TESTS OF LEPTOGENESIS AT LOW ENERGY

T. HAMBYE
CPT-MARSEILLE

1| LEPTOGENESIS WITH HEAVY RIGHT-HANDED NEUTRINOS

FUKUGITA-YANAGIDA (86)

- L ASYMMETRY PRODUCED AT $T \gg 100$ GeV

$\Downarrow$ ← SPHALERONS IN EQUILIBRIUM FOR $100 \text{ GeV} \lesssim T \lesssim 10^{12}$ GeV (B+L VIOLATING BUT B−L CONSERVING)

B ASYMMETRY (WHICH BELOW $T \sim 100$ GeV REMAINS CONSTANT)

- TO GENERATE A L ASYMMETRY AT $T \gg 100$ GeV:

HEAVY RIGHT-HANDED NEUTRINOS : N_{R_i}, $i=1,2,3$.

$$\mathcal{L} = \mathcal{L}_{SM} + h_{ij}\, \bar{N}_{R_i} L_j \Phi^* + \frac{1}{2} \bar{N}^c_{R_i} M_{N_{ij}} N_{R_j} + h.c.$$

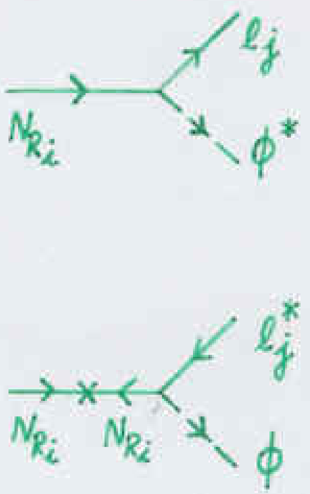
↑ YUKAWA ($\Delta L = 0$)

↑ MAJORANA MASS TERM ($\Delta L = 2$)

⇒ L VIOLATION IN THE N_R DECAYS

N_R DECAYS:

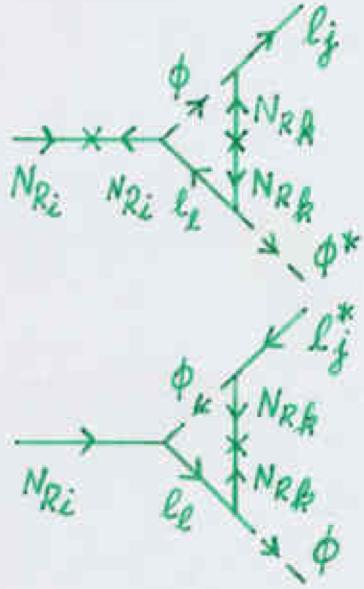
TREE LEVEL



$L_{FIN} = +1$

$L_{FIN} = -1$

ONE LOOP



↳ DON'T CREATE THE LEPTONS AND ANTILEPTONS IN EQUAL NUMBERS:

$$\varepsilon_{N_i} = \sum_j \frac{\Gamma(N_i \to \ell_j \phi^*) - \Gamma(N_i \to \ell_j^* \phi)}{\Gamma_{N_i}^{TOT}}$$

↑

REQUIRES CP-VIOLATION ← PROVIDED BY THE h_{ij} YUKAWA COUPLINGS

⇒ ε_{N_i} AT LOWEST ORDER: TREE LEVEL – ONE LOOP INTERFERENCE.

⇒ RESULTS:

$$\varepsilon_{N_i} = \sum_k \frac{1}{8\pi} \frac{M_{Nk}}{M_{N_i}} \left[1 - \left(1 + \frac{M_{Nk}^2}{M_{N_i}^2}\right) \ln\left(1 + \frac{M_{N_i}^2}{M_{Nk}^2}\right) \right]$$

$$\cdot \frac{\sum_{j,l} \mathrm{Im}\left[h_{ij}^* h_{il}^* h_{kj} h_{kl} \right]}{\sum_j |h_{ij}|^2}$$

⇒ IF THE OUT-OF-EQUILIBRIUM CONDITION IS SATISFIED:

$$\Gamma_{N_i} = \frac{1}{16\pi} \sum_j |h_{ij}|^2 M_{N_i} \lesssim H(T = M_{N_i}) \sim \frac{T^2}{M_{PLANCK}} \Big|_{T = M_{N_i}}$$

THEN: $\frac{n_L}{s} \sim \sum_i \frac{\varepsilon_{N_i}}{g_*} \quad \left(\sim \frac{n_B}{s}\right)$

