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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.762 - 9

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

13 June - 29 July 1994

NEUTRINO PHYSICS

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ICTP

Please note: These are preliminary notes intended for internal distribution only.

SMIRNOV (1)

IN THREE LECTURES:

NEUTRINO PHYSICS
OR
LOOKING FOR NOTHING

(IN SEARCH FOR NOTHING)

ν & SUSY

15 minutes?
WHAT is MAIN, Basic?
WHAT WE KNOW?

SUMMARIZE

Def • Neutrino is
→ LIGHT OR MASSLESS $M \approx 0$
→ NEUTRAL : $Q = 0$; $Q_c = 0$
→ WITH SPIN 1/2.

PARTICLE

INTERACTIONS • ~~Neutral lepton → weak interactions gravity~~

EM INTERACTIONS IN HIGH ORDERS

3ν LEPTON • THREE NEUTRINOS : ν_e ν_μ ν_τ
AND CORRESPOND to CHARGE e μ τ.

→ THIS CORRESPONDENCE is DESCRIBED BY ~~LF~~ CONSERVING LEPTON NUMBERS

INTER • NEUTRAL LEPTON → weak interaction.

NO EM, STRONG →

• HUGE PENETRATION ABILITY, ESPECIALLY AT LOW E

• rise of σ (cross sections) with E

• THE INTERACTIONS ARE WELL DESCRIBED BY STANDARD MODEL

MOREOVER
ν played a crucial role in building and check of SM

→ NC. In ν-interactions

• STABLE ?

$\nu \to \nu \gamma$
φ

BOUND

• The antiparticle

$\bar{\nu}_e$

MAJORANA ? $\nu = \bar{\nu}$?

(*) ABUNDANCE — MAIN (UNIVERSAL) COMPONENT IN THE Universe:

ν:

Number density: → MORE THAN NUMBER OF PHOTONS

(Universal)

NATURAL SOURCES

- • Relic neutrinos.
- • PRODUCED SUN.
- • Collapsing stars
- • AGN.
- Earth's Atmosphere
- •

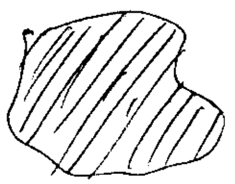
ELEMENTARY PROC.

- $\gamma \to \nu\bar{\nu}$ — e capture
- β decay, π, μ, K ...
- annihilation

Neutralinos.

ARTIFICIAL:

- ACCELERATORS
- SOURCES ^3H, ^{51}Cr ...
- MESON FACTORIES ^{76}Ge -2β



$6 \cdot 10^{10} \times 10^4$

$\approx 10^{14}\ \nu\ sec^{-1}\ cm^{-2}$ ← this is proven

Normal: 85 °C.

RELIC

Relic $4 \cdot 10^2 \cdot 3 \cdot 10^{10} \cdot 10^4 \geq 10^{17}$ 10^{-4}

more are large if local density is higher.

energy scales: (25 orders)

• Relic ——— CR.

10^{-4} eV ——— 10^{20} eV

→ (N) → give (appreciable) (main!) CONTRIBUTION TO ENERGY DENSITY in the universe → DYNAMICS of THE UNIVERSE

$\beta = \frac{E}{m}$

$\beta = \frac{1}{\sqrt{1 + m}}$

$\beta = \frac{p}{\sqrt{m^2 + p^2}}$ 10^{-3} 10^{-8}

$\beta = \frac{p^2}{2m^2}$

IN MINIMAL VERSION:

No ν_R

MASSLESS

NO coupling with Higgses which GENERATE MASSES of CHARGED LEPTON

~~MASSLESS~~ NO LEPTON ~~MIXING~~

~~DOES even in SM one can~~

Lepton number conservation

L_e, L_μ, L_τ.

INVARIANT

$$\nu_L \to e^{i2L_e} \nu_L$$

$$l_R, l_L \to e^{i2L_e} l_L$$

THE LARGER THE SCALES THE MORE IMPORTANT ROLE OF NEUTRINOS: → IMPORTANT FOR Astrophysics Cosmology

→ responsible for Large scale structure of the Universe

→ PLAY CRUCIAL ROLE IN THE EVOLUTION OF STARS!

