

# Adding Neutrino Mass Terms

## 1) Simplest possibility: add 3 right handed neutrino fields

$$\begin{array}{c} v_L \ g_N \ v_R \\ \hline \vdots \\ x \\ <\phi> = v \end{array}$$

$$\begin{array}{c} v_R \ x \ v_R \\ \hline x \\ \text{Majorana} \\ L \end{array}$$



$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

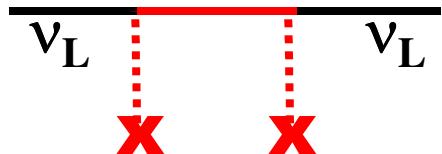
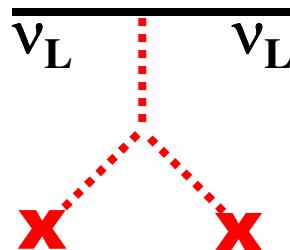
New ingredients:  
1) Majorana mass (explicit)  
2) lepton number violation

6x6 block mass matrix  
block diagonalization  
 $M_R$  heavy → 3 light  $\nu$ 's

**NEW ingredients, 9 parameters → beyond SM → SM+**

# Other Neutrino Mass Operators

2) new scalar or fermionic triplets:



→ left-handed Majorana mass term:

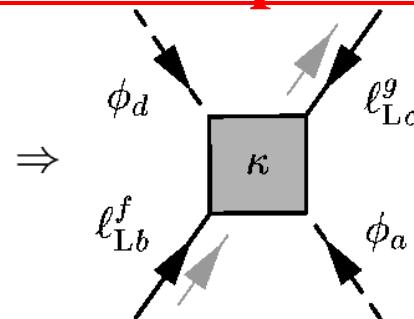
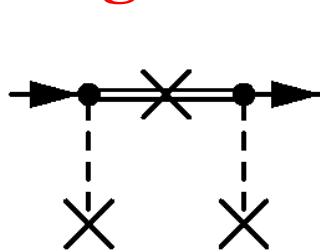
$$\rightarrow M_L \bar{L} L^c$$

3) Both  $v_R$  and new triplets:

→ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

4) Higher dimensional operators: d=5, ...



↔

$$\mathcal{L}_{\text{mass}} = \kappa \cdot \bar{\nu}_L^C \nu_L \Phi^T \Phi$$

$$\rightarrow M_L \bar{L} L^c$$

5-N) ...

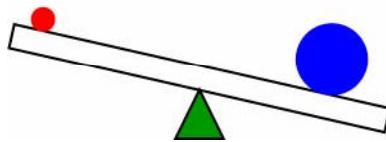
# Suggestive Seesaw Features

QFT: natural value of mass operators  $\leftrightarrow$  scale of symmetry

$m_D \sim$  electro-weak scale

$M_R \sim$  L violation scale  $\leftarrow ? \rightarrow$  embedding (GUTs, ...)

See-saw mechanism (type I)



$$m_\nu = m_D M_R^{-1} m_D^T$$

$$m_h = M_R$$

Numerical hints:

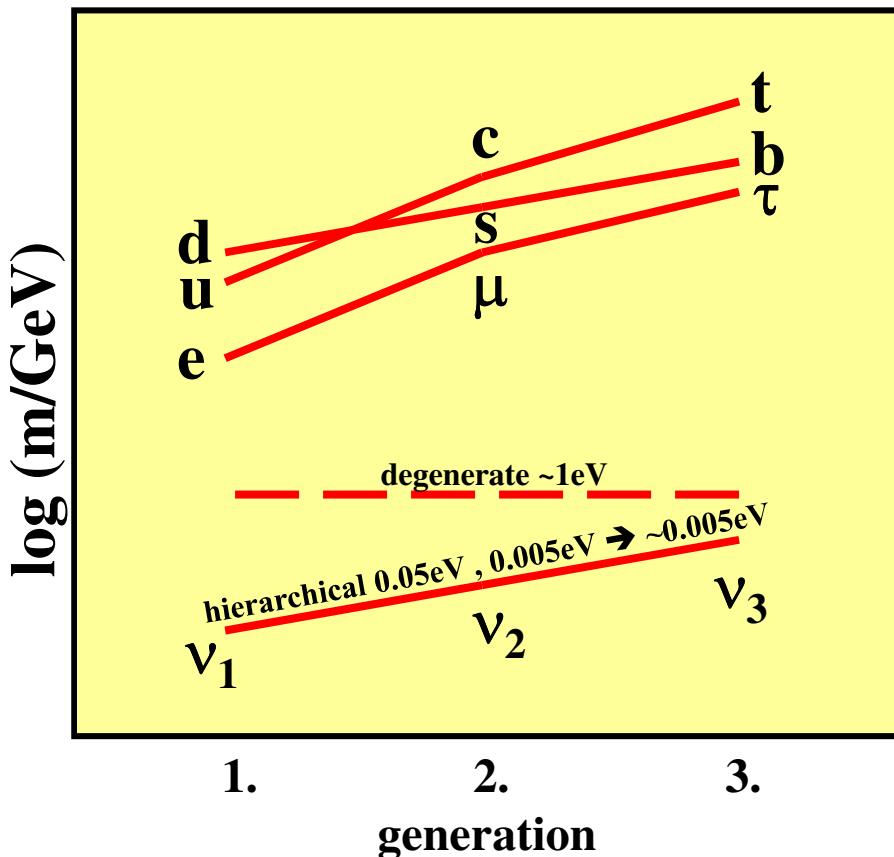
For  $m_3 \sim (\Delta m_{\text{atm}}^2)^{1/2}$ ,  $m_D \sim$  leptons  $\rightarrow M_R \sim 10^{11} - 10^{16} \text{ GeV}$

