3) NEUTRINO MASSES

- NONZERO NEUTRINO MASSES IMPLY THE EXISTENCE OF NEW DEGREES OF FREEDOM BEYOND $Q u^c d^c L e^c H \oplus SU(3) \times SU(2) \times U(1)$

- WE DON'T KNOW WHAT ARE THESE NEW DEGREES OF FREEDOM. THEY CAN BE FERMIONS OR BOSONS, VERY LIGHT, VERY HEAVY, ETC.

a) DIRAC NEUTRINOS:

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{matrix} u^c \\ d^c \end{matrix} \qquad L = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \begin{matrix} \nu^c \\ e^c \end{matrix}$$

$$-\mathcal{L} \supset \lambda_\nu L \nu^c H \xrightarrow{\langle H \rangle} m_D \nu \nu^c$$

$$-\tfrac{1}{2} \quad +\tfrac{1}{2} = 0$$

L_D DIRAC

$$\nu^c \Rightarrow [1, 1, 0]$$

$SU(3)$ $SU(2)_L$ $U(1)_Y$

$$-\mathcal{L} \supset \frac{M}{2} \nu^c \nu^c$$

ASIDE: GLOBAL SYMMETRIES OF THE SM

QudLEH + GAUGE SYMMETRIES $\Rightarrow \begin{cases} U(1)_B \\ U(1)_L \end{cases}$ ACCIDENTAL,* CLASSICAL* GLOBAL SYMM.

e.g. $Q_L(L) = +1 \times 2$ $\quad \sum Q = 0$

$Q_L(e^c) = -1 \times 1$ $\quad \sum Q^3 = 0$

$\boxed{Q_L(\nu^c) = -1}$ $\quad +1 \to 0$

[* $U(1)_{B-L}$ ANOMALY FREE]

* - WE DID NOT "ASK" FOR THEM

- IF YOU EXTEND THE SM, THERE IS NO REASON TO EXPECT THEY WILL STILL BE CONSERVED

- VIOLATED BY QUANTUM GRAVITY (?)

ν^c

$$-\mathcal{L} \ni \underline{\underline{\lambda_\nu}} \, \overset{+1}{L} \, \overset{0}{\nu^c} \, \overset{0}{H} \quad \cancel{+ \frac{M}{2} \, \overset{0}{\underset{-1}{\nu^c}} \, \overset{0}{\underset{-1}{\nu^c}}}$$

$$\phantom{-\mathcal{L} \ni \lambda_\nu} \; +1 \; -1 \quad 0$$

$$Q_L(L) = +1 \qquad Q_L(\underline{\underline{\nu^c}}) = -1$$

$$Q_L(e^c) = -1 \qquad\qquad = 0$$

IF $\underline{\underline{L \text{ IS GOOD}}}$

$$\lambda_\nu = 0 \longrightarrow m_\nu = 0$$

$$\underline{\underline{M = 0}} \longrightarrow \underline{\underline{m_\nu = \lambda_\nu v}}$$

PERFECTLY GOOD MODEL

- NEW PARTICLE ν^c, VERY LIGHT FERMION
- LEPTON NUMBER IS NOT ACCIDENTAL SYMM.
  $\to$ FUNDAMENTAL SYMM.

$\mathcal{L} \to Q u^c d^c L e^c \nu^c H$ + GAUGE SYMM + L IS GOOD

COMPLAINT(S)

$m_\nu = \lambda_\nu v$

$v \to 100$ GeV

$\lambda_\nu \to 10^{-12}$

$\lambda_e \sim 10^{-5}$

$$-\mathcal{L} \supset \lambda_\nu L \nu^c H \qquad \lambda_\nu \sim \underline{\underline{10^{-12}}} \sim 0$$

SYM.

$$Q_{NEW}(\nu^c) = +1 \qquad Q_{NEW}(QudLeH) = 0$$

$$Q_{NEW}(\phi) = -1$$

$$\frac{L\nu^c H\phi}{\Lambda} \xrightarrow{\langle H\rangle,\ \langle\phi\rangle} m_\nu \nu^c \nu \ ; \quad m_\nu \sim \frac{v \cdot v_\phi}{\Lambda}$$