TO HAVE $\Gamma_{N_i} \lesssim H$ AND $\frac{n_L}{s} \sim 10^{-10}$ WE NEED: $M_{N_i} \gtrsim 10^{10}\,\mathrm{GeV}$

FOR $M_{N_i} \gtrsim 10^{10}\,\mathrm{GeV}$ FROM THE SAME INTERACTIONS ARE GENERATED IN ADDITION THE ν MASSES FROM THE SEESAW MECHANISM: $m_\nu \sim \frac{h^2 v^2}{M_{N_i}}$

MOREOVER THIS MODEL IS QUITE NATURAL IN THE CONTEXT OF GUT SUCH AS SO(10)

⇒ VERY ATTRACTIVE MODEL!

BUT: WHAT ABOUT ITS TESTABILITY?

↳ INDIRECT TESTS:

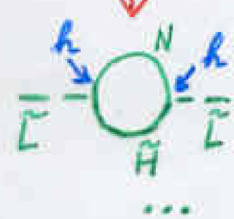
- IN GENERAL: WITH $3\nu_L + 3N_R$:

6 PHASES

↙ 3 COMBINATIONS IN THE LIGHT ν MASS MATRIX

↘ 3 OTHER COMBINATIONS DECOUPLE
↳ e.g. NECESSARY FOR TESTING LEPTOGENESIS

- SUPERSYMMETRIC SEESAW MODEL: NON DECOUPLING EFFECTS FROM THE h_{ij} AND M_{N_i} ON THE SOFT SLEPTON MASS TERMS ← RGE'S



⇒ INFLUENCE ON:

DAVIDSON-IBARRA (01), ELLIS ET AL (01) BLAZEK-KING (01), CASAS-IBARRA (01) LAVIGNAC ET AL (01) ...

- e^- AND μ^- EDM
- T-ASYMMETRY IN $\mu \to eee$
- SLEPTON OSCILLATIONS AT COLLIDERS
- $\mu \to e\gamma$, $\tau \to \mu\gamma$
- SNEUTRINO-ANTISNEUTRINO OSCILLAT° ($\Delta L = 2$).
- ...

⇒ COMBINED WITH ν OSCILLAT° (AND $0\nu 2\beta$) EXPTS, CHANCE FOR A LOW ENERGY PROGRAM OF LEPTOGENESIS TESTS

• GUT WITH TEXTURES: MORE RELATIONS BETWEEN LEPTOGENESIS PARAMETERS AND LIGHT ν MASS PARAMETERS

⇑

NEED FOR MORE PRECISE INFORMATION ON THE ν MASS MATRIX (ν HIERARCHY ...)

BÜCHMULLER, PLUMACHER. (98...)
BRANCO, GONZALEZ-FELIPE, JOACHIM, REBELO (01)
JOSHIPURA, PASCHOS, RODEJOHANN (01)

...

2| E_6 LEPTOGENESIS

T.H., E. MA, M. RAIDAL,
U. SARKAR, PLB512 (01)

* IN E_6 THE N_R ARE PREDICTED AS IN SO(10)

↳ IN THE FUNDAMENTAL REPRESENTATION: 27

= 15 : A STANDARD MODEL GENERAT° } 16 OF SO(10)
+ 1 : N_R
+ 4 : 2 $SU(2)_L$ DOUBLETS: $\tilde{H}$ AND $\tilde{H}^c$ } 10 OF SO(10)
+ 6 : 2 $SU(3)_c$ TRIPLETS : h AND h^c
+ 1 : 1 $SU(2)_L$-$SU(3)_c$ SINGLET } 1 OF SO(10)

* LOW ENERGY TESTS : MORE IN E_6

↳ FROM THE OBSERVATION OF A Z' OR A W' AT THE ~FEW 100 GeV – FEW TeV SCALE ⇐ FROM A EXTRA U(1) OR SU(2).

- FOR SO(10): A Z' OR W' WOULD EXCLUDE:
  - THE STANDARD LEPTOGENESIS MECHANISM
  - THE SEESAW MECHANISM ← IN SO(10)

⇑

IMPOSSIBLE TO HAVE A SO(10) SUBGROUP AT ~TeV WITHOUT HAVING N_R LIGHT : $M_{N_R} \sim$ TeV.

