A Dirac neutrino portal to $SU(2)_D$ dark matter

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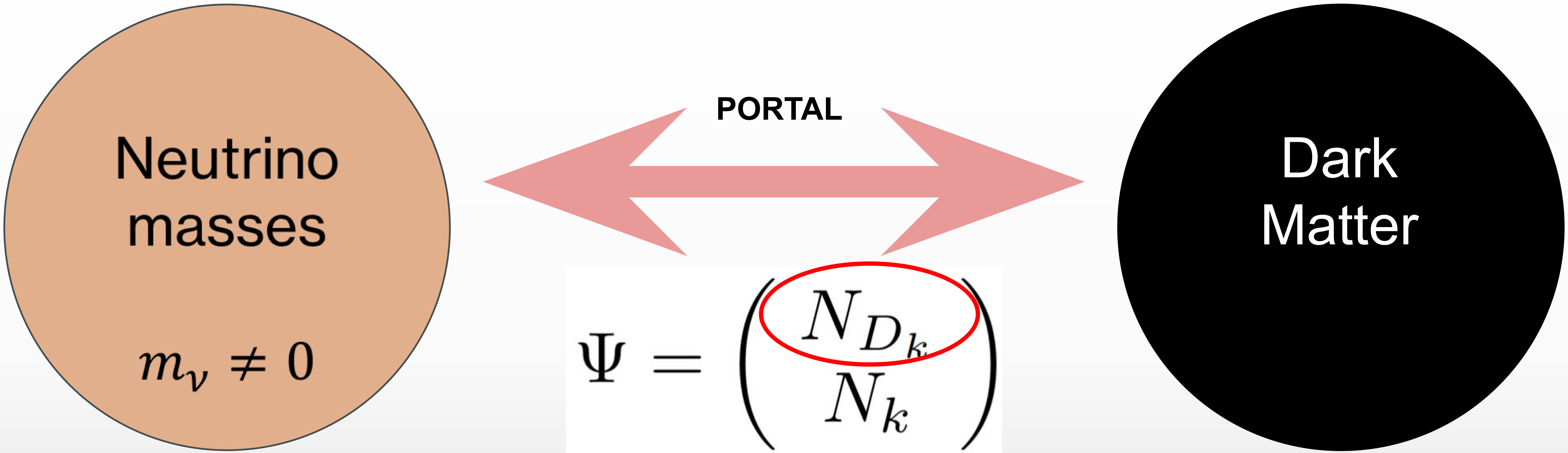
Motivation

Neutrino masses

$m_\nu \neq 0$

Dark Matter

Motivation



$$\Psi = \begin{pmatrix} N_{D_k} \\ N_k \end{pmatrix}$$

Is Z2 odd

We use the FPVDM construction [Belyaev et al., arXiv:2204.03510] an SU(2)D vector-like fermion doublet Ψ, in addition with a ν_R as the portal, applied here to Dirac neutrino masses.

The model

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} V^{a}_{\mu\nu} V^{a\mu\nu} + \sum_k \bar{\Psi}_k (iD - \mathbb{M}_\Psi)_{kk} \Psi_k + (D^\mu \Phi_D)^\dagger D_\mu \Phi_D$$

$$+\mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D (\Phi_D^\dagger \Phi_D)^2 - \lambda_{HD} \left(\Phi^\dagger \Phi_D\right) |H|^2$$

$$\boxed{k = 1, 2 \text{ and } l = e, \mu, \tau}$$

$$+ \sum_k i \bar{\nu}_{Rk} \partial \nu_{Rk} - \sum_{l,k} \mathbb{Y}^\nu_{lk} \bar{L}_l i \sigma_2 H^* \nu_{kR} - \sum_k \mathbb{Y}'_{kk} \bar{\Psi}_{kL} \Phi_D \nu_{kR} + h.c.$$

