Tiny Neutrino Masses
A Theoretical Perspective

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Neutrinos have mass

Oscillation data implies neutrinos have mass

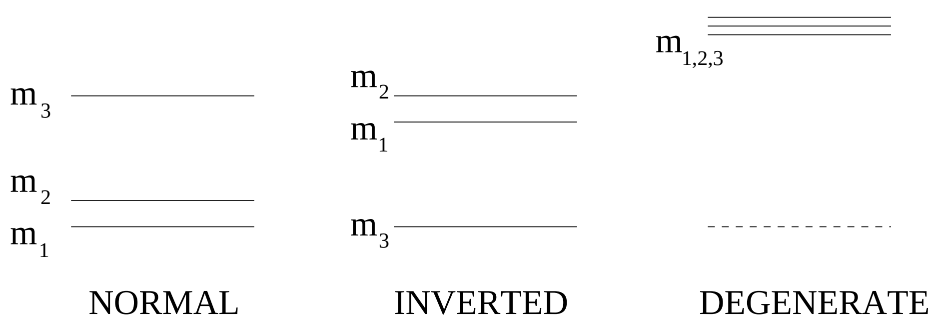
$$\Delta m^2_{\rm solar} = 7 \times 10^{-5}\ {\rm eV}^2\ , \quad \tan^2\theta_{solar} = 0.4$$

$$\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}\ {\rm eV}^2\ , \quad \tan^2\theta_{atm} = 1$$

Have to extend Standard Model (SM)

Questions:

- What is the scale of m_ν
- Is the ν a DIRAC or MAJORANA particle (Is $L_\#$ good)
- Which mass spectrum



- Is there CP violation in the lepton sector
- How about LSND (Is there a $4^{\rm th}$ ν)

What is the right Theory?

Can we explain such a tiny m^ν?

Some theoretical proposals:

- Dirac ν: Add ν_R with TINY (10^{-12}) Yukawa coupling
- Type I seesaw: Add ν_R and a BIG $(10^{13}\ \mathrm{GeV})$ mass
- Type II seesaw: Add scalar ξ with TINY $(0.1\ \mathrm{eV})$ VEV
- Extra dimensions: Add BULK ν_R with BRANE coupling to ν_L

How do we tell if any of these is right?

Dirac ν

SM + ν_R Assign $L_{\#}(\nu_R) = 1$

$$\mathcal{L}_{Yuk} \supset -\overline{L} \cdot H^\dagger \lambda^\nu \nu_R \qquad L = \begin{pmatrix} \nu_L \\ \ell \end{pmatrix}$$

$$\mathcal{L}_{mass} = -\overline{\nu}_L m \nu_R \qquad m \equiv \frac{v}{\sqrt{2}} \lambda^\nu$$

ν is a Dirac particle: $\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$

Properties:

- Similar to quark sector
- $L_{\#}$ good quantum number
- $\lambda^\nu \sim 10^{-12}$ - why?
- ν_R has no SM quantum numbers - why no Majorana mass term?

Experimental consequence: $0\nu\beta\beta$ cannot occur

Type I seesaw

SM + ν_R

SM gauge symmetry allows: $\mathcal{L} \supset -M\nu_R\nu_R$

If we allow such a term, $L_\#$ is broken

$$\mathcal{L}_{Yuk} \supset \left[-\overline{L} \cdot H^\dagger \lambda^\nu \nu_R - \overline{\nu_R^c} M \nu_R\right] +$$

- $$\mathcal{L}_{mass} = -\left(\overline{\nu}_L \quad \overline{\nu_R^c}\right) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

  Eigenvalues: $m_1 \approx \frac{m^2}{M}$ and $m_2 \approx M$

- For $M \sim 10^{13}$ GeV, $\lambda \sim \mathcal{O}(1)$: $m_1 \sim 0.1$ eV

  Naturally explains tiny m^ν

ν is a Majorana particle. ν is its own antiparticle

Type II seesaw

SM + ξ (Higgs Triplet) $\quad \xi = \begin{pmatrix} \xi^{++} \\ \xi^{+} \\ \xi^{0} \end{pmatrix} \to \begin{pmatrix} \frac{\xi^{+}}{2} & \frac{\xi^{++}}{\sqrt{2}} \\ \frac{\xi^{0}}{\sqrt{2}} & -\frac{\xi^{+}}{2} \end{pmatrix}$

$$\begin{aligned} \mathcal{L} \quad &\supset \quad -\frac{\kappa}{\sqrt{2}}\overline{L^c} \cdot \xi L - \sqrt{2}\mu H^T \cdot \xi^\dagger H - 2M^2 Tr\left[\xi^\dagger \xi\right] - V\left(H, \xi\right) \\ &\supset \quad \kappa\left[-\xi^0 \overline{\nu_L^c}\nu_L + \sqrt{2}\xi^+ \overline{\ell^c}\nu_L + \xi^{++}\overline{\ell^c}\ell\right] \end{aligned}$$