• IN E_6: AMONG THE MANY POSSIBLE $U(1)$ OR $SU(2)$ AT ~TeV, THERE EXIST (ONLY) TWO CONSISTENT WITH LEPTOGENESIS AND SEESAW

⇑

WHICH ALLOW HEAVY N_R
(i.e. FOR WHICH N_R ARE SINGLETS ⇒ M_{N_R} NOT PROTECTED)

⇒ $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_N$
OR
$SU(3)_c \times SU(2)_L \times SU(2)_R^A \times U(1)_{Y_L + Y_R'}$

} POSSIBLE GAUGE SYMMETRIES AT ~1 TeV

($Q_N = \cos\alpha\, Q_\psi + \sin\alpha\, Q_\chi \leftarrow tg\,\alpha = \sqrt{\frac{1}{15}}$

↑ $E_6 \to SO(10) \times U(1)_\psi$

↑ $SO(10) \to SU(5) \times U(1)_\chi$

$SU(2)_R^A : (h^c, u^c)$: DOUBLET)

IN THESE 2 CASES THE MODEL WORKS FINE FOR GENERATING LEPTOGENESIS AND ν MASSES WITH IN ADDITION A RICH PHENOMENOLOGY AT ~1TeV:

- ONE Z' FOR $U(1)_N$ AND $1\,Z' + 2\,W_R$ FOR $SU(2)_R^A$

EXAMPLE: $\Gamma(Z' \to \nu\bar{\nu} + S\bar{S}) = \frac{62}{15}\,\Gamma(Z' \to l^+ l^-) \leftarrow U(1)_N$

$m_{W_R} = \frac{\cos 2\theta_W}{\cos\theta_W}\, m_{Z'} = 0.84\, m_{Z'} \leftarrow SU(2)_R^A$

- 11 EXTRA PARTICLES FROM THE 27 AT ~1 TeV

⇒ WOULD PROVIDE STRONG INDICATIONS FOR THE ORIGIN OF LEPTOGENESIS AND ν MASSES THROUGH THE N_R

BUT:

IS IT REALLY IMPOSSIBLE
TO CONSTRUCT A LEPTOGENESIS
MODEL AT A DIRECTLY TESTABLE
SCALE (~1-10 TeV) ???

3| PROBLEMS TO INDUCE LEPTOGENESIS AT ~ 1-10 TeV

- **A|** NON EQUILIBRIUM CONDITION: $\underset{\overset{?}{T}}{\Gamma_A} < \underset{\overset{?}{T^2}}{H}(T=M_A)$

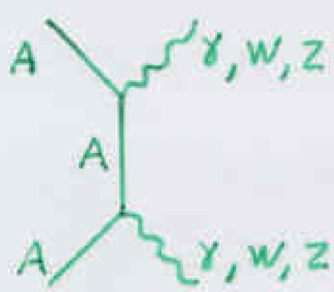
↳ MUCH MORE DIFFICULT TO SATISFY AT $T \sim 1-10$ TeV THAN AT $T \sim 10^{10}-10^{15}$ GeV

↳ FOR EXAMPLE: AT $T \sim 10$ TeV, $\Gamma_N < H$ REQUIRES $h \lesssim 10^{-6}$

$$\Rightarrow \frac{n_L}{s} \sim \frac{\varepsilon_N}{g_*} \sim \frac{1}{g_*}\frac{1}{8\pi}h^2 \sim 10^{-15}!$$

- **B|** SCATTERING DAMPING EFFECTS:

↳ IF THE DECAYING PARTICLE A IS NOT NEUTRAL AND $SU(2)_L$ SINGLET, THE GAUGE SCATTERINGS ARE VERY FAST



⇒ NO DEPARTURE FROM THERMAL EQUILIBRIUM FOR A

⇒ ASYMMETRY DAMPED BY ~5 ORDERS OF MAGNITUDE AT ~10 TeV

↳ WE NEED A NEUTRAL AND $SU(2)_L$ SINGLET DECAYING PARTICLE

• C| NEUTRINO MASS CONSTRAINTS:

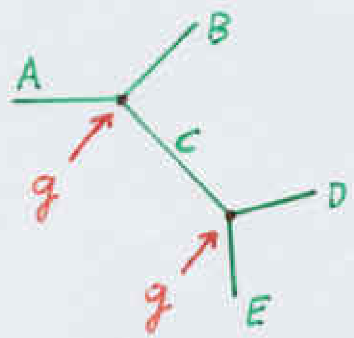
↳ VALUES OF THE L VIOLATING COUPLINGS REQUIRED TO INDUCE THE m_ν ARE TOO LARGE TO SATISFY THE CONDITION $\Gamma < H$ AT 1–10 TeV

