UNIVERSITY OF Southampton
School of Physics and Astronomy

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Why heavy new νs?

Steve King

Durham,

April 9th 2025

New-ν Physics:
from Colliders to
Cosmology

Based on:

``Right-handed neutrinos: seesaw models and signatures,'' 2502.07877

Standard Model

Gauge bosons

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Fermions

$$L_e = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \quad e_R, \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix}^{r,b,g}, \quad u_R^{r,b,g}, \quad d_R^{r,b,g}$$

$$L_\mu = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \quad \mu_R, \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}^{r,b,g}, \quad c_R^{r,b,g}, \quad s_R^{r,b,g}$$

$$L_\tau = \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}, \quad \tau_R, \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}^{r,b,g}, \quad t_R^{r,b,g}, \quad b_R^{r,b,g}$$

Hypercharges

$$Y = -\frac{1}{2}, \quad -1, \quad \frac{1}{6}, \quad \frac{2}{3}, \quad -\frac{1}{3}$$

N.B. no RHNs ν_R (Y=0)

Higgs **EWSB**

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

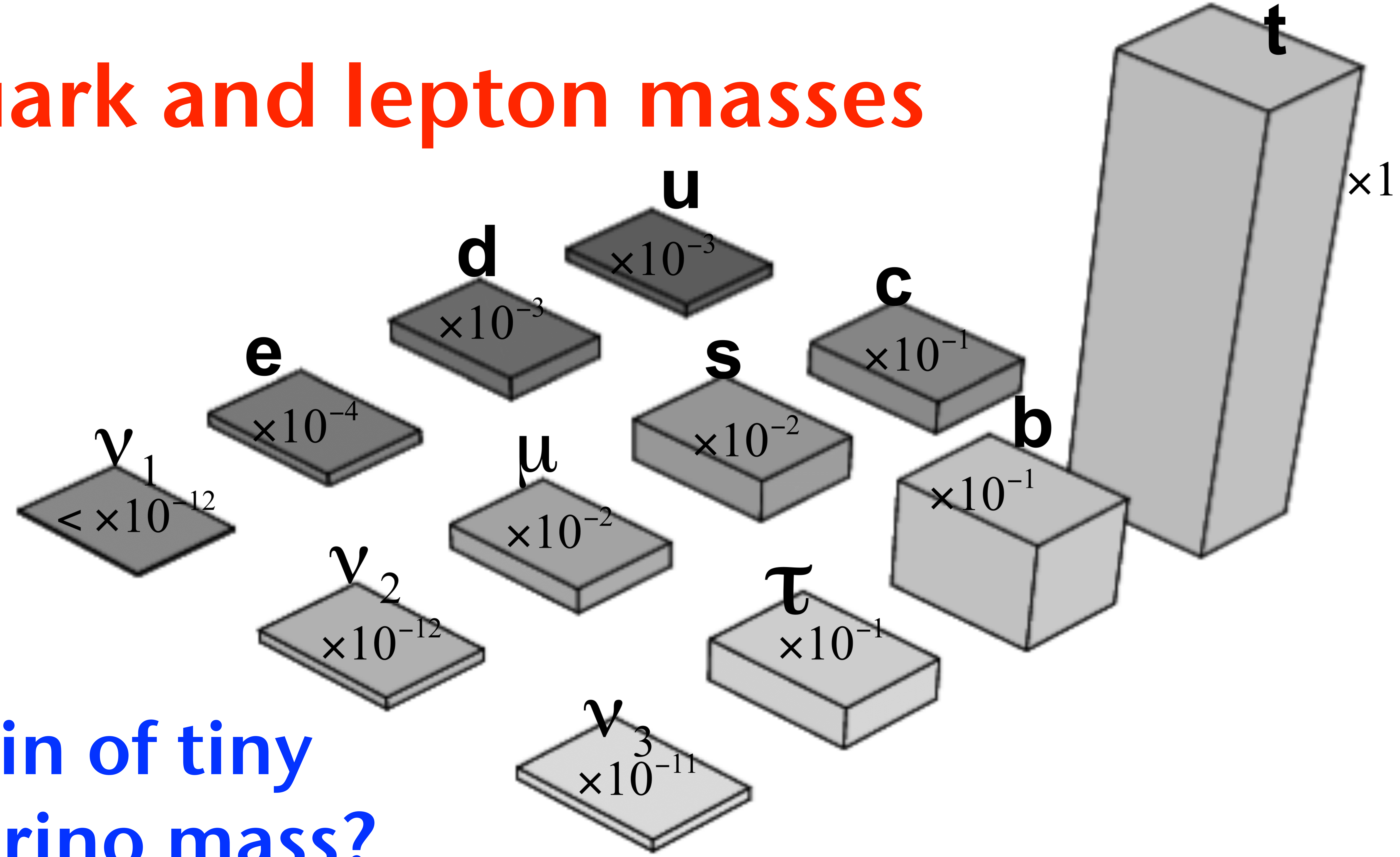
$$\frac{1}{2}$$

$$\langle h^0 \rangle = v/\sqrt{2}$$

$$SU(2)_L \times U(1)_Y \to U(1)_Q$$

$$Q = T_{3L} + Y$$

Quark and lepton masses



Origin of tiny neutrino mass?

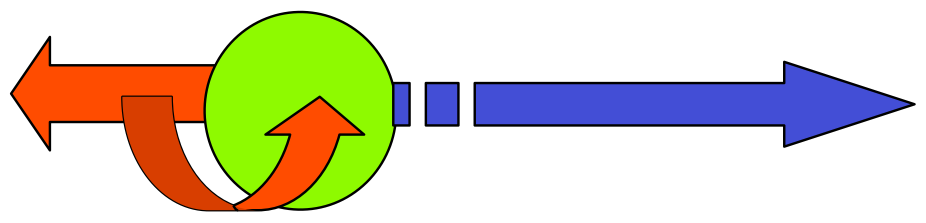
Weinberg operator

Non-renormalisable operators $\sim \dfrac{1}{\Lambda}$

$$(L_i^T \tilde{H}^*)(\tilde{H}^\dagger L_j) \rightarrow m_{ij}^{\nu\dagger}\, \overline{\nu^c_{Li}}\, \nu_{Lj}$$

Generates small Majorana neutrino masses $\sim \dfrac{v^2}{\Lambda}$

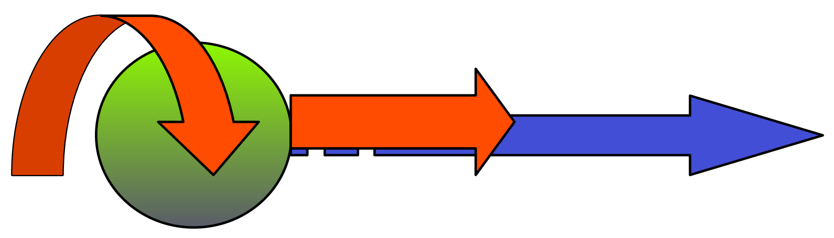
ν_L



Majorana

$m_L \overline{\nu}_L \nu_L^c$

ν_L^c



Charged lepton and neutrino mass matrices

Yukawas **Weinberg**

$$\mathcal{L}^{\text{lepton}}_{\text{mass}} = -\overline{e}_{Li} m^{e}_{ij} e_{Rj} - \frac{1}{2}\overline{\nu_{Li}} m^{\nu}_{ij} \nu^{c}_{Lj} + H.c.$$