→ [illegible], [illegible]: GRAVITATIONAL COLLAPSE · SN

→ cooling of stars

→ Nucleosynthesis of the elements in the universe

- Direct
- Indirect → expansion of the universe. 2 – 4 neutr → ^4He
- Nucleosynthesis in SN.

→ Problems!

· AFTER t - quark · ?

→ NEUTRINO MASSES (NATURE OF NEUTRI-

→ Lepton Mixing.

→ L - CONSERVATION.

→ NEW INTERACTIONS

~~No [illegible]~~

* LABORATORY experiments → bounds

(FROM TIME TO TIME SOME INDICATIONS:
- TTE D
- RUGER
- 17 keV
- ?
- oscillation at Los Alamos

* More steady (difficult to check

- solar neutrino
- ATMOSPHERIC NEUTRINOS
- Cosmological – large scale str

NEUTRINO PHYSICS

- MASSES AND LEPTON MIXING

I. INTRINSIC NEUTRINO PROPERTIES
(WHAT WE KNOW AND WHAT IS NOT KNOWN)

II. PROPAGATION OF MIXED NEUTRINOS IN VACUUM AND MATTER

III. "NEUTRINO ANOMALIES"
ASTROPHYSICS HINTS
AND NEUTRINO MASS SPECTRUM

PURPOSE: SHOW LEPTON MIXING MATTERS IN THE SEE-SAW MECHANISM

CONFIRMATE

COVERS THE FOLLOWING TOPICS

NEUTRINO (ν)

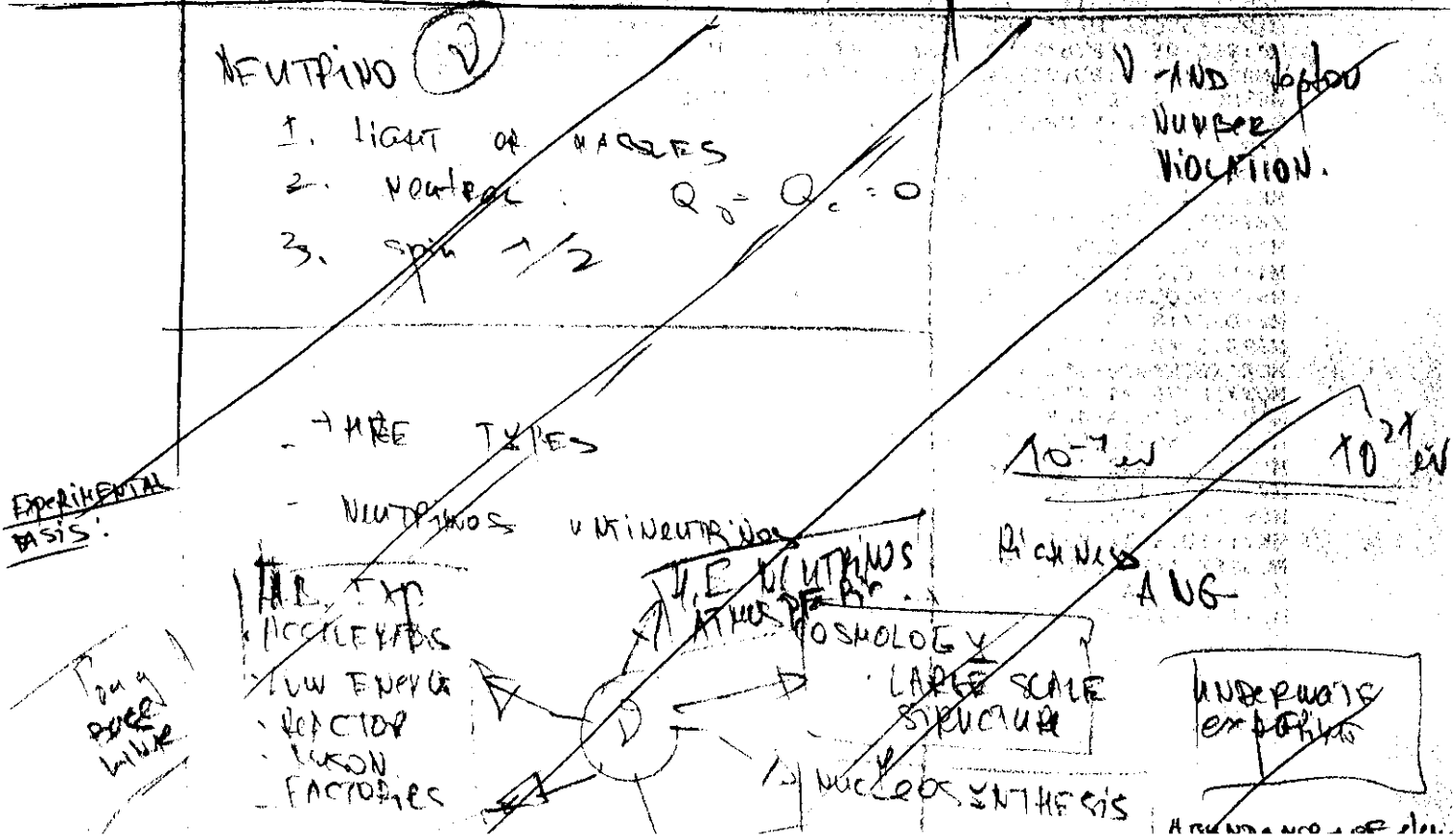
1. LIGHT OR MASSLESS
2. NEUTRAL $Q_0 = Q_c = 0$
3. SPIN 1/2