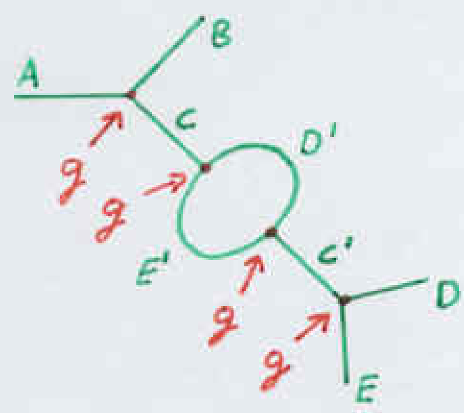
↳ GIVES A SUPPRESSION OF m_L/Λ

- OF ORDER ~100 IN THE SEESAW MODEL WITH N_{R_i}
- OF ORDER ~10^6 IN THE RADIATIVE ν MASS MODELS (WITH R-PARITY VIOLAT°, ZEE MODEL)

4| A SIMPLE SOLUTION WITH 3-BODY DECAYS

T.H., NPB633 (2002)

- 



$\Rightarrow \Gamma_A \sim g^4$ AND $\varepsilon_A \sim \frac{g^6}{g^4} \sim g^2$

$\Rightarrow$

2 BODY DECAYS	3 BODY DECAYS
$\Gamma \sim h^2 < H \Rightarrow h^2 \lesssim 10^{-12}$ (↑ AT $T \sim 10$ TeV)	$\Gamma \sim g^4 < H \Rightarrow g^4 \lesssim 10^{-12} \Rightarrow g \lesssim 10^{-3}$ (↑ AT $T \sim 10$ TeV)
$\Rightarrow \varepsilon \sim h^2 \lesssim 10^{-12}$!	$\Rightarrow \varepsilon \sim g^2 \sim 10^{-6}$!
$\Rightarrow$ NEED FOR A MUCH HIGHER SCALE	$\Rightarrow$ VERY NATURAL AT 1-10 TeV

MOREOVER: A VALUE OF A L-VIOLATING COUPLING g OF ORDER 10^{-3} IS TYPICALLY THE VALUE WE NEED TO INDUCE RADIATIVELY ν MASSES OF ORDER ~0.1-1 eV.

⇒ IF THE LAST L-VIOLATING DECAY IS A 3-BODY DECAY AT $T \sim 1-10$ TeV, LEPTOGENESIS AS WELL AS ν MASSES COULD BE GENERATED NATURALLY AT THIS SCALE

⇒ ALTERNATIVE AND TESTABLE GENERAL FRAMEWORK OF LEPTOGENESIS AND ν MASSES AT THE $\sim 1-10$ TeV SCALE % USUAL FRAMEWORK AT THE GUT SCALE.

5| AN EXPLICIT MODEL

T.H., NPB 633 (2002)

- WE NEED DECAYS OF A NEUTRAL $SU(2)_L$ SINGLET: WE TAKE 3 N_{R_i}
- N_{R_i} 3-BODY DECAYS REQUIRE HEAVIER VIRTUAL PARTICLES:

  WE TAKE CHARGED SCALAR $SU(2)_L$ SINGLETS: $S^{\pm}_{1,2}$

  + WE TAKE 2 HIGGS DOUBLETS: $H_{1,2}$

- PRELIMINARY CONDITION: N_{R_i} WITH $M_{N_i} \sim 1-10$ TeV REQUIRE TINY $h_{ij}\, \bar{L}_i N_{R_j} H_{1/2}$ YUKAWA COUPLINGS TO AVOID $m_\nu \gtrsim$ eV.