$\rightarrow$   $\nu$ 's are Majorana particles,  $m_\nu$  probes  $\sim$  GUT scale physics!

$\rightarrow$  smallness of  $m_\nu \leftrightarrow$  high scale of  $L$ , symmetries of  $m_D, M_R$

# 2nd Look Questions

Quarks & charged leptons → hierarchical masses → neutrinos?



Quarks and charged leptons:

$$m_D \sim H^n ; n = 0, 1, 2 \rightarrow H \geq 20 \dots 200$$

Neutrinos:  $m_\nu \sim H^n \rightarrow H \leq \sim 10$

See-saw:

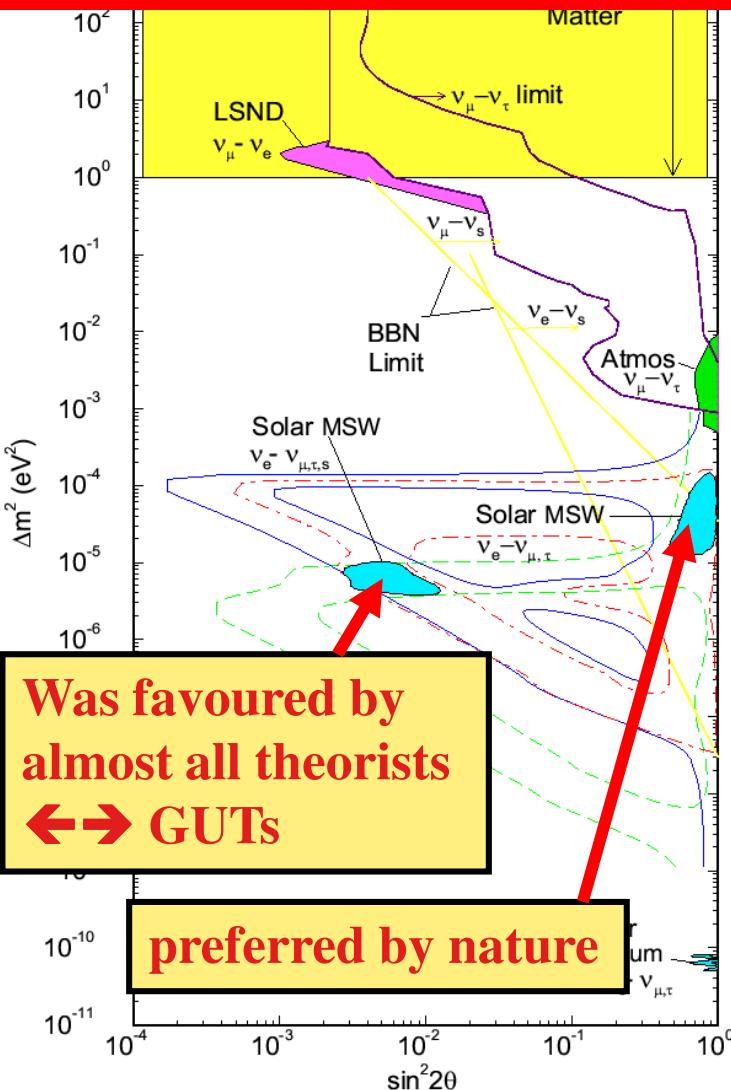
$$m_\nu = -m_D^T M_R^{-1} m_D$$

$\updownarrow$        $\updownarrow$        $\updownarrow$        $\updownarrow$   
 H       $\sim 10$        $\geq 20$       ?       $\geq 20$

- less hierarchy in  $m_D$  or correlated hierarchy in  $M_R$ ? → theoretically connected!
- mixing patterns: not generically large, why almost maximal,  $\theta_{13}$  small?