Diagonalise

$$V_{e_L} m^{e} V^{\dagger}_{e_R} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad V_{\nu_L} m^{\nu} V^{T}_{\nu_L} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Charged currents

$$-\frac{g}{\sqrt{2}} W^{-}_{\mu} \begin{pmatrix} \overline{e}_L & \overline{\mu}_L & \overline{\tau}_L \end{pmatrix} \gamma^{\mu} U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Lepton mixing matrix

$$U_{\text{PMNS}} = V_{e_L} V^{\dagger}_{\nu_L}$$

PMNS Lepton mixing matrix

$$U_{PMNS}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}}\end{pmatrix}$$

Atmospheric Reactor Solar Majorana

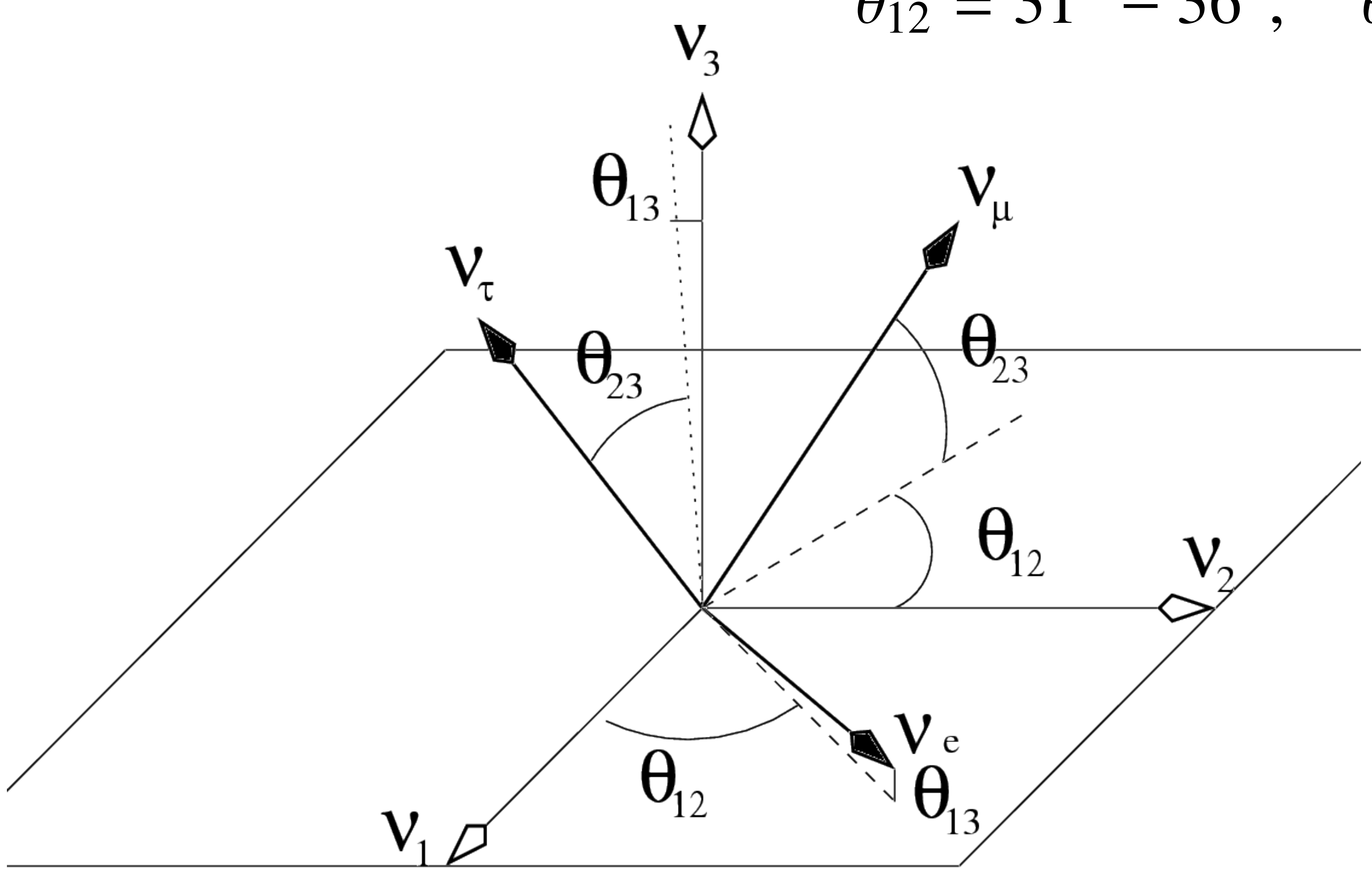
$$=\begin{pmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}$$

$$\times\,\mathrm{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$$

PMNS Lepton mixing matrix

$$\theta_{12} = 31^\circ - 36^\circ, \quad \theta_{23} = 40^\circ - 52^\circ, \quad \theta_{13} = 8.2^\circ - 8.9^\circ$$

Pontecorvo
Maki
Nakagawa
Sakata



Thomas Schwetz

$$\frac{\Delta^2_{21}}{10^{-5}\mathrm{eV}^2} = 6.8 - 8.0$$

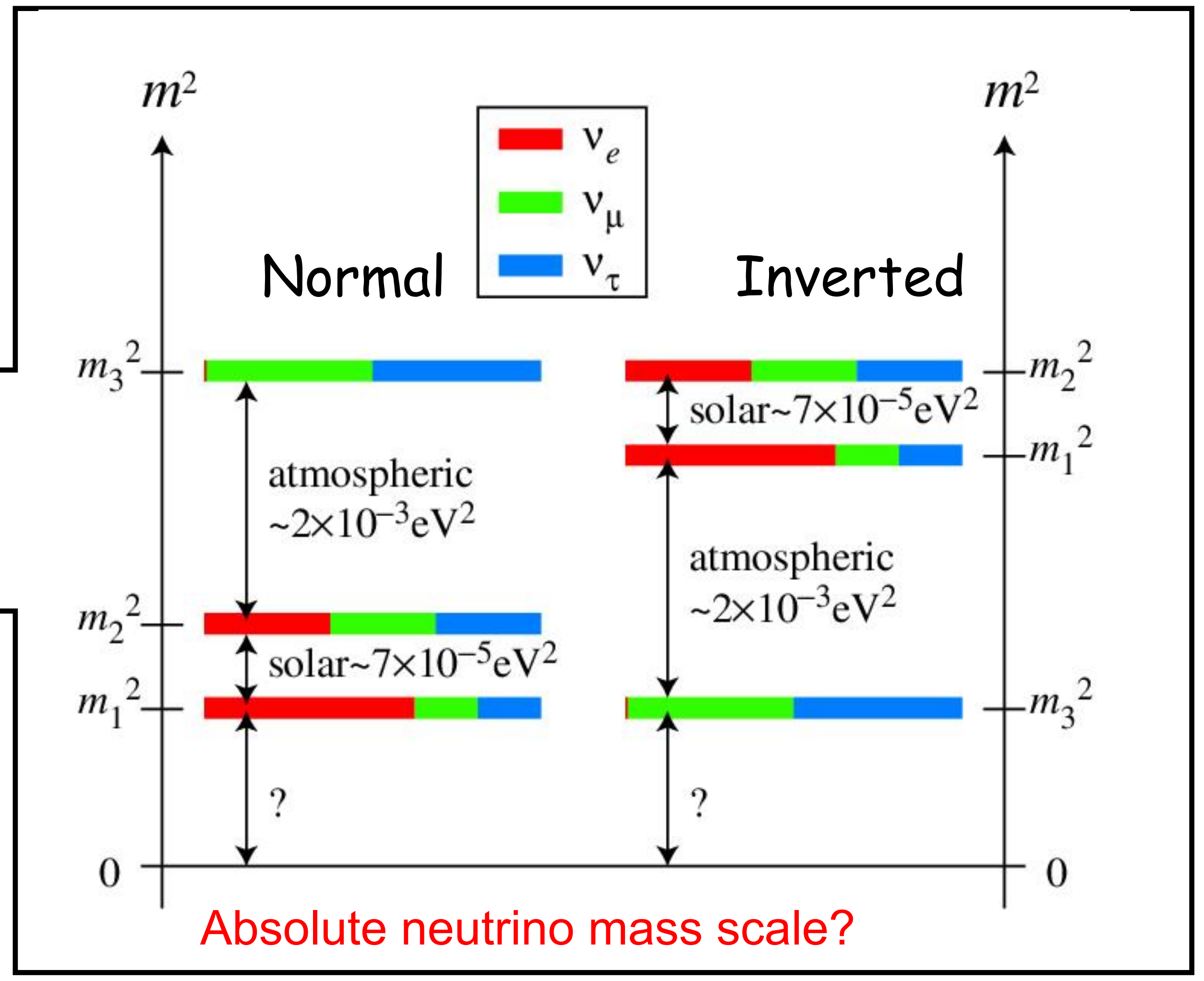
$$\frac{\Delta^2_{31}}{10^{-3}\mathrm{eV}^2} = 2.4 - 2.6.$$