DARK SECTOR

$$\nu^c \longrightarrow L\nu^c H$$

$$\underline{\underline{\phi}} \longrightarrow |\phi|^2 |H|^2$$

$$v_\phi, v \ll \Lambda$$

MAJORANA MASSES

$$\mathcal{L} \supset \cancel{m \nu \nu} \quad 0+0 \neq 0 \quad \longrightarrow \quad \text{NO NEW LIGHT FIELD}$$

VIOLATES $SU(2)$ $\longrightarrow$ $L = \begin{pmatrix} \nu \\ e \end{pmatrix}$

$$m \cancel{L L}$$

$$L \to -1/2 - 1/2 = -1$$

VIOLATES GAUGE INVARIANCE

$$\boxed{\overset{-1/2 + 1/2}{(LH)}(LH)}$$

GAUGE SINGLET

LORENTZ SINGLET

$$-\mathcal{L} \supset \boxed{\frac{(LH)(LH)}{\Lambda}} \longrightarrow \text{DIMENSION-5}$$

WEINBERG (79).

NEW

WEAK

$\Lambda \sim 10^{15}$ GeV

$\not{L}$

$$-\mathcal{L}(\langle H \rangle) = m_\nu \nu\nu$$

$$\boxed{m_\nu = \frac{v^2}{\Lambda}}$$

$$\underbrace{v}_{m_{\text{CHARGED}}} \cdot \underbrace{\left(\frac{v}{\Lambda}\right)}_{\varepsilon}$$

$m_{\text{CHARGED}} \times \varepsilon \longrightarrow$ EXPERIMENT

$\Lambda \sim 10^{15}$ GeV $\longrightarrow$ ENERGY ABOVE WHICH WE ARE SURE THE SM BREAKS DOWN

$$\mathcal{L} \overset{?}{\supset} \frac{1}{\sqrt{2}} G_F \; \bar{\mu}\, \gamma_\mu P_L \nu_\mu \; \bar{\nu}_e\, \gamma^\mu P_L\, e$$

