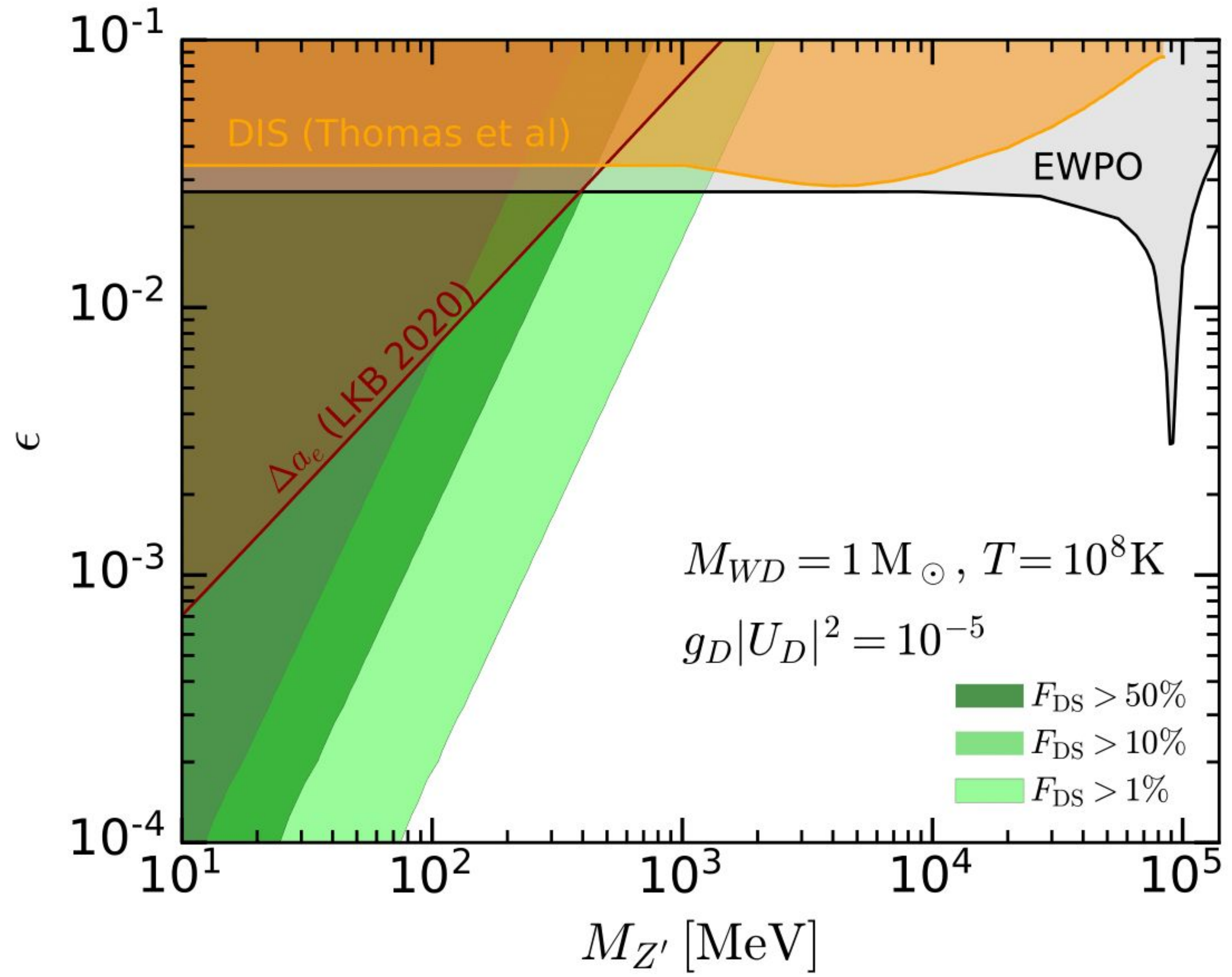
6. Results (2)

$M_{WD} = 1 M_\odot$
$g_D |U_D|^2 = 10^{-5}$
$T = 10^8$ K

$10 < M_{Z'} < 10^4$ MeV

$(M_{Z'} / M_Z)^2 \ll 1$

$F_{DS} \equiv (L_{DS+SM} - L_{SM}) / L_{SM}$



6. Conclusions

1. We computed the luminosity of a WD of 1 $M_\odot$ and considered the scenario of a dark photon contribution to its cooling (from 3 Portal).
2. Depending on the parameters, the luminosity from new physics can really exceed the SM one.
3. We looked for limits of 1%, 10% and 50% of extra dark contribution.
4. Cooling of WDs is REALLY promising to searching for new physics: a very compact object whose EoS is approximately well understood.