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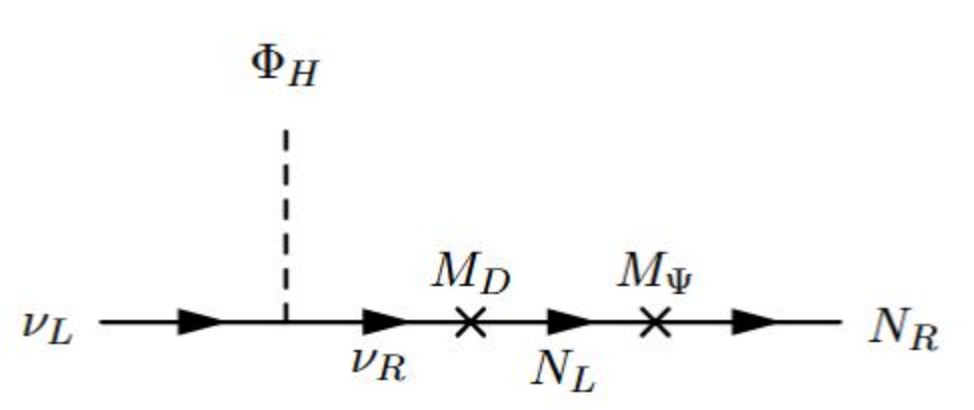
Fields	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$\Phi_D = \begin{pmatrix}\varphi_{1/2}\\ \varphi_{-1/2}\end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{2}$	$-$ $+$
$V_{D\mu} = \begin{pmatrix}V^+_{D\mu}\\ V^0_{D\mu}\\ V^-_{D\mu}\end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{3}$	$-$ $+$ $-$
$L = \begin{pmatrix}\nu_l\\ l\end{pmatrix}_L$	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$+$
ν_{Rk}	$\mathbf{1}$	0	$\mathbf{1}$	$+$
$\Psi_k = \begin{pmatrix}N_{Dk}\\ N_k\end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{2}$	$-$ $+$

There is also a $U(1)_{YD}$ global symmetry

- Dirac Neutrinos, lepton number conserved.
- Masses from a Dirac seesaw with ν_R .
- One massless neutrino (rank≤ 2).



6-dimensional parameter space

In this work, we consider:

Dirac-seesaw limit

$M_D >> M_\Psi$

No Higgs Portal

$\lambda_{HD} = 0$

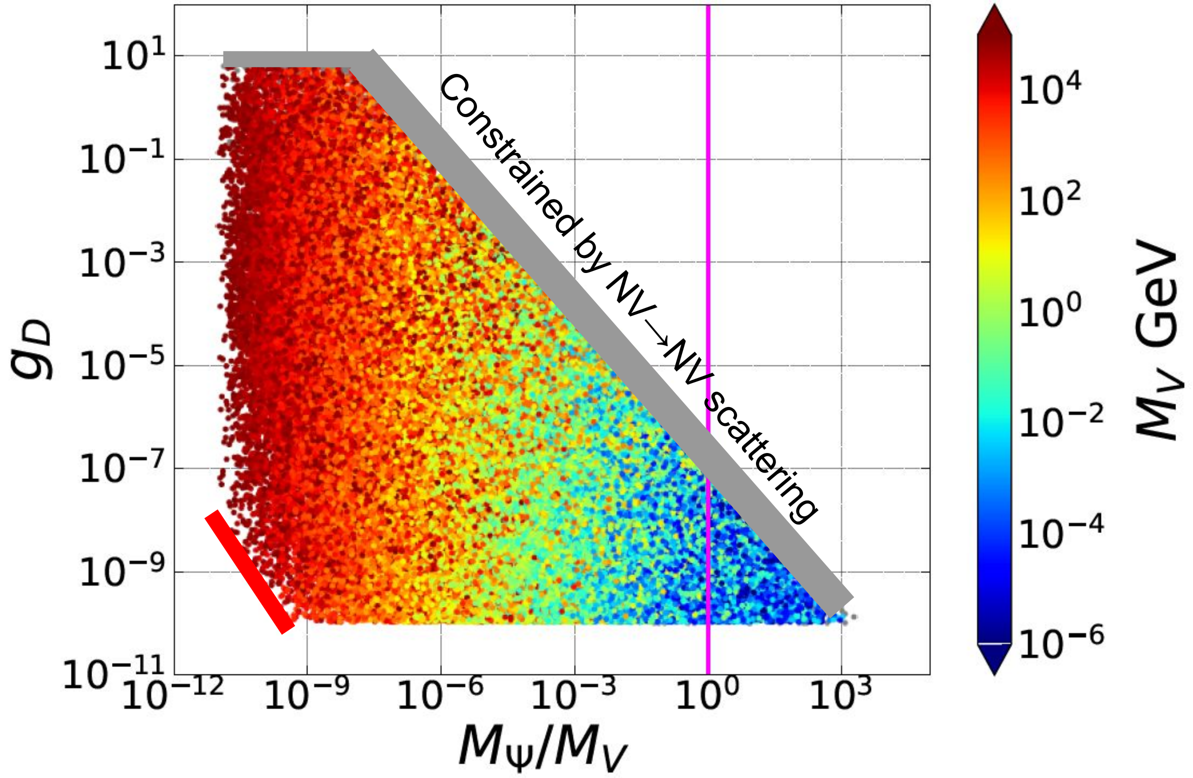
Degeneracy in the fermion masses

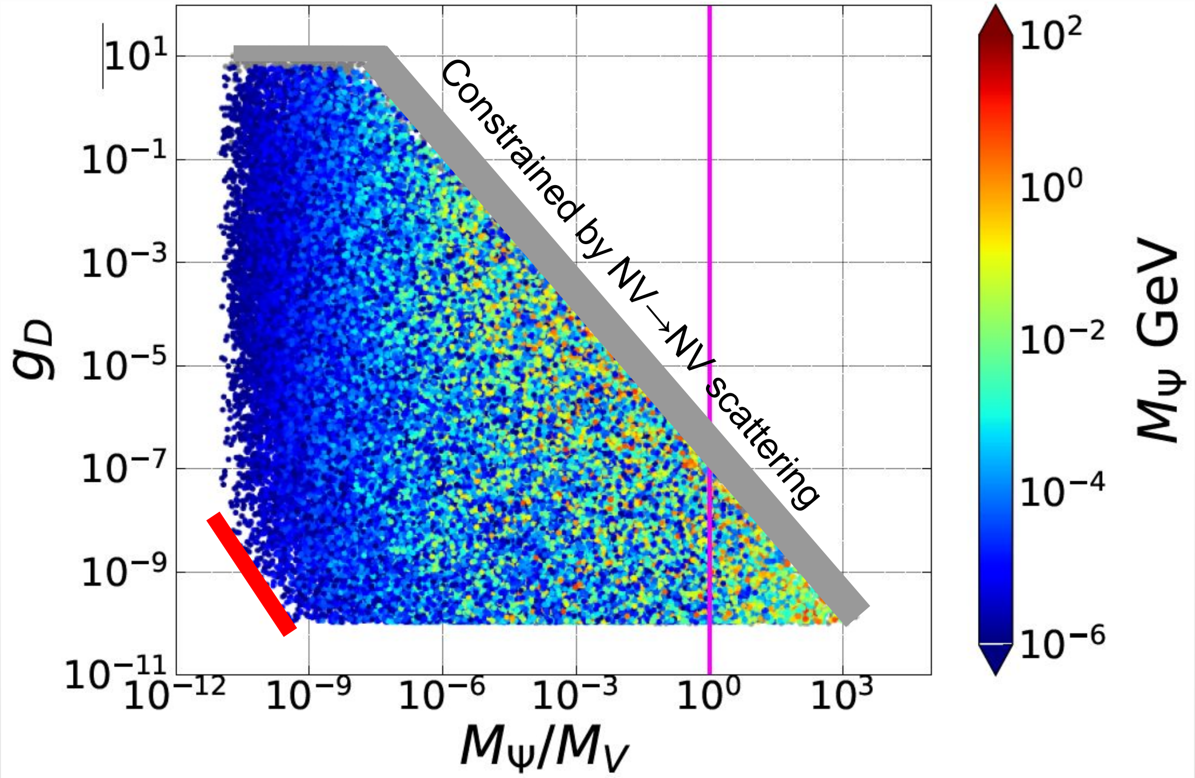
$M_\Psi = M_{\Psi_1} = M_{\Psi_2}$ $M_D = M_{D_1} = M_{D_2}$

The lightest Z2-odd particle is the DM candidate

Parameter	Description
M_V	Tree-level dark gauge-boson mass, $M_V = g_D v_D/2$
M_Ψ	Vector-like mass of the dark neutrino N_D
g_D	$SU(2)_D$ gauge coupling
M_{H_D}	Dark Higgs mass
M_D	Dirac portal mass, $M_D \sim Y' v_D$
ρ	Simplified angle parametrising a reduced 3×2 Y^ν Yukawa structure