Minimize $V(H, \xi)$: $\left\langle \xi^0 \right\rangle \equiv u = -\mu \frac{v^2}{M^2}$ (and as usual $\left\langle h^0 \right\rangle \equiv v \neq 0$)

$$\mathcal{L} \supset -m\overline{\nu_L^c}\nu_L \qquad m = \kappa u$$

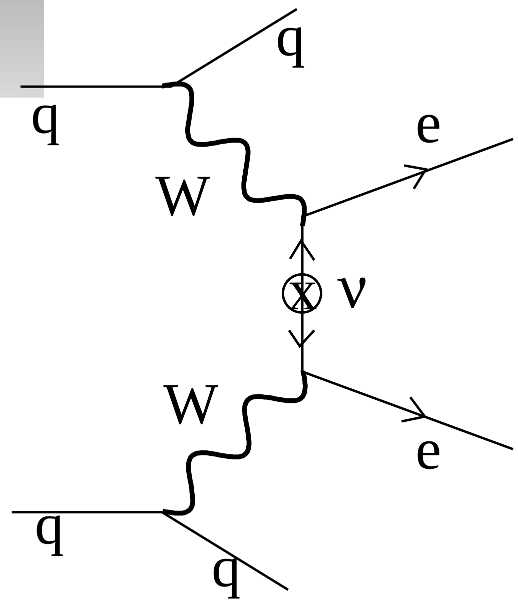
Two possibilities:

(1) $\mu = M \sim 10^{13}\ \mathrm{GeV} \Rightarrow u \sim 0.1\ \mathrm{eV}$

(2) $M = v\ ,\ \mu \sim 0.1\ \mathrm{eV} \Rightarrow u \sim 0.1\ \mathrm{eV}$

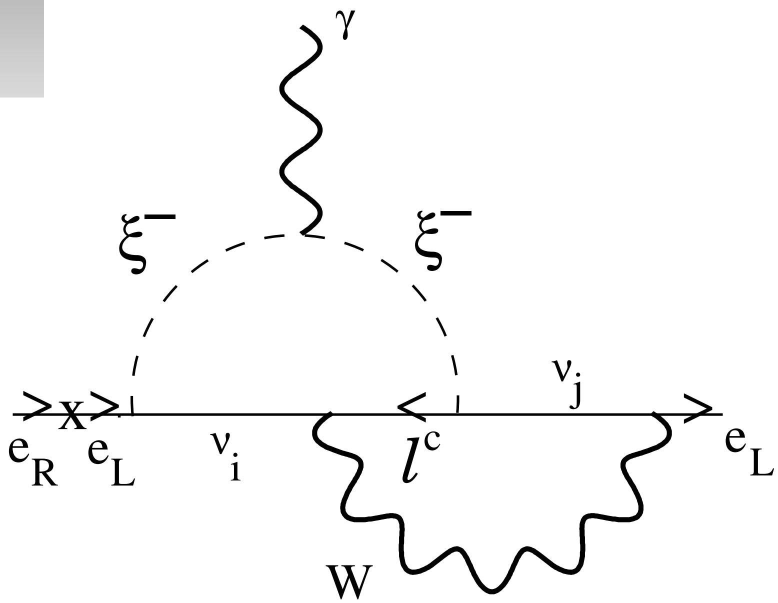
ν-less double β decay

$0\nu\beta\beta$ only for Majorana ν



e^- **EDM**

New Higgs triplet (ξ) contribution



Conclusions

SM needs to be extended to give Neutrinos mass

Is the neutrino Dirac or Majorana?

Various theoretical ideas explain tiny neutrino mass

Most appealing is the Seesaw explanation (Type I, II)

Probes: $0\nu\beta\beta$, e^- EDM, $\mu \to e\gamma$, $\mu \to eee$, ...