Standard Model states

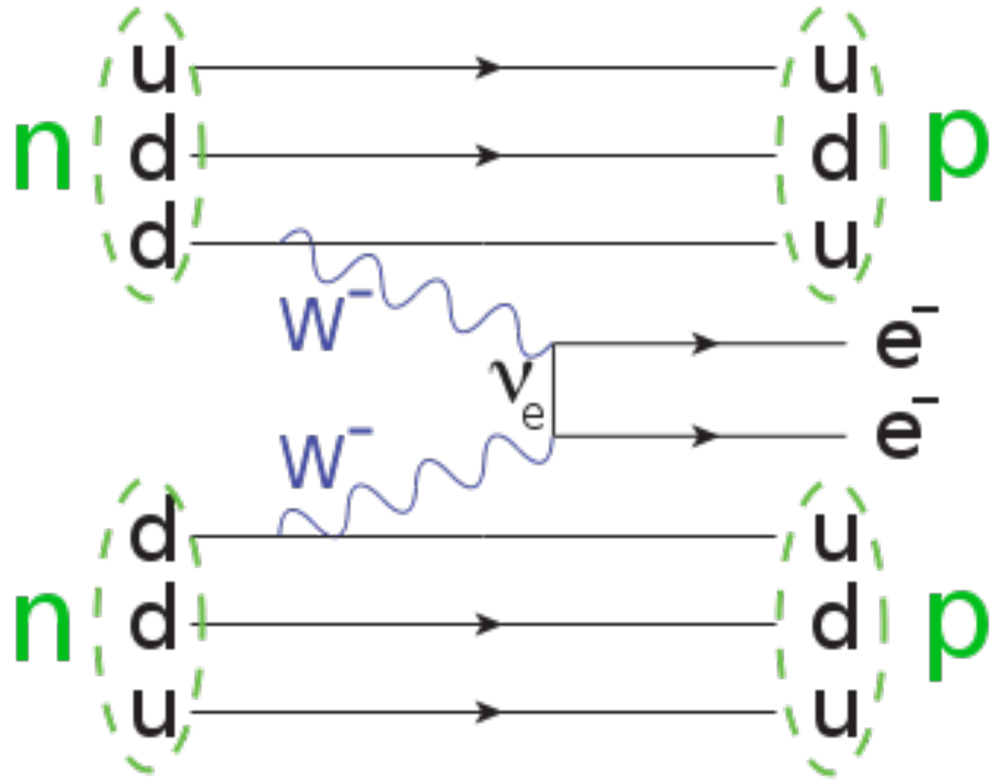
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrinoless Double Beta Decay



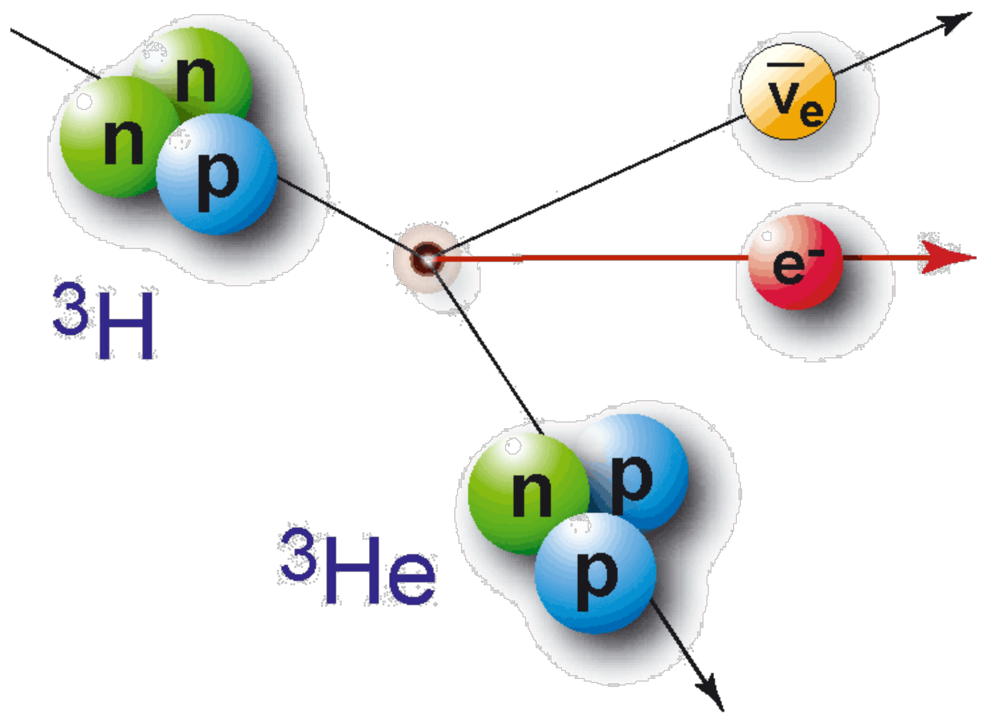
$$m_{ee} \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$m_{ee} \lesssim 0.1 \text{ eV}$$

Vaisakh Plakkot

N.B. m_{ee} is equal to to the first element of the neutrino mass matrix in the flavour basis