Scan: perturbativity + unitarity

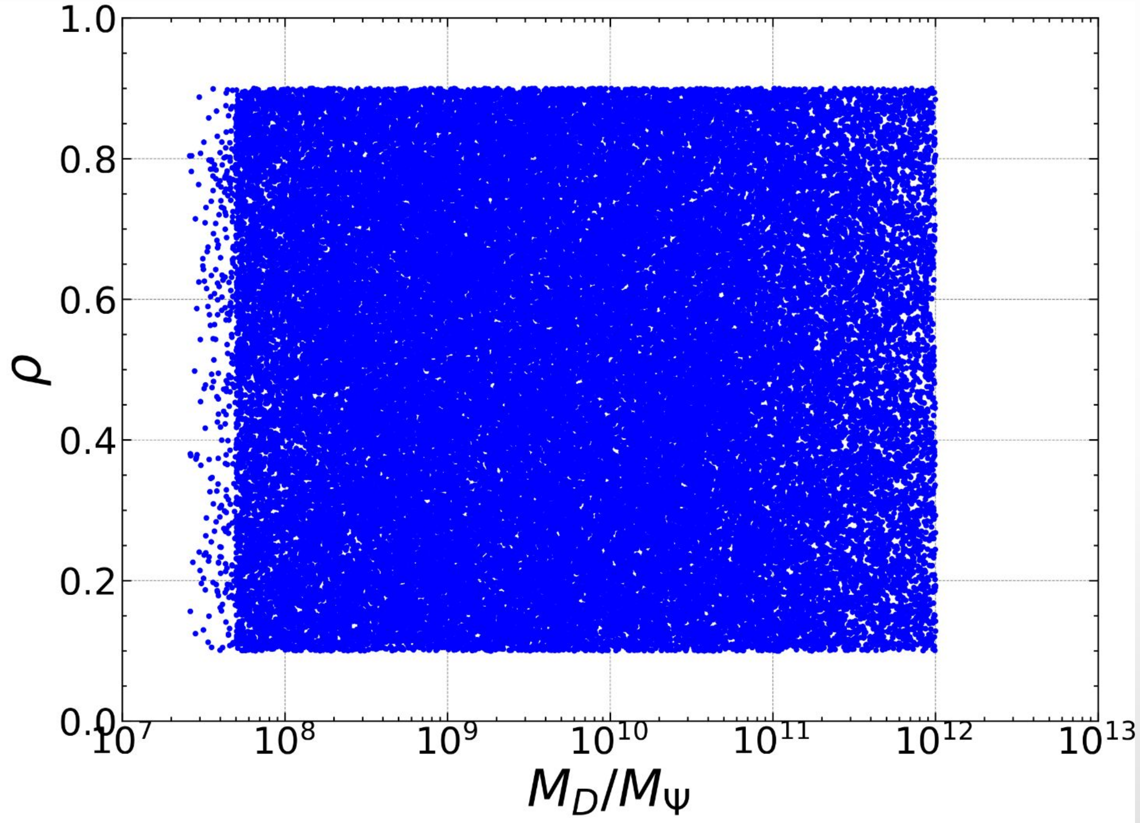


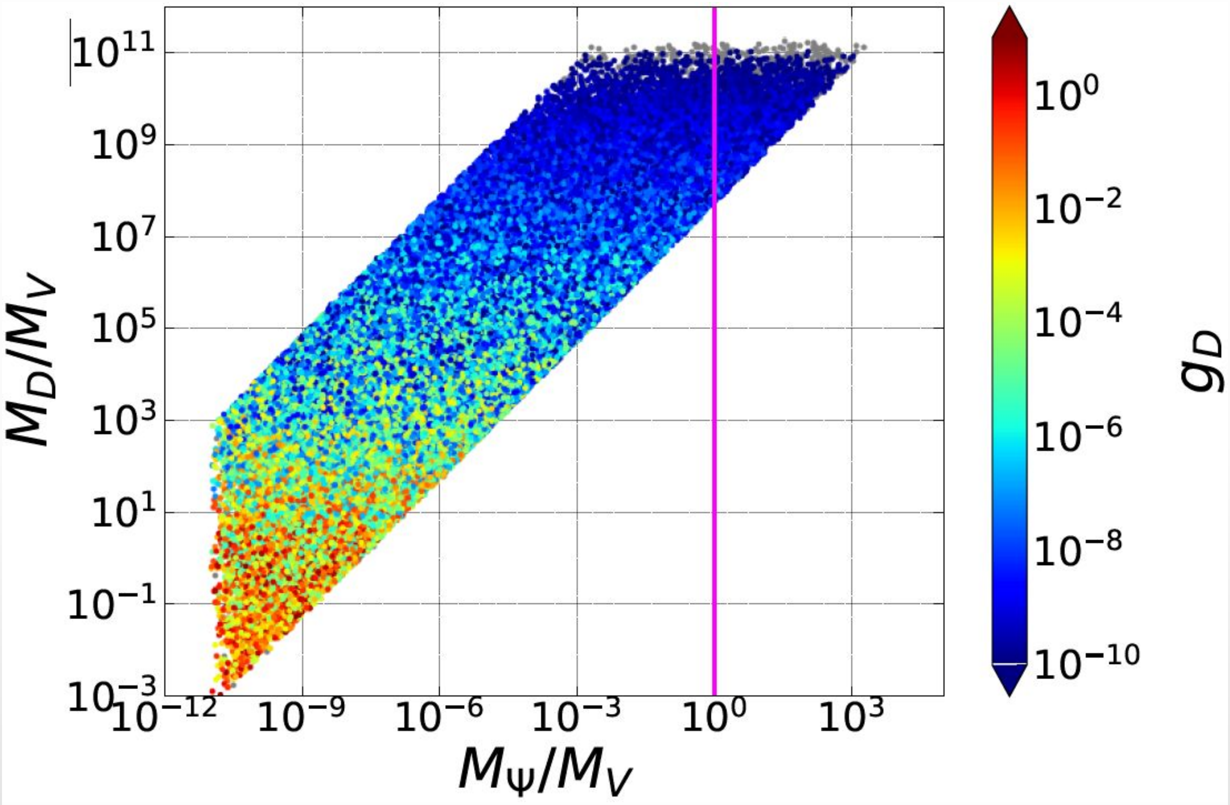


The **lower-left diagonal region in the plots corresponds to the limit where $Y' \simeq 10^{-6}$ and $Y^{\nu}_{ij} \simeq 4\pi$**, whereas the **upper-right region represents points from the parameter space with $Y^{\nu}_{ij} \simeq 10^{-6}$**. It is important to mention that **these regions are already mildly constrained by the unitarity bound (gray points)** arising from the NV->NV scattering channel.

Relic density, direct detection ,among other cosmology observables have **not** been applied yet!!

Dirac-seesaw hierarchy





$$m_\nu \sim Y^\nu v \cdot \frac{M_\Psi}{M_D}$$

- Dirac seesaw mechanism lift Y^ν between $\sim 10^{-6}$ to 4π
- From the Dirac-seesaw suppression arises small neutrino masses

Future Work

- Analyse separately the relic density in the allowed parameter space for the fermion (N_D) and Vector ($V_D^{\pm}$) DM candidate. Furthermore, compare in which scenario the relic density is full reproduced, i.e, freeze-out vs freeze-in (in the tiny g_D region).

- Identify regions of the parameter space that avoid direct detection (loop-induced Υ-V` mixing as in FPVDM) constraints.