ν AND LEPTON NUMBER VIOLATION.

- THREE TYPES
- NEUTRINOS vs ANTINEUTRINOS

10^{-7} eV — 10^{21} eV

EXPERIMENTAL BASIS:



I. NEUTRINO PROPERTIES

I.1 ν IN THE STANDARD MODEL

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

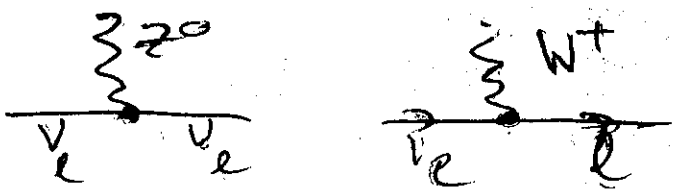
DOUBLETS of SU_2 Doublets

- THREE NEUTRINOS

= CAN BE CHARACTERIZED BY:

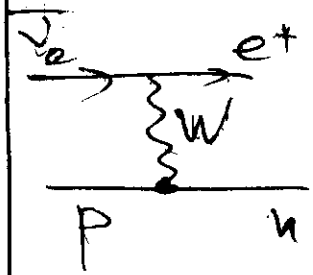
- $I_3 = \frac{1}{2}$ ← WEAK ISOSPIN
  $Y = -1$ HYPERCHARGE

$Q = 0$ ⇐ NO DIRECT COUPLING WITH PHOTON

- 

← THIS INTERACTION DETERMINES THE FLAVOR

fix "FLAVOR" OF NEUTRINO STATE



IN BUSS:

- Proton → singlet of SU_3

← NEUTRALITY DETERMINES DOUBLE PLACE OF ν IN NATURE

link to what I REMIND

CHARGES fix THE FLAVOR

- NEUTRINO OSCILLATIONS PLAY IN COUNTS establishing the SM
- ν & e
- NOW CHECK with VERY HIGH PRECISION

RH. NEUTRINOS?

RH. NEUTRINOS
STERILE
B-L

ν_R ? **DO THEY EXIST?**

WHY NOT? SYMMETRY?
WHY CHARGED COMPONENTS HAVE

Suppose ν_R exist:

$T_3 = 0$

$Y = 0$ $\quad Q = 0$

WHY IT IS SO SPECIAL

IN CONTRAST WITH CHARGED FERMIONS

NO ELECTROWEAK INTERACTIONS W Z,

STERILE

- DO THEY EXIST
- WHAT IS THE MASS
- HOW THEY INTERACT WITH "active" sector

- INTERACTIONS with Higgses
  - → MASSES OF NEUTRINOS
    WHY THEY ARE SUPPRESSED
    → NO ν_R
    → VERY HEAVY
    → SYMMETRY
      WHY THIS SYMMETRY DOES NOT PROTECT MASSES OF FERMIONS