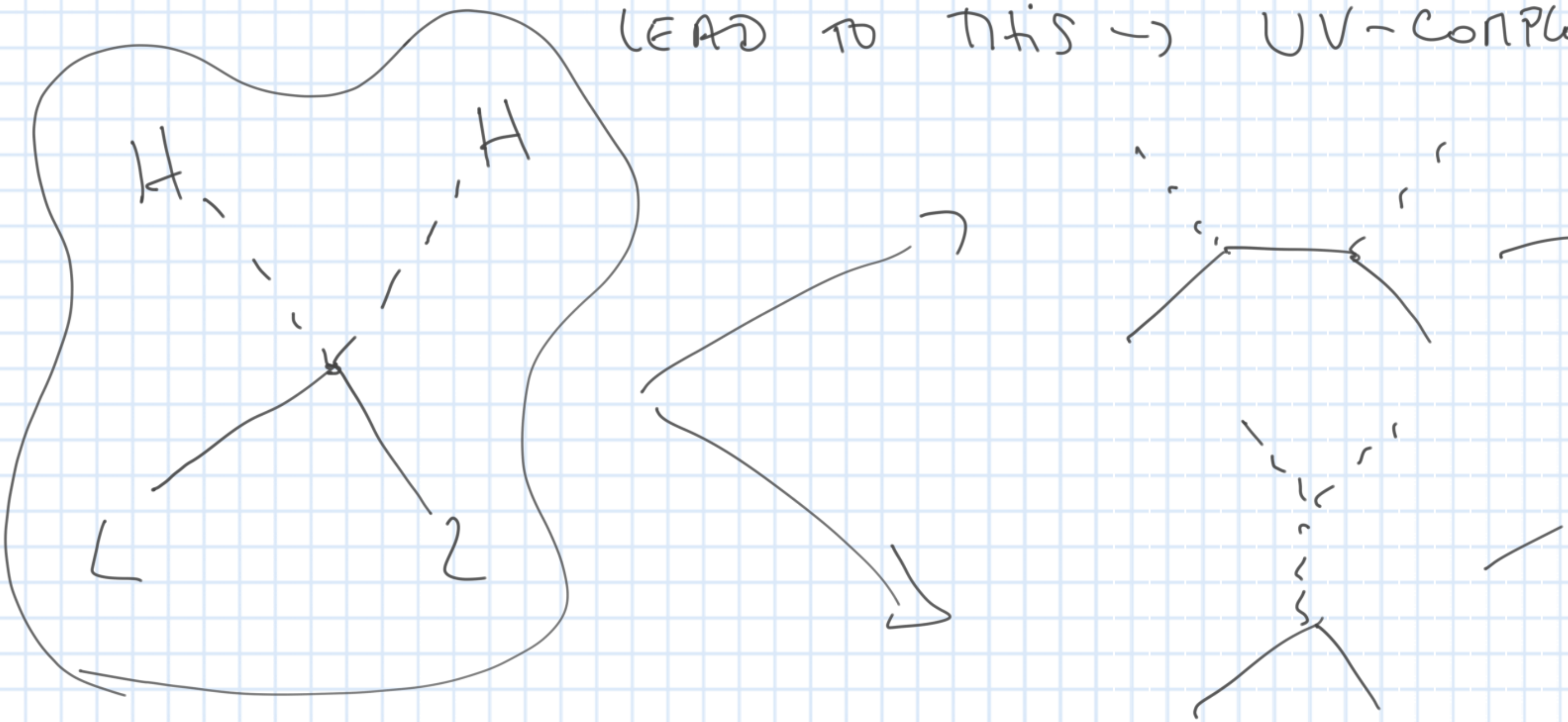
$$G_F \sim \left(\frac{1}{246\,\text{GeV}}\right)^2$$

$M_W \sim 80$ GeV

$K^+ \to \pi^0 W^+$

$|H|^2 (LH)^2$ → – WHERE DOES THIS COME FROM?

– WHAT ARE THE PARTICLES THAT LEAD TO THIS → UV-COMPLETION



TYPE-II SEESAW

$(Y=-1)$ LL CAN BE COMBINED INTO A TRIPLET

$$\begin{pmatrix}\nu\\ e\end{pmatrix}\begin{pmatrix}\nu\\ e\end{pmatrix} = \begin{pmatrix}\nu\nu\\ (\nu e + e\nu)\frac{1}{\sqrt{2}}\\ ee\end{pmatrix}$$

$$\boxed{Q_L(T) = -2}$$

$$\underline{\lambda\, L T L} \ni -\mathcal{L}$$

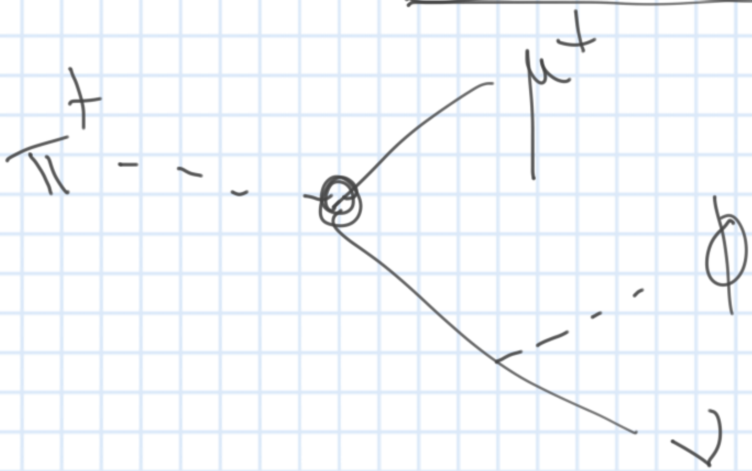
$$T = \begin{pmatrix}t^{++}\\ t^{+}\\ t^{0}\end{pmatrix}$$