Tritium Beta Decay

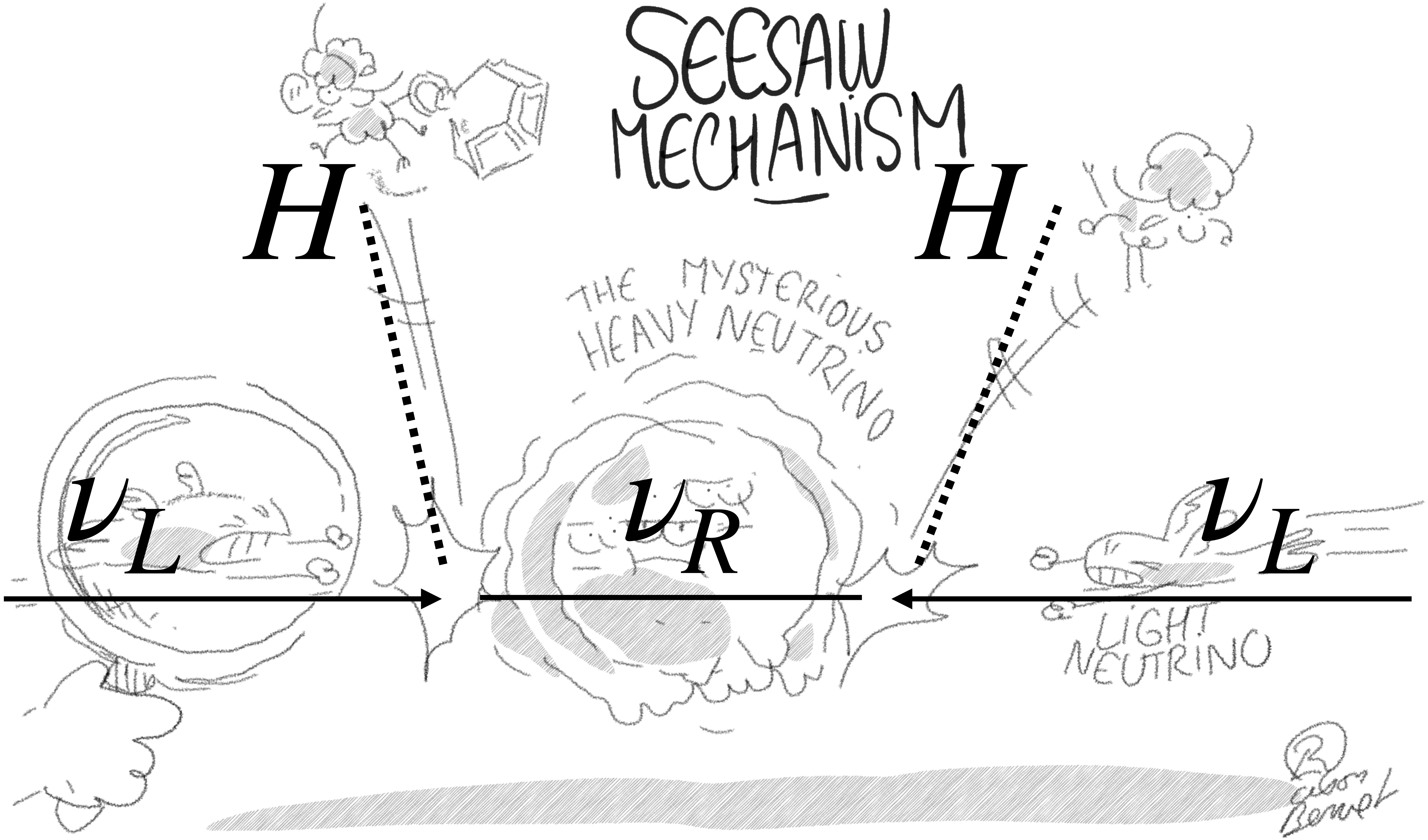


$$m_{\nu_e}^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 |m_i|^2$$

$$m_{\nu_e} < 0.8 \text{ eV}$$

KATRIN

Claudio Silva



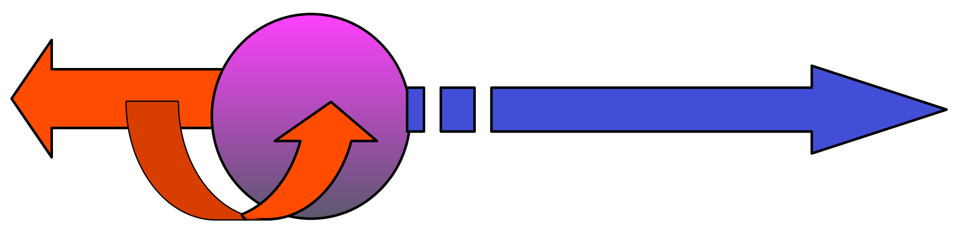
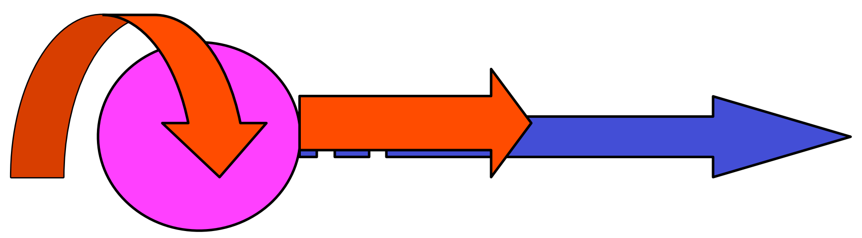
Replace Weinberg operator by a renormalisable theory

→ physical prediction: Heavy Neutral Leptons (HNLs)

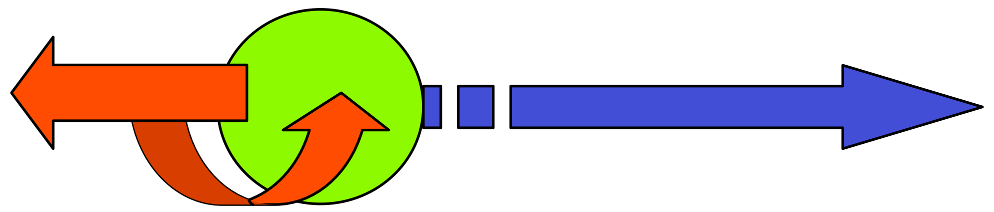
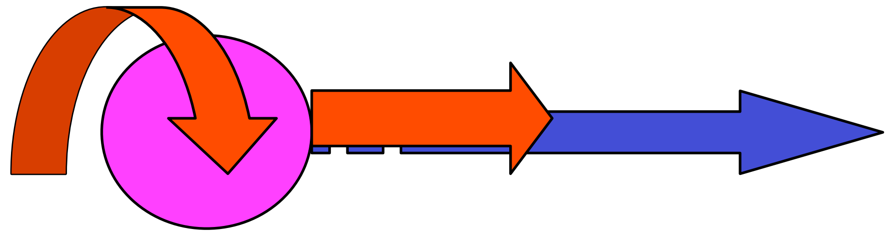
Single Right-handed Neutrino (the simplest case)

Allows two types of mass

ν_R^c Majorana ν_R

 $M_R \overline{\nu}_R^c \nu_R$ 

ν_L Dirac ν_R

 $m_D \overline{\nu}_L \nu_R$ 

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

N.B. zero in first element
(no Weinberg operator)

Diagonalising the seesaw matrix

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} m_- & 0 \\ 0 & m_+ \end{pmatrix}$$

$$\tan 2\theta = \frac{2m_D}{M_R}$$

Light and heavy mass eigenstates

$$\begin{pmatrix} \nu \\ N \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

$$m_\mp = \frac{M_R \mp \sqrt{M_R^2 + 4m_D^2}}{2} \qquad (m_+)(m_-) = -m_D^2$$

For fixed m_D if m+ goes up then m- goes down ......like a seesaw

Heavy right-handed neutrinos

$$M_R \gg m_D \qquad \sin\theta \approx \tan\theta \approx \theta \approx m_D/M_R$$

Heavy Neutral Lepton

$$N \approx \nu_R + \theta\nu_L^c, \qquad \nu \approx \nu_L - \theta\nu_R^c$$

Light neutrino

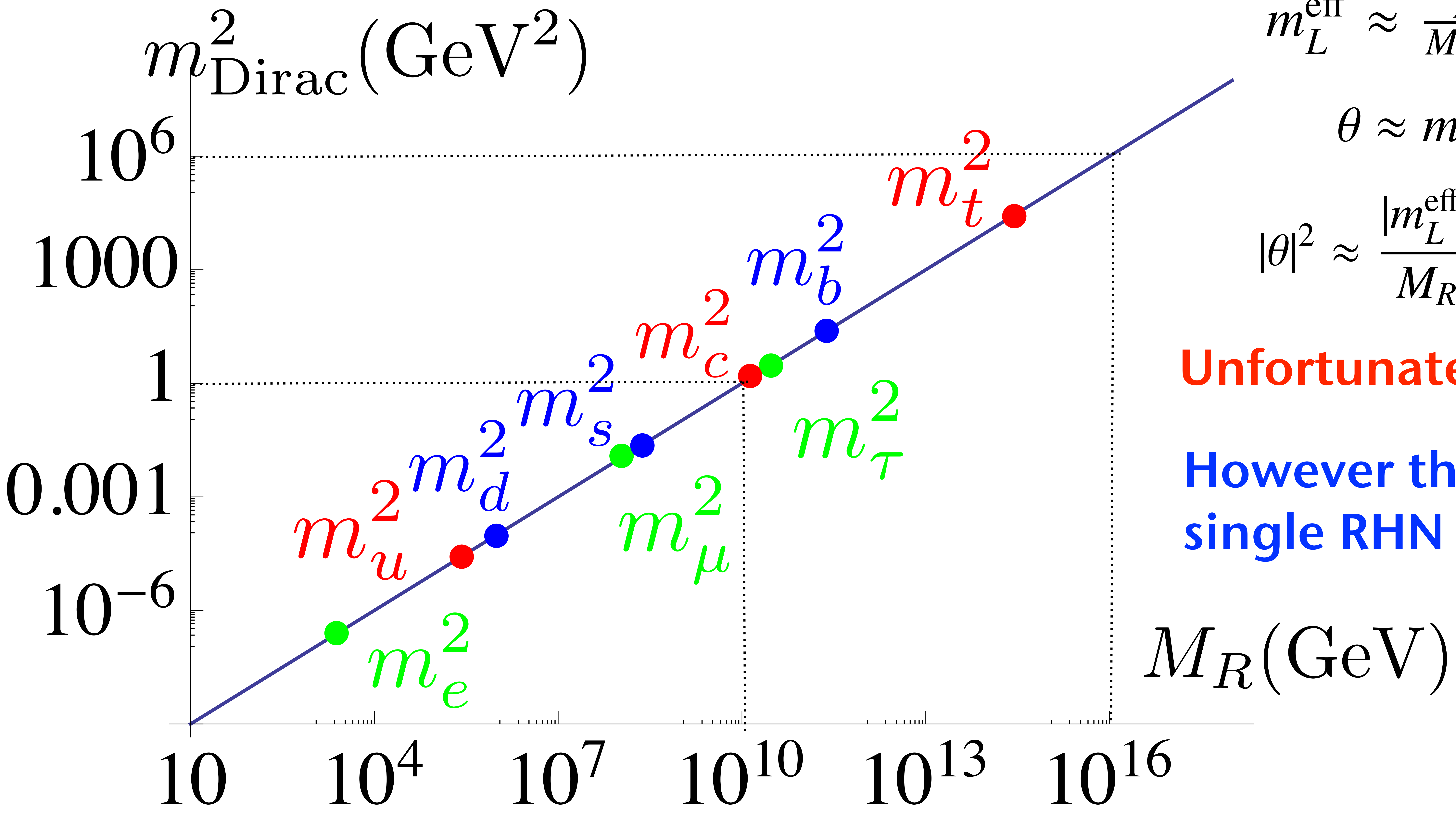
$$m_+ \approx M_R \qquad m_- \approx m_L^{\text{eff}} \approx -\frac{m_D^2}{M_R}$$