# Learning about Flavour

## History: Elimination of SMA



## Next: Smallness of $\theta_{13}$ , $\theta_{23}$ maximal

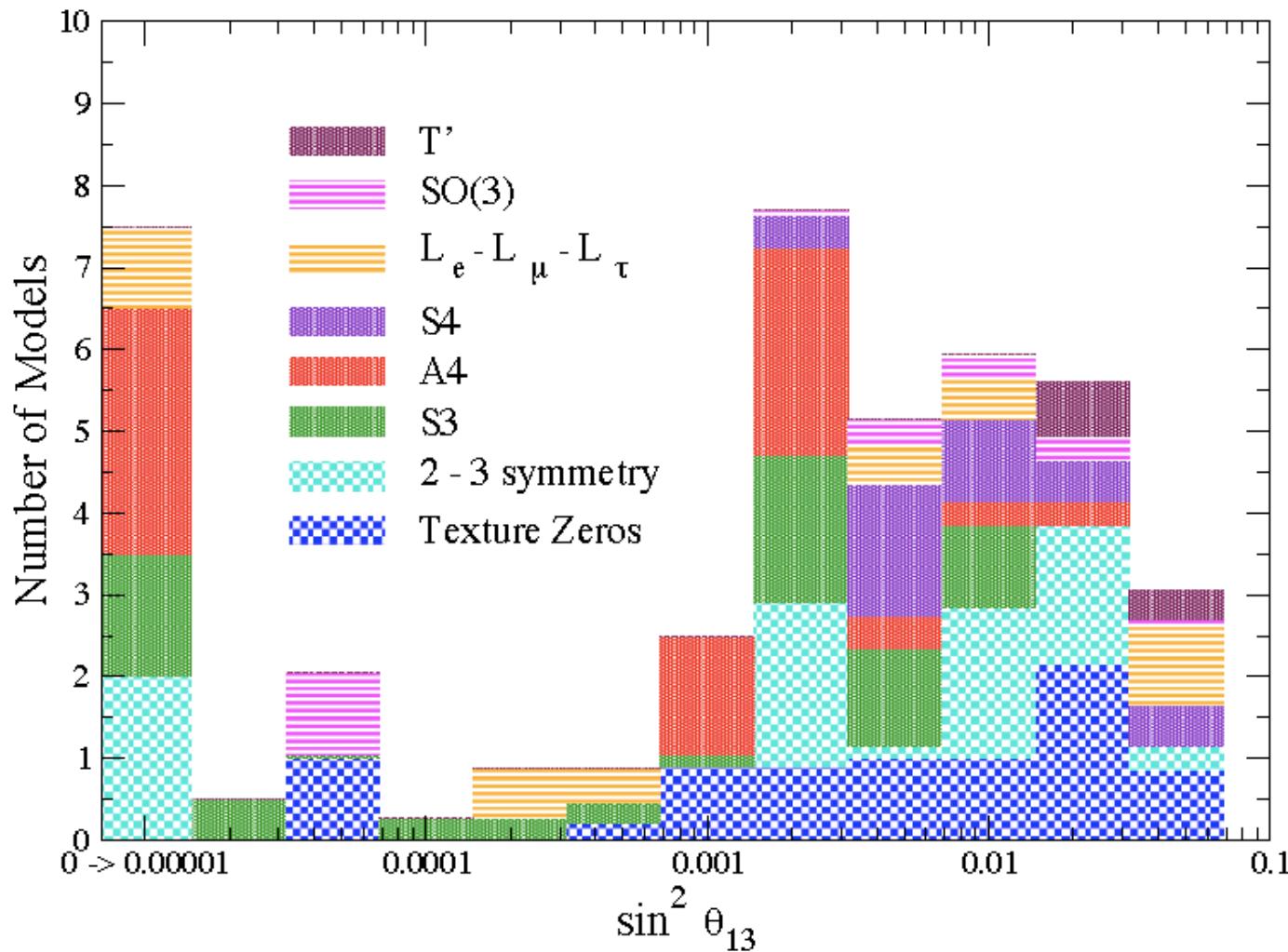
- models for masses & mixings
- input: known masses & mixings
  - distribution of  $\theta_{13}$  predictions
  - $\theta_{13}$  expected close to ex. bound
  - well motivated experiments

what if  $\theta_{13}$  is very tiny?  
or if  $\theta_{23}$  is very close to maximal?

- numerical coincidence unlikely
- special reasons (symmetry, ...)
- addressed by coming precision

# $\theta_{13}$ – Tiny or only small?

## Predictions of Lepton Flavor Models



Albright