Extra information

A. Salpeter EoS

Salpeter, Astrophysical Journal, vol. 134, p.669

$$E = E_0 + E_C + E_{TF} + E_{Ex} + E_{Cor}$$

- E_0 : energy from electron-degenerated ideal gas.
- E_C : total electrostatic energy per electron using the Wigner-Seitz approximation.
- E_{TF} : Thomas-Fermi energy, deviations from uniformity of charge distribution
- E_{Ex} : Exchange energy, effect of antisymmetrized wave functions for Coulomb potential, i.e., the exchange interaction spin-spin.
- E_{Cor} : correlation energy, it measures the effect of the EM field on the distribution of the electrons.

B. Tolman-Oppenheimer-Volkoff (TOV) equations

Einstein field equations for a perfect fluid in the metric of the interior of a star
Tolman, R. C. 1939, Phys. Rev., 55, 364 / Oppenheimer, J. R., & Volkoff, G. M. 1939, Phys. Rev., 55, 374

$$ds^2 = e^{\nu}dt^2 - e^{\lambda}dr^2 - r^2 d\Omega^2$$

$$e^{\nu} = (1-2M/R)\exp(-2\int^{p(r)} dp(p+\varepsilon(p))^{-1})$$

$$e^{-\lambda} = 1-2m(r)/r$$

$$T_{\alpha\beta} = (\varepsilon+p)u_{\alpha}u_{\beta} - pg_{\alpha\beta}$$

$$\frac{dp(r)}{dr} = -\frac{G}{c^2}\frac{\varepsilon(r)+p(r)}{r(r-\frac{2G}{c^2}m(r))}\left[m(r)+\frac{4\pi}{c^2}p(r)r^3\right]$$

$$\frac{dm(r)}{dr} = \frac{4\pi}{c^2}\varepsilon(r)r^2$$

Arun Mathew and Malay K. Nandy 2017 Res. Astron. Astrophys. 17 061

C. Dispersion relations

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

In Coulomb gauge ($\nabla \cdot A=0$) and momentum ($\omega,\mathbf{k}$):

$D^{00} = (\mathbf{k}^2-\Pi_l)^{-1} \longrightarrow (\omega_l/\mathbf{k})^2 * Z_l / (\omega^2-\omega_l^2)$ as $\omega \rightarrow \omega_l$

$D^{ij} = (\omega^2-\mathbf{k}^2-\Pi_t)^{-1}(\delta_{ij}-\hat{k}^i\hat{k}^j) \longrightarrow Z_t / (\omega^2-\omega_t^2)\,(\delta_{ij}-\hat{k}^i\hat{k}^j)$ as $\omega \rightarrow \omega_t$

THEN:

$$\omega_t(k)^2 = k^2 + \Pi_t(\omega_t(k),k)$$

$$k^2 = \Pi_l(\omega_l(k),k)$$

C. Dispersion relations (2)

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

Coupling strength of plasmon:

$Z_t(k) = [1 - \partial\Pi_t/\partial\omega^2(\omega_t(k),k)]^{-1}$

$Z_l(k) = [- \partial\Pi_l/\partial\omega^2(\omega_l(k),k)]^{-1} * k^2 / \omega_l(k)^2$

Polarization vectors:

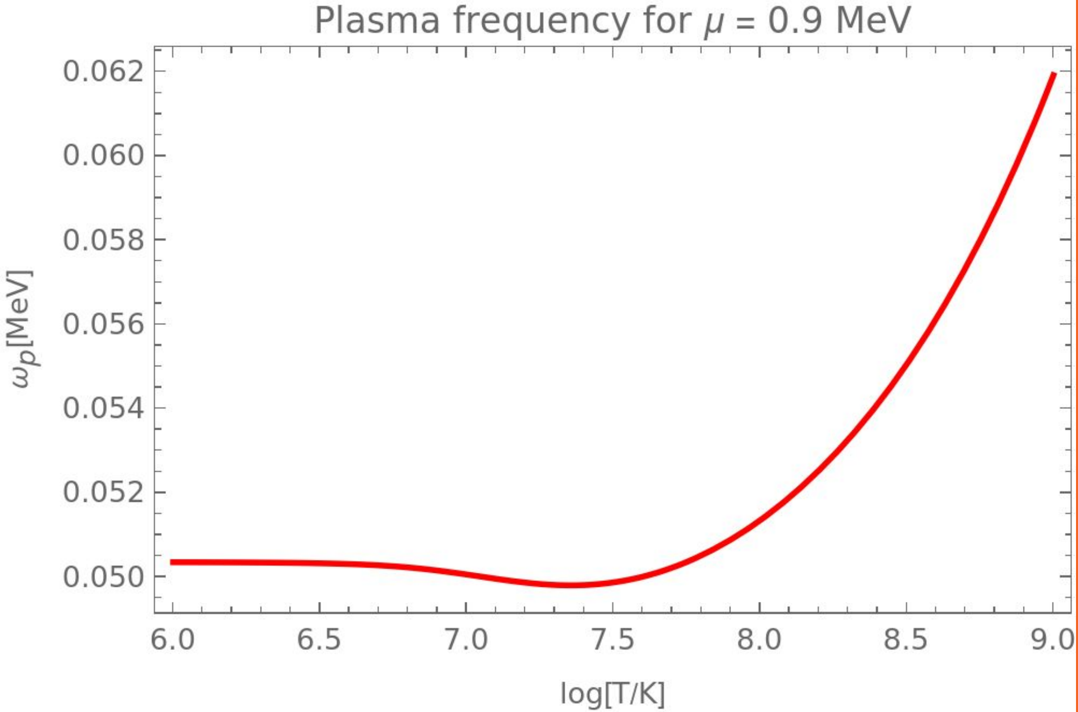
$\varepsilon^\mu(\mathbf{k},\lambda=0) = \omega_l(k) / k \sqrt{Z_l(k)}\,(1,0)^\mu$
$\varepsilon^\mu(\mathbf{k},\lambda=\pm 1) = \sqrt{Z_t(k)}\,(0,\varepsilon_\pm(k))^\mu$

D. Plasma in WD

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

Plasma frequency
v ≡ p/E

$$\omega_p^2 = \frac{4\alpha}{\pi}\int_0^\infty dp\,\frac{p^2}{E}\left(1-\frac{1}{3}v^2\right)\left[n_F(E) + \bar{n}_F(E)\right]$$



E. Three Portal model

Three Portal Model: Abdullahi, A. et al., Physics Letters B, 820, 136531

$$\begin{aligned}\mathscr{L} =& \mathscr{L}_{\rm SM} + \overline{\nu}_D i \not{D}^x \nu_D \\ & + (D^x_\mu \Phi)^\dagger (D^{x\mu}\Phi) - V(\Phi, H) \\ & - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2c_W} B_{\mu\nu} X^{\mu\nu} \\ & + \overline{N} i \not{\partial} N - [y_\nu^\alpha (\overline{L}_\alpha \cdot \widetilde{H}) N^C + \frac{\mu'}{2} \overline{N} N^C + y_N \overline{N} \nu_D^C \Phi + \text{h.c.}]\end{aligned}$$

neutrino mass matrix

$$\begin{pmatrix} 0_{3\times3} & m_{DR}^{\rm T} & m_{DL}^{\rm T} & 0 & 0 \\ m_{DR} & \mu'_R & \mu_D^T & \Lambda_{RR}^{\rm T} & \Lambda_{RL}^{\rm T} \\ m_{DL} & \mu_D & \mu'_L & \Lambda_{LR}^{\rm T} & \Lambda_{LL}^{\rm T} \\ 0 & \Lambda_{RR} & \Lambda_{LR} & 0 & \mu_{DD}^T \\ 0 & \Lambda_{RL} & \Lambda_{LL} & \mu_{DD} & 0 \end{pmatrix} \text{ acting on: } \begin{pmatrix} \nu_\alpha \\ N_R^C \\ N_L \\ \nu_{DR}^C \\ \nu_{DL} \end{pmatrix}$$