$$-\frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L \gamma^\mu \nu_{eL} \quad \Rightarrow \quad -\frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L \gamma^\mu (\nu + \theta N^c)$$

HNL

HNL coupling enables discovery if M_R not too large and θ not too small

Seesaw line



$$m_L^{\mathrm{eff}} \approx \frac{m_D^2}{M_R} \approx 0.1\ \mathrm{eV},$$

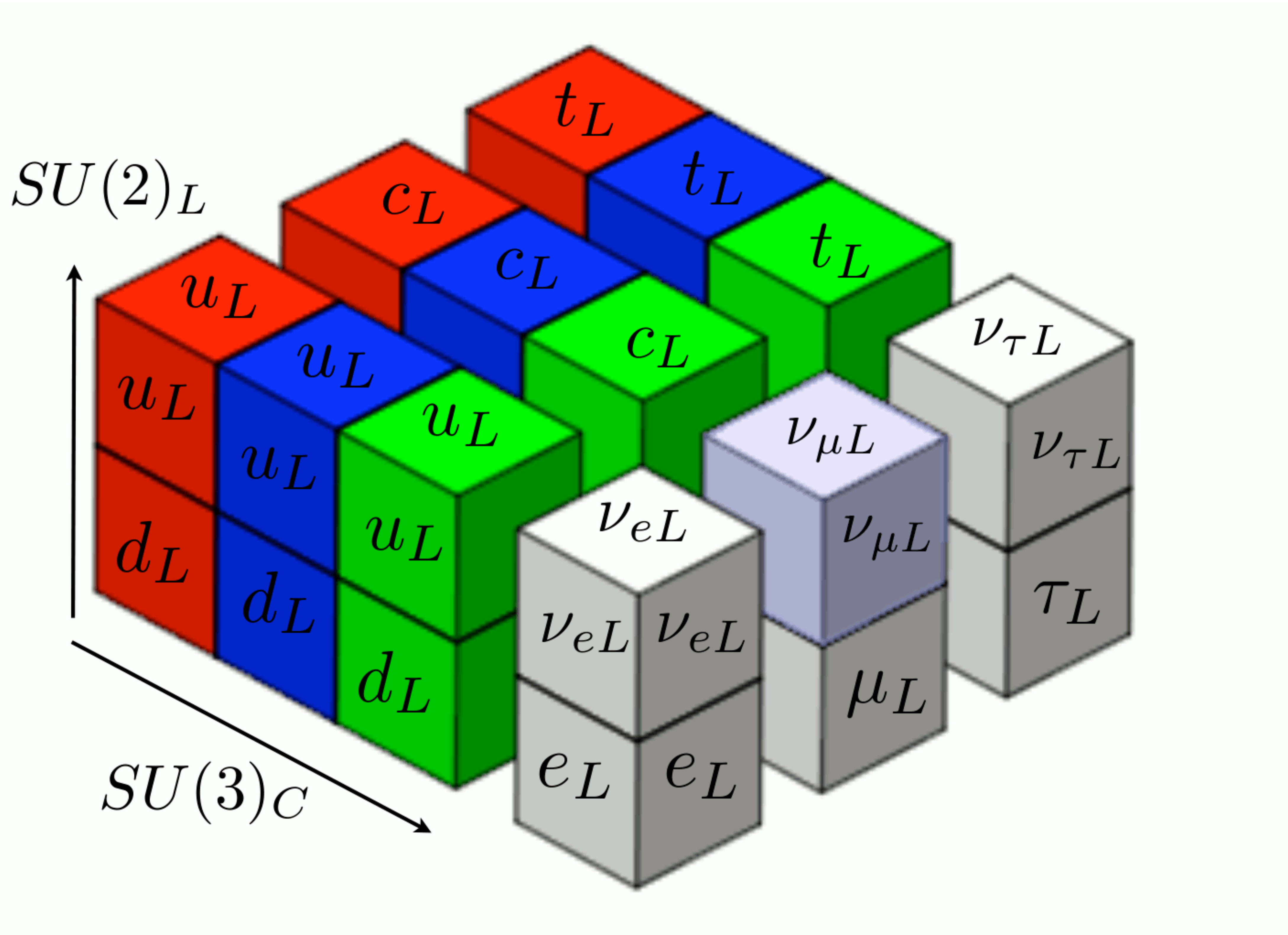
$$\theta \approx m_D/M_R$$

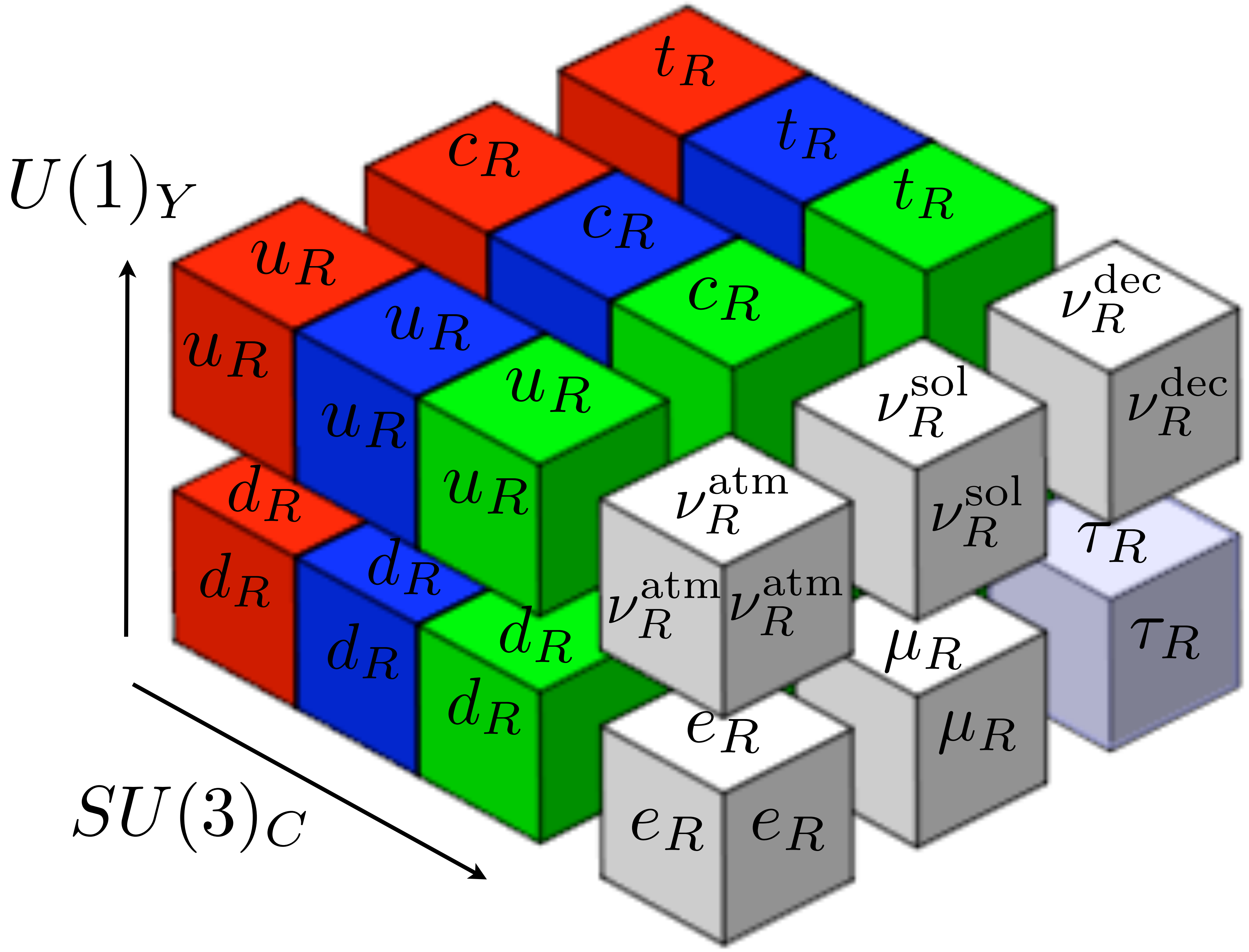
$$|\theta|^2 \approx \frac{|m_L^{\mathrm{eff}}|}{M_R} \approx 10^{-10}\left(\frac{1\mathrm{GeV}}{M_R}\right)$$