ACTUALLY: THE EXISTENCE OF ν_R AND THEIR PROPERTIES (MASSES, CHARGES)
→ MAIN ISSUE OF ν-physics

The problem of ν-physics
it can be reduced to ν_R

we will return to it

Pauli: had reduced the problems of β-decays to something very light and very difficult to observe

Now we reduce the problem of ν to something which have even more weak interactions

FLAVORS

- ν_e
- ν_μ
- ν_τ

flavor states : fixed by CC weak interactions

corresponding to charge lepton — have the lepton numbers

Difference with q-sector

→ up to now → no lepton number violation

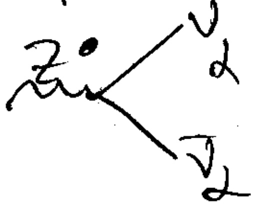
$\nu_e \not\leftrightarrow \nu_\mu$ ν_τ

affects no transition between neutrinos

⊗ NUMBER OF NEUTRINO SPECIES: N_ν.

ALREADY DISCUSSED.

LEP : invisible width of Z^0



$\Gamma_{inv} \propto N_\nu$

$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu}$

$\Gamma_{inv} = \Gamma_{tot} - \Gamma_{vis}$

radiative corrections

$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu} = \frac{\Gamma_{inv}}{\Gamma_e}\left(\frac{\Gamma_e}{\Gamma_\nu}\right)_{SM}$

$= \left(\frac{\Gamma - \Gamma_e - \Gamma_h}{\Gamma_e}\right)\left(\frac{\Gamma_e}{\Gamma_\nu}\right)_{SM}$

$N_\nu = 2.985 \pm 0.023$ 90% cl — line shape from all 4 exp

many implications

basic figures

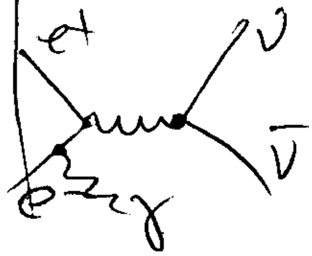
IMPLICATIONS : THREE light neutrinos, no new

$M_\nu > 47$ GeV

- THREE generations (?) But
- BOUNDS ON new physics
  - → new additional channels
  - NON-singlet MAJORONS — excluded
  - → ADMIXTURE OF HEAVY LEPTONS

implications to ν physics

shape



$N_\nu = 3.04 \pm 0.16$

Neutrinos

NUCLEOSYNTHESIS

Bound on number of light degrees of freedom

($m \geq 40$ MeV) — from density

$N_\nu < 3.3$

3.01

→ criticized.

NEUTRINOS AND NUCLEOSYNTHESIS.

→ direct / indirect INFLUENCE

COSMOLOGY

MASSES → BOUNDS

direct KINEMATICS !

ν_e $m \leq 4$–5 eV (MAINZ) (TROITSK)

$^3H \to {}^3He + e + \bar{\nu}_e$ 18 keV

$\cdot\ m(\nu_e)/m_e < 10^{-5}$

ν_μ $\cdot\ \pi \to \mu \nu_\mu$ PSI:

rest: m_π p_μ m_μ

$m < 220$ keV

$m(\nu_\mu)/m_\nu \leq 2 \cdot 10^{-3}$

PSI

ν_τ $\tau \to \nu_\tau 5\pi$

$m(\nu_\tau)$ < 31 MeV ARGUS → 29 MeV

< 32.6 CLEO

POW-

$m^2 = -8 \pm 12$ eV^2

($-39 \pm 34 = -15$)

m^2

SYSTEMATICS. $m < 4$ eV

3-

Future plans

Nucleosynthesis:

$m_\nu < 0.1$ MeV $\tau > 10^3$ s $\tau > 10^3$ s.

Cosmology: (energy density ↔ expansion RATE ↔ age)

$\sum_i m_i < 50\,eV$

$20-$ ↑ DIRAC MAJORANA (Different)

← THESE BOUNDS DO NOT depend ON NATURE

SN 87A

$m < 20\,eV$

spread of signal

Resume

→ MUCH SMALLER THAN CHARGE LEPTON MASS

→ **splitting** = CHARGE

↑ ↓ NEUTRINO

→ SINGLED OUT ④

SMALLNESS OF νm_ν → NEUTRALITY

→ OTHER BOUNDS ON ν

- P LEPTON NUMBER VIOLATION

→ NOT PURE BOUND BUT

MODEL FOR P-PARITY VIOLATION

MASSES (THEORY ...)