$Y=+\underline{1}$

$$\langle T\rangle = v_t \ll v$$

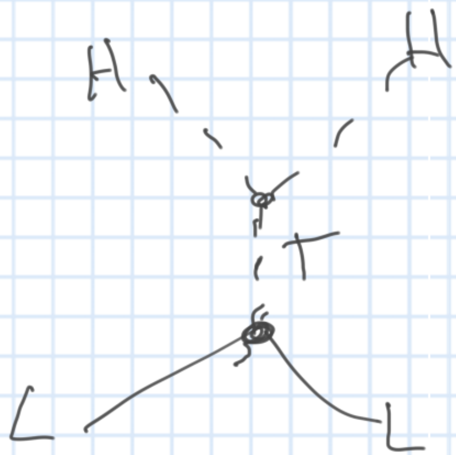
$$\boxed{m_\nu = \lambda v_t}$$

BREAK L SPONTANEOUSLY $\longrightarrow$ GOLDSTONE BOSON (MASSLESS SCALAR)



$\longrightarrow$ [MAJORON]

$$m_T \gg m_H$$



$$(LH)(LH)\,\frac{\lambda\kappa}{m_T^2}$$

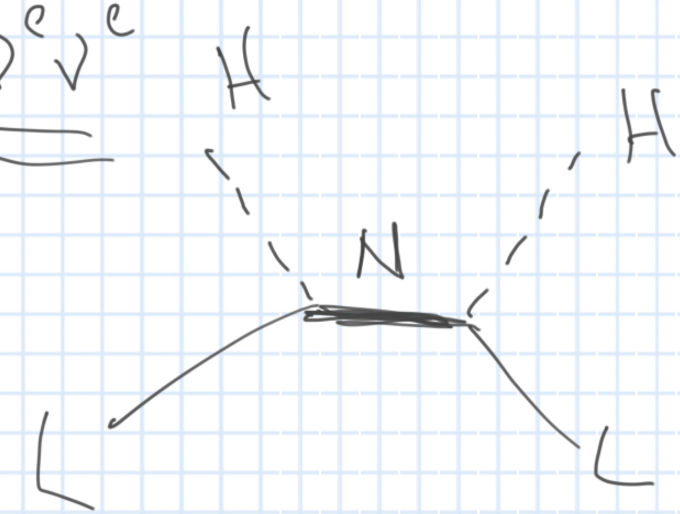
$$\frac{1}{\Lambda} \sim \frac{\lambda\kappa}{m_T^2}$$

$$U \supset \underline{\underline{\kappa}}\;\underset{0}{\tilde{H}}\;\underset{-2}{T}\;\underset{0}{\tilde{H}}$$

TYPE-I SEESAW

$$-\mathcal{L} \supset \underline{\underline{\lambda_\nu}}\, L \nu^c H + \frac{M}{2}\, \underline{\underline{\nu^c \nu^c}}$$

$$M \gg m_H$$



$$\frac{(L H)^2}{\Lambda} \Rightarrow \boxed{\frac{1}{\Lambda} = \lambda_\nu^2 \frac{M}{M^2}}$$

$$-\mathcal{L} \supset \underline{\lambda_\nu L H \nu^c} + \frac{M}{2}\nu^c\nu^c$$

$$\Big\downarrow \langle H \rangle$$

$$-\mathcal{L} \supset m_D \nu \nu^c + \frac{M}{2}\nu^c\nu^c = \frac{1}{2}\begin{pmatrix}\nu & \nu^c\end{pmatrix}\underbrace{\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}}_{\text{MASS MATRIX}}\begin{pmatrix}\nu \\ \nu^c\end{pmatrix}$$

EXPLAINS NEUTRINO MASSES

MAJORANA, NEW FERMIONS!