Unfortunately this is very small

However this is for unrealistic single RHN case...

Three Right-handed Neutrinos (canonical case)





- Motivated by Grand Unified Theories such as SO(10)
- Allows leptogenesis (other cosmo/astro implications)

Jacobo Lopez-Pavon, William Giare, Ivan Martinez Soler

Three Right-handed Neutrinos (canonical case)

$$\mathcal{L}^{\text{lepton}}_{\text{mass}} = -\sum_{l=e,\mu,\tau} \bar{l}_L m_l l_R - \bar{\nu}_{lL} m^D_{la} \nu_{Ra} - \frac{1}{2}\overline{\nu^c_{Ra}} M^a_R \nu_{Ra} + \text{H.c.}$$

Diagonal mass matrices for charged leptons and RHNs (“flavour basis”)

U matrix is unitary 6x6

$$U \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} U^T \approx \begin{pmatrix} m_\nu & 0 \\ 0 & M_R \end{pmatrix}$$

3x3 block diagonal

$$U \approx \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix}$$

θ is 3x3 matrix of angles

$$\theta \approx m_D M_R^{-1}$$

Seesaw formula

$$m^\nu \approx -m_D M_R^{-1} m_D^T$$

Diagonalise light neutrinos

$$V_{\nu_L} m^\nu V_{\nu_L}^T = \text{diag}(m_1, m_2, m_3)$$

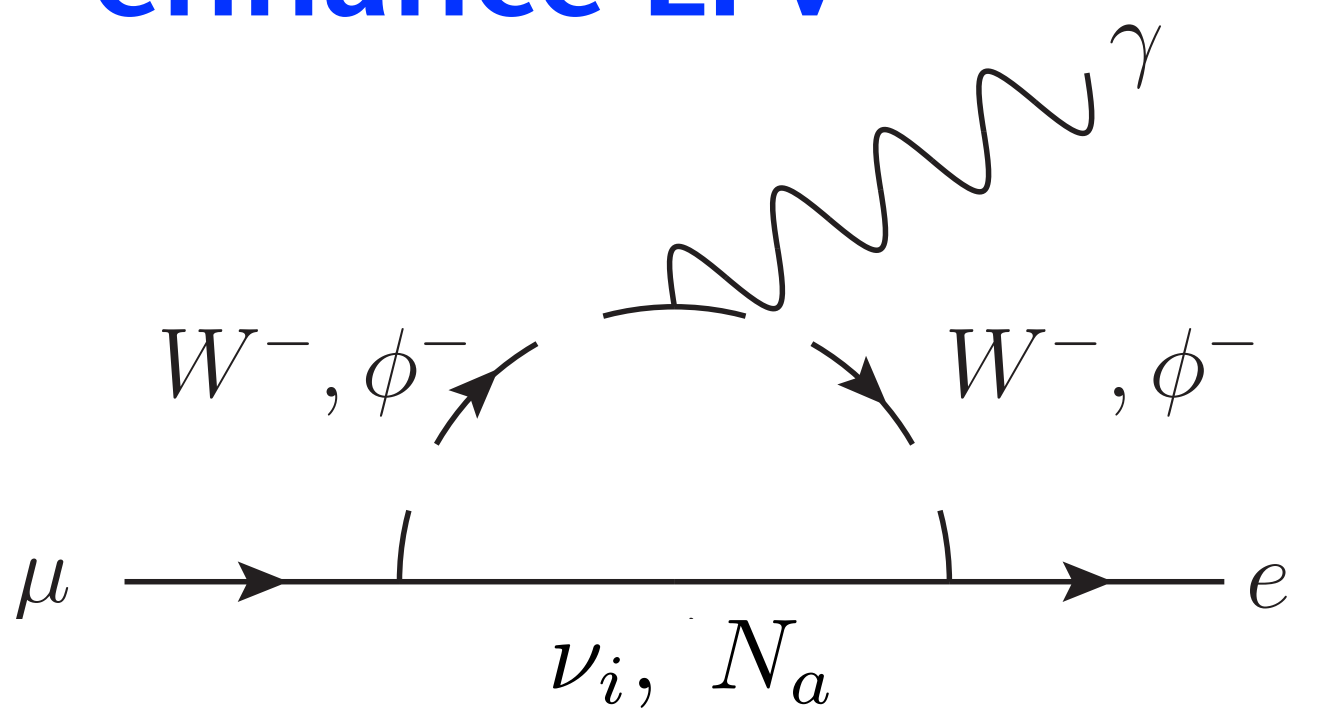
Arsenii Titov, Jelle Groot, Tim Kretz, Sam Bates

Phenomenology of HNLs

Non-unitary PMNS matrix

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = (1 - \frac{1}{2}\theta\theta^{\dagger})V_{\nu L}^{\dagger} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \equiv U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