MASS LEPTON NUMBERS

To move further some more theoretical consideration

Weyl — Dirac — Majorana

① IN SM: ν_L – weil spinor, massless.

weil $m_\nu = 0$

CP: $\bar{\nu}_L$ (two component) ... an

, L-conserva...

Majorana ② If there are ν_R? suppose there is ν_R

→ Dirac particle as

$$\mathcal{L} = \dots - m_D(\bar{\nu}_L \cdot \nu_R + \bar{\nu}_R \cdot \nu_L)$$

$\Psi = \nu_L + \nu_R \qquad m_D(\bar{\Psi} \cdot \Psi)$ allow to introduce

→ 4 components

③ Can two components neutrino have a mass?

⇒ Mass term change chirality note

$$\nu_L \xrightarrow{m_D} \nu_R$$

→ ν_L C: $C(\nu_L)^c = \nu^c_R$

CHARGE CONJUGATION

C – operator change the sign of currents

$(\nu_L)^c \rightarrow C(\bar{\nu}_L)^T \rightarrow \nu^c_R$ (Dirac conjugate)

$C = i\gamma^2\gamma^0$

$(1+\gamma_5)$

$\gamma_5^+ = -\gamma_5$

$$-\frac{1}{2} M(\bar{\nu}_L \nu^c_R + \bar{\nu}^c_R \cdot \nu_L) = M \bar{\nu}_M \nu_M$$

$\nu_M = \nu_L + \nu^c_R$

what is the sense?

Properties:

1. $\nu_M^c = (\nu_L)^c + \nu_L - \nu_M$

NEUTRINO ≡ ANTINEUTRINO

true NEUTRAL ⇒ MAJORANA

2. It is IMPOSSIBLE TO INTRODUCE CONSERVING Lepton NUMBERS

3. $L(\nu_L) = 1$ then

MASS TERMS: $|\Delta L| = 2$

⇒ effect of lepton number violation

4. $\tilde{\nu}_\mu = \nu_L - \nu_R$

MASS TERM $+\frac{1}{2} m \bar{\tilde{\nu}}_M \tilde{\nu}_M$

properties $\tilde{\nu}_\mu^c = -\tilde{\nu}_M$ opposite CP PARITY ≡ different sign of MASS

$\left(\nu_L \to \nu_L = i\nu' = e^{i\pi}\nu' \right.$

$\nu_R^c = -i\nu_R^c$

$\left. \tilde{\nu}_M = i(\nu_L' + \nu_R^{c\prime}) = \right.$

$\boxed{\tilde{\nu}_M = i\nu_M}$ – relation

for ν_M – positive mass. but the interaction will be changed.

5. $m(\nu_L^T C \nu_L + h.c.)$

FOR THOSE WHO KNOWS → INTRODUCTION OF NOTATIONS

← can exist for neutral fermion

suppose all terms but MASS conserve L

ν - MAJ

→ different sign of mass → opposite to different CP parities

ARE RELA

sign of mass can be removed by redefinition of the field ν_M respective sign is important.

change THE coupling

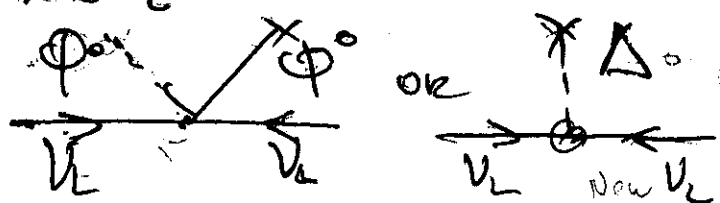
CAN BE REWRITTEN check.

NEUTRINO MASSES AND SM

on basis of SM GAUGE SYMMETRY STRUCTURE

- NO RH.