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$$\underbrace{\phantom{\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}}}_{(3+N)\times(3+N)}$$

N = # OF ν^c-FIELDS $(N \geq 2)$

$M \gg m_D$

$m_H \sim M$

$m_{LIGHT} \sim \boxed{-\frac{m_D^2}{M}}$

NOT PHYSICAL

SEESAW

$\nu_H \sim \nu^c + \varepsilon\nu$

$\nu_{LIGHT} \sim \nu - \varepsilon\nu^c$

$\varepsilon \sim \frac{m_D}{M}$

$$\boxed{\theta_{AS}^2 \sim \frac{m_{LIGHT}}{m_H}}$$

$$\boxed{\sim \sqrt{\frac{m_{LIGHT}}{m_H}}}$$

$\rightarrow M \ll m_D$

$m_{\pm} = \pm m_D + M$

PSEUDO-DIRAC REGIME

$\Delta m^2 \sim 4 M m_D$

$\nu_+ = \frac{1}{\sqrt{2}} (\nu + \nu^c)$

$\nu_- = \frac{1}{\sqrt{2}} (\nu - \nu^c)$

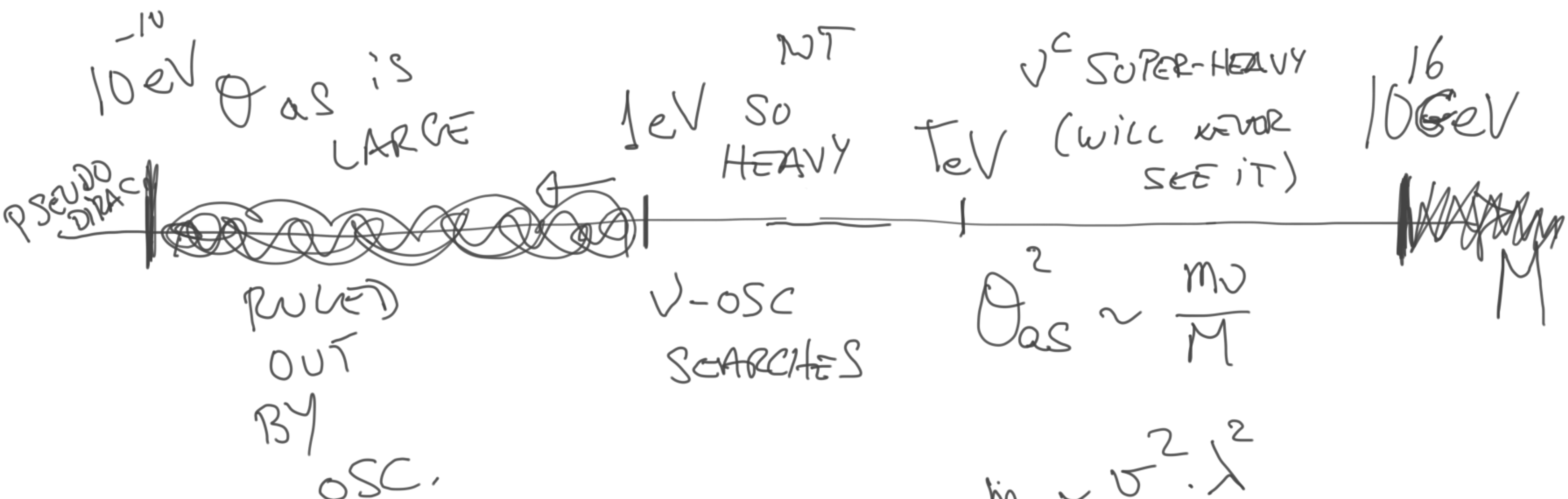
(SOLAR)

$\lesssim 10^{-12}\ eV^2$

$$-\mathcal{L} \supset \underbrace{\lambda_\nu} L \nu^c H + \frac{M}{2} \nu^c \nu^c$$

λ_ν, M

DATA (NEUTRINO DATA)



$$\theta_{as}^2 \sim \frac{m_\nu}{M}$$

$$m_\nu \sim \frac{v^2}{M} \cdot \lambda^2$$