HNL can significantly enhance LFV

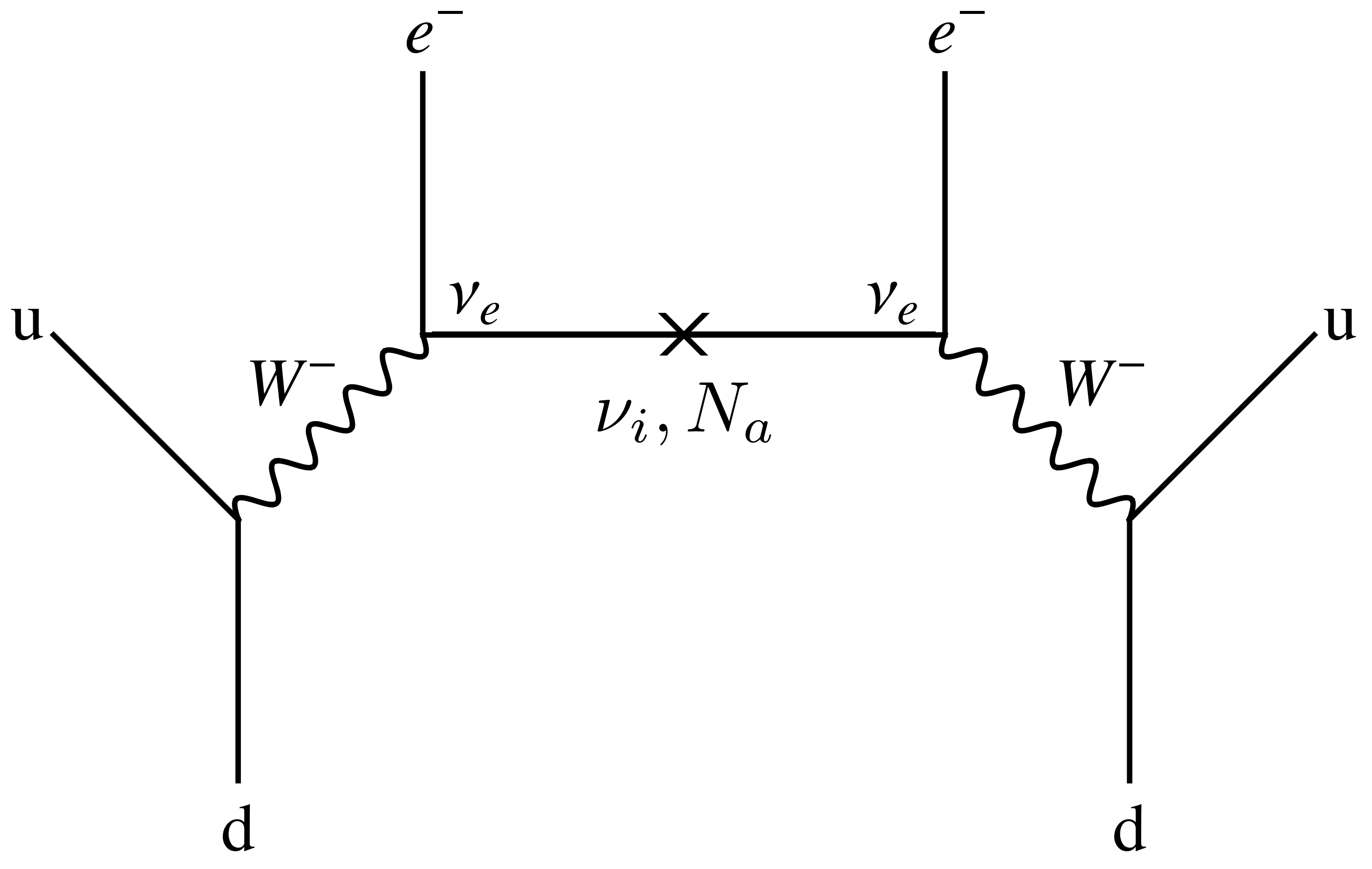


Charged currents for light and heavy neutrinos

$$-\frac{g}{\sqrt{2}} W_{\mu}^{-} \bar{l}_L \gamma^{\mu} (U_{li}^{\mathrm{PMNS}} \nu_i + \theta_{la} N_a^c)$$

HNL contributions to neutrinoless double beta decay

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^{\mathrm{PMNS}\,2} m_i + \sum_{a=1}^{3} \theta_{ea}^2 M_a \frac{\mathcal{A}(M_a)}{\mathcal{A}(0)} \right|$$



$M_a^2 \ll p^2, \quad m_{\beta\beta} \to 0$

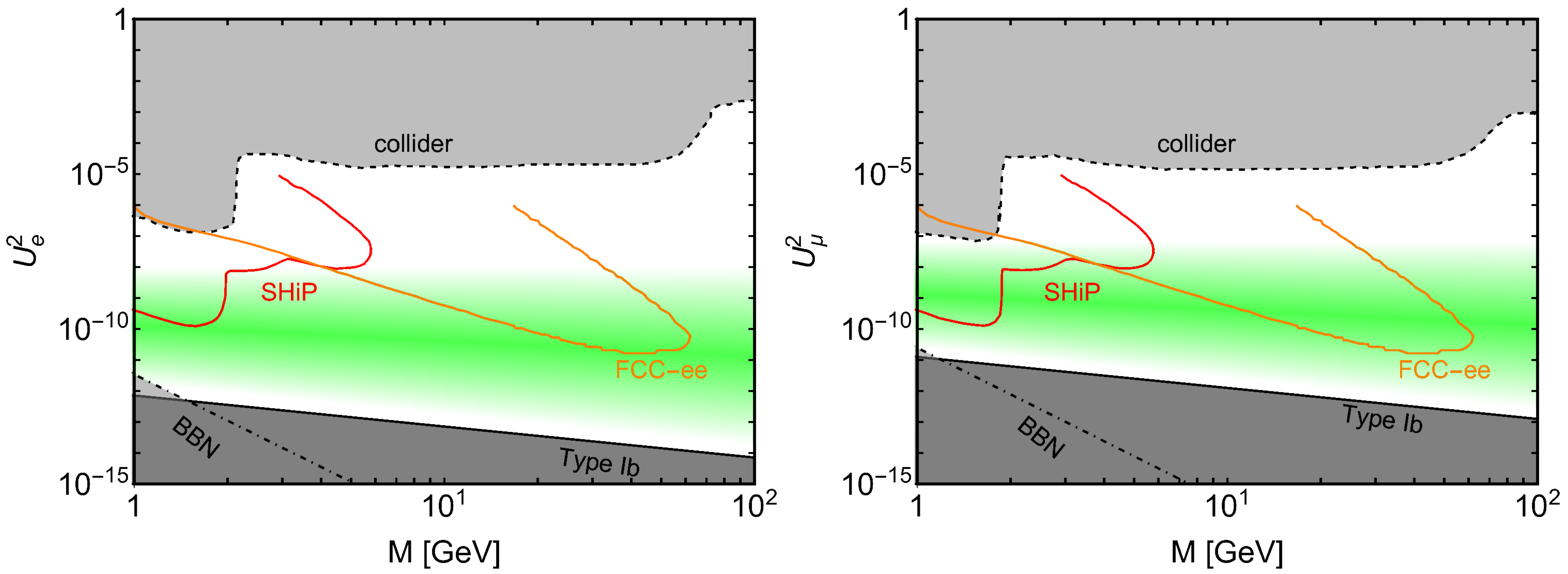
$M_a^2 \gtrsim \mathrm{GeV}, \quad m_{\beta\beta} \to m_{ee}$

$$\frac{\mathcal{A}(M_a)}{\mathcal{A}(0)} \approx \frac{p^2}{p^2 + M_a^2} \qquad p \sim 100 \text{ MeV}$$

Vaisakh Plakkot

Richard Ruiz, Anne-Mazarine Lyon, Matthias Saimpert, Manimala Mitra, Margaret Lutz, Haifa Sfar

Collider searches for HNLs



Recall single RHN result

$$|\theta|^2 \approx \frac{|m_L^{\rm eff}|}{M_R} \approx 10^{-10}\left(\frac{1\,\text{GeV}}{M_R}\right)$$

How does this result apply to U_e^2 and U_μ^2 in realistic models?

Two Right-handed Neutrinos (minimal case)

First consider diagonal RHNs

$$M_R = \begin{pmatrix} M_{\text{atm}} & 0 \\ 0 & M_{\text{sol}} \end{pmatrix}$$

Dirac matrix

$$m^D = \begin{pmatrix} d & a \\ e & b \\ f & c \end{pmatrix}$$

Seesaw $\quad m^\nu \approx -m_D M_R^{-1} m_D^T$

$$m^\nu = \frac{1}{M_{\text{atm}}} \begin{pmatrix} d^2 & de & df \\ de & e^2 & ef \\ df & ef & f^2 \end{pmatrix} + \frac{1}{M_{\text{sol}}} \begin{pmatrix} a^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

If first matrix dominates, get natural hierarchy

$$m_1 \ll m_2 \ll m_3$$

E.g. Littlest Seesaw gives good fit to data

$$d = 0 \qquad b = 3a$$
$$e = f \qquad c = a$$
$$\arg(a^2/e^2) = \exp(2\pi i/3)$$

$$\Rightarrow$$

$$\theta_{23} \approx 45^o$$
$$\theta_{12} \approx 34^o$$
$$\theta_{13} \approx 8.5^o$$
$$\delta \approx 270^o$$