$\psi_L \begin{pmatrix} \nu \\ l \end{pmatrix}_L$



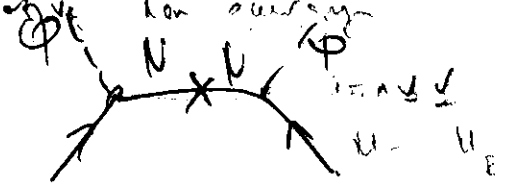
$T_3 = 1$

effective operator

$\frac{1}{M} \psi^\dagger \psi \cdot \Phi^\dagger \Phi$ ← GAUGE INVARIANT BUT NON RENORMALIZABLE ORIGIN.

something beyond.

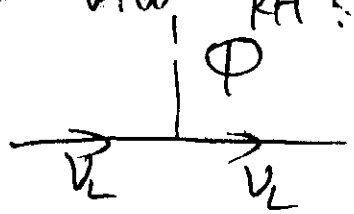
- effective low energy



- NON-RENORMALIZABLE ⇒ GRAVITY !

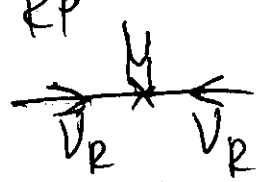
$\mu = \mu_{PL}$ ← FROM UNITARITY

- With RH : DIRAC



$T_3 = \frac{1}{2}$

- RH



$T_3 = 0$

origin ?

MOST GENERAL
BOTH MAJORANA AND DIRAC

$$\frac{1}{2}\begin{pmatrix} \bar\nu_L \\ \nu^c_L \end{pmatrix} \begin{array}{c|cc} & \nu^c_R & \nu_R \\ \hline & m_L & m_D \\ & m_D & m_R \end{array}$$

$\begin{pmatrix} \nu_L \\ \nu^c_L \end{pmatrix} \hat{M}$ MASS MATRIX

ν_L, ν^c_L, $\bar\nu_L$, ν_R ...

$$\frac{1}{2}\begin{pmatrix} m_L & m_D \\ m_D & M_R \end{pmatrix} \quad (\nu^c_{LR}, \nu_R)$$

ν_L ν_L

ν_L ν_R

ν^c_R

° DEPENDING ON RELATIONS BETWEEN THE ELEMENTS m_L, m_R, m_D — DIFFERENT

Special cases:
$m_L, m_R \ll m_D$
⇒ pseudodirac neutrino

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* SEE-SAW

1) SUPPOSE THERE IS NO Δ MINIMAL STRUCTURE: $m_L = 0$

induced ⇒ small

AND NEUTRINOS HAVE

2) USUAL DIRAC MASS TERM

$$m_D \sim m_e, m_q$$

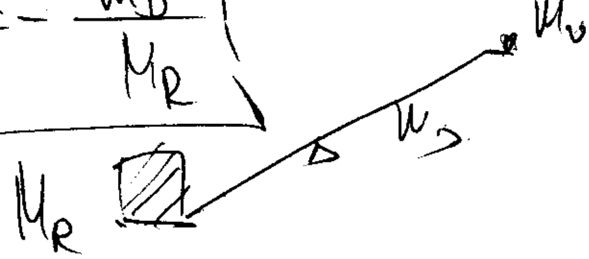
NATURAL

° ν_R HAVE MAJORANA MASS TERMS

$$M_R \gg m_D$$

⇒ DIAGONALIZATION GIVES

$$m_\ell = -\frac{m_D^2}{M_R}$$



See-saw relates

SMALLNESS OF ν MASSES IN COMPARISON. $\Longleftrightarrow$ NEUTRALITY

ν - NEUTRAL

ν_R MAY HAVE MAJORANA MASS

ν_R is SINGLET of $SU_2 \times U_1$

M_R in unprotectable

ν_R: M_R ?

unprotected

AGAIN

$\rightarrow$ explicit (BARE MASS TERMS)

$\rightarrow$ SPONTANEOUS $\nu_R^T C \nu_R S$

MAJORON (SPONTANEOUS VIOLATION)

↳ MASSLESS

$\Rightarrow$ CAN BE GAUGED as in SO_{10}

L is violated by MASS term of ν_R.

in SUSY:

$\rightarrow$ GRAVITY effects

$\rightarrow$ BOUNDS ON SCALE OF SPONTANEOUS VIOLATION

mixing with LH.

$$\frac{m_D}{M_R} \ll 1$$

if ν_R light $\Rightarrow$ mixing bound.