- Discuss possible signals at colliders such as : HL-LHC and FCC-hh, only if g_D is sufficiently large and the dark-sector masses are around the electroweak/TeV scale.

$$V_L^+V_L^- \to V_L^+V_L^- \,:\; g_D^2\left(\frac{2M_{H_D}^2}{M_V^2}+1\right) \leq 32\pi\sqrt{2}$$

$$N_L\bar{N}_L \to V_L^+V_L^- \,:\; g_D^2\left(\frac{4M_\Psi^2}{M_V^2}+1\right) \leq 128\sqrt{2}$$

$$N_LV_L^+ \to N_LV_L^+ \,:\; g_D^2\left(\frac{M_D^2}{M_V^2}+3\right) \leq 24\pi\sqrt{2}$$

$$\nu_RV_L^+ \to \nu_RV_L^+ \,:\; g_D^2\left|\frac{M_\Psi^2}{M_V^2}-3\right| \leq 24\pi\sqrt{2}$$

Tree-level partial-wave unitarity

$$a_0(s) = \frac{1}{32\pi}\int_{-1}^{1}\mathcal{M}\,dcos\theta$$

with $\mathrm{Re}(a_0) \leq 1/2$

The subscript $\boldsymbol{L}$ in $\boldsymbol{V}^{\pm}$ stands for longitudinal degrees of freedom, while, in the fermion $\boldsymbol{N}$ denotes a left-handed neutrino.

$$10^{-6} \leq |\mathbb{Y}'_{ii}| = \frac{M_D\,|g_D|}{\sqrt{2}M_V} \leq 4\pi$$

$$10^{-6} \leq |\mathbb{Y}^{\nu}_{ij}| = \frac{\sqrt{2}M_D}{vM_\Psi}\underbrace{|(m_a\vec{u}, m_b\vec{v})_{ij}|}_{\text{function of }\rho} \leq 4\pi$$

HIERCHACHY IN THE YUKAWA COUPLINGS

Yukawa coupling for Dirac neutrinos in the SM typically $y \sim 10^{-13}$. In order to have sizeable couplings, we choose: $y \geq 10^{-6}$