Predicts

U_e^2

U_μ^2

$$|\theta_{lN}|^2 \approx \begin{pmatrix} 0 & \frac{m_2}{3M_{\text{sol}}} \\ \frac{m_3}{2M_{\text{atm}}} & \frac{3m_2}{M_{\text{sol}}} \\ \frac{m_3}{2M_{\text{atm}}} & \frac{m_2}{3M_{\text{sol}}} \end{pmatrix} \approx \begin{pmatrix} 0 & 0.03 \\ 0.25 & 0.26 \\ 0.25 & 0.03 \end{pmatrix} \times 10^{-10} \left(\frac{1\text{GeV}}{M}\right)$$

Both smaller than SRHN estimate

Two Right-handed Neutrinos (minimal case)

Now consider off-diagonal RHNs

$$M_R = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}$$

Heavy Dirac neutrino (HNL)

$$\mathcal{L}^{\text{lepton}}_{\text{mass}} = -\sum_{l=e,\mu,\tau} \bar{l}_L m_l l_R - \bar{\nu}_{lL} m^D_{l1} \nu_{R1} - \bar{\nu}_{lL} m^D_{l2} \nu_{R2} - \overline{\nu^c_{R1}} M \nu_{R2} + \text{H.c.}$$

Diagonal charged leptons

Two Dirac columns

Seesaw $m^\nu \sim \dfrac{m^D_1 m^D_2}{M}$

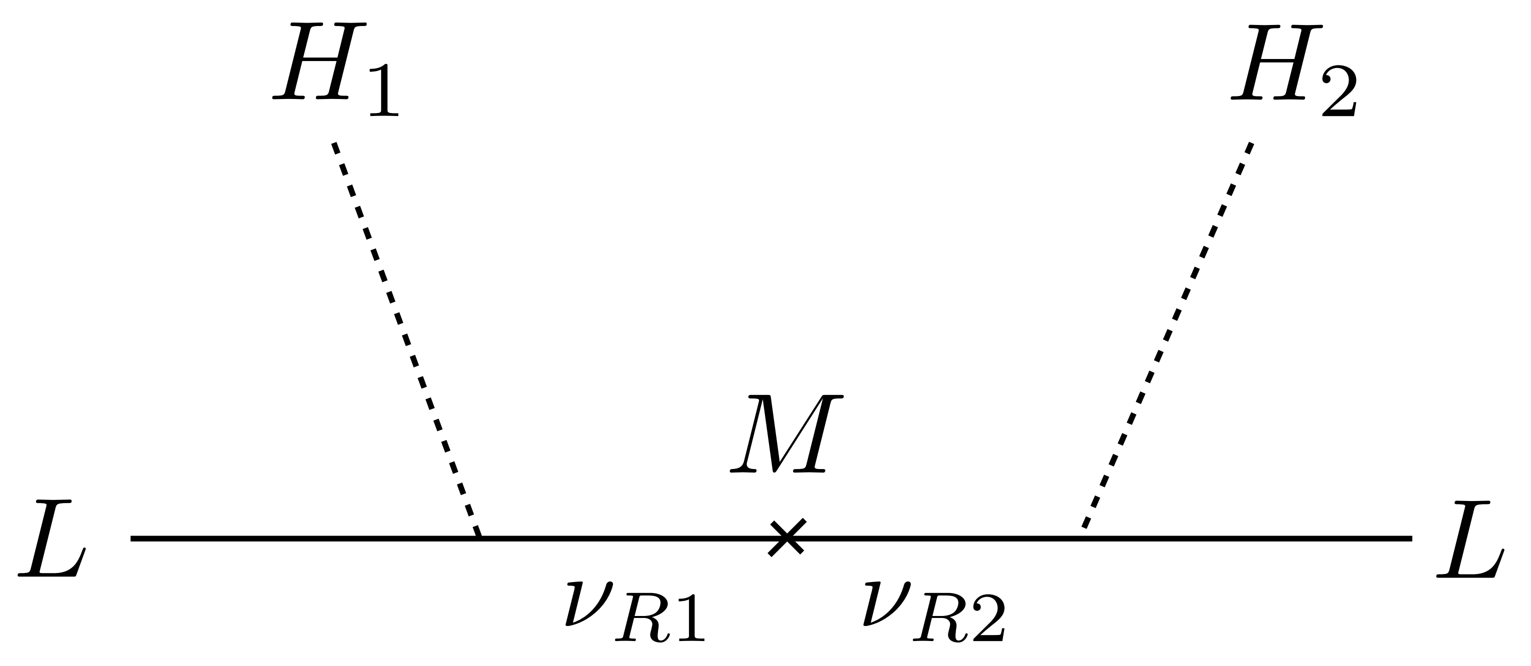
HNL mixing $\theta^2 \sim \dfrac{(m^D_1)^2}{M^2} + \dfrac{(m^D_2)^2}{M^2}$

If $m^D_1 \ll m^D_2$ then, for fixed m^ν, HNL mixing is large and may be observable if not too heavy

E.g. Type Ib seesaw

$$\omega = \exp(2\pi i/3)$$

	L_i	e_{Rj}	H_1	H_2	ν_{R1}	ν_{R2}
$SU(2)_L$	**2**	**1**	**2**	**2**	**1**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0
Z_3	1	ω	ω	ω^2	ω^2	ω



Inverse seesaw mechanism

Consider RHNs and singlets

$$(\nu_L^c, \nu_R, S_R)$$

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

In limit $\mu \to 0$

$$\overline{\nu}_R(MS_R^c + m_D\nu_L) = M\overline{\nu}_R(S_R^c + \theta\nu_L) \equiv M\overline{\nu}_R N,$$

$$N = S_R^c + \theta\nu_L, \qquad \nu = \nu_L - \theta S_R^c \qquad \theta \approx m_D M^{-1}$$

Massive HNL — Massless ν — HNL mixing

Now switch on small mass μ

$$\mu \overline{S}_R S_R^c \to m_\nu = \mu \frac{m_D^2}{M^2} \qquad |\theta|^2 \approx \frac{|m_\nu|}{\mu}$$

Large HNL mixing if μ is small

E.g. Minimal Inverse Seesaw model

$$m_D = \begin{pmatrix} d & a \\ e & b \\ f & c \end{pmatrix}, \quad M = \begin{pmatrix} M_{\rm atm} & 0 \\ 0 & M_{\rm sol} \end{pmatrix}, \quad \mu = \begin{pmatrix} \mu_{\rm atm} & 0 \\ 0 & \mu_{\rm sol} \end{pmatrix}$$

Inverse seesaw formula $m_\nu = m_D (M^T)^{-1} \mu M^{-1} m_D^T$

$$m^\nu = \frac{\mu_{\rm atm}}{M_{\rm atm}^2}\begin{pmatrix} d^2 & de & df \\ de & e^2 & ef \\ df & ef & f^2 \end{pmatrix} + \frac{\mu_{\rm sol}}{M_{\rm sol}^2}\begin{pmatrix} a^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

Littlest Inverse Seesaw predicts

$$|\theta_{lN}|^2 \approx \begin{pmatrix} 0 & \frac{m_2}{3\mu_{\rm sol}} \\ \frac{m_3}{2\mu_{\rm atm}} & \frac{3m_2}{\mu_{\rm sol}} \\ \frac{m_3}{2\mu_{\rm atm}} & \frac{m_2}{3\mu_{\rm sol}} \end{pmatrix}$$

HNL mixing enhanced by small μ

Conclusions

- RHNs and seesaw mechanism is simplest renormalisable mechanism for explaining tiny neutrino masses (uv completion of Weinberg operator)
- Well motivated from GUTs and Leptogenesis (not considered here)
- Expect heavy new neutrinos (HNLs) with masses ~ GeV or higher with new couplings to W, Z, Higgs (only considered W couplings here)
- HNL mixing angles may be small (e.g. two diagonal RHNs with natural hierarchy) or large (e.g. two off-diagonal RHNs, Inverse seesaw models)
- Lots of interesting implications for such new-ν physics from colliders to cosmology (as will be discussed in detail at this workshop)