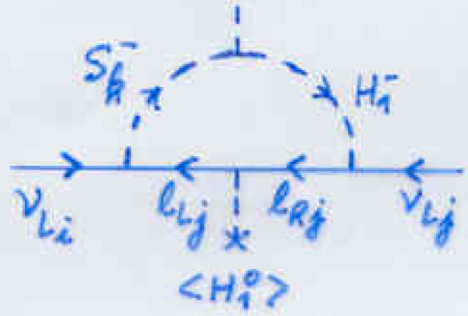
  ⇒ WE ASSUME THEM NEGLIGIBLE

- YUKAWA INTERACTIONS:

$$\mathcal{L} \ni f^k_{ij}\, L^T_i C^{-1} i\tau_2 L_j S^-_k + \lambda^k_S H^T_1 i\tau_2 H_2 S^-_k + h^k_{R_{ij}}\, \ell^T_{R_j} C^{-1} N_{R_i} S^-_k$$

↑ ↑ COUPLINGS OF THE ZEE MODEL ← VIOLATE L

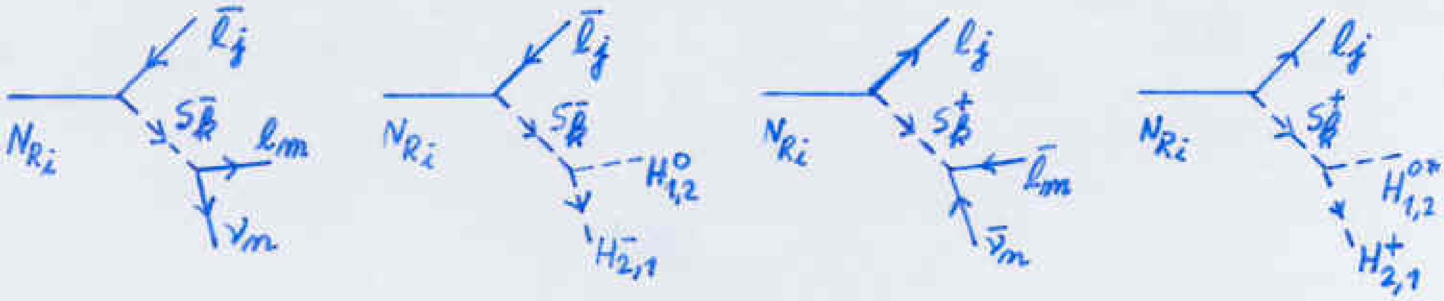
⇓



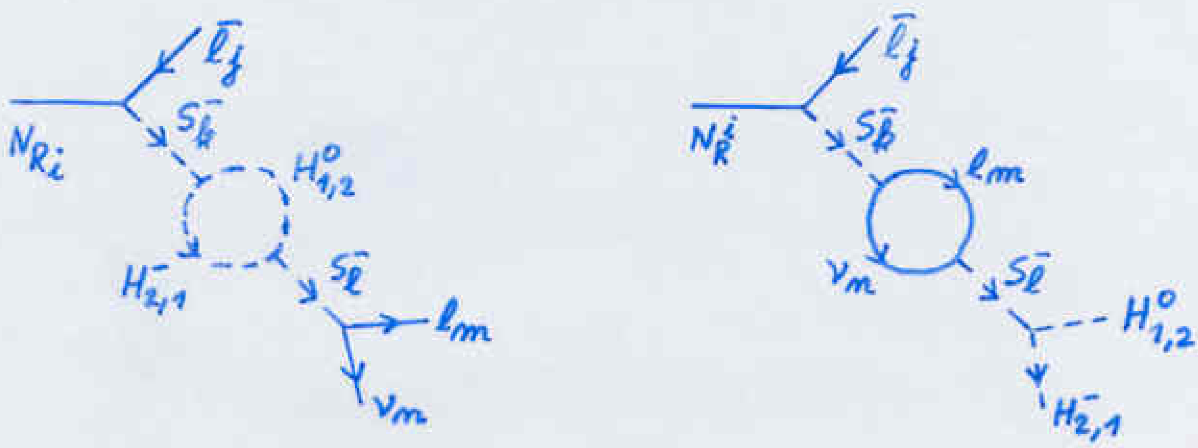
$$\Rightarrow (m_\nu)_{ij} = \frac{1}{(4\pi)^2} \sum_k \frac{\lambda^k_S}{m^2_{S_k} - m^2_{h^+}} \frac{v_2}{v_1} f^k_{ij} \cdot (m^2_{\ell_j} - m^2_{\ell_i}) \ln \frac{m^2_{S_k}}{m^2_{h^+}}$$

⇒ A MINIMAL WAY TO INDUCE THE ν MASSES.

• LEPTOGENESIS:



⇒ THE LEPTONIC ASYMMETRY IS OBTAINED FROM THE INTERFERENCE WITH:



$$\Rightarrow \varepsilon_{N_i} = \frac{1}{\Gamma_{N_i}} \frac{1}{(2\pi)^3} \frac{1}{12} \frac{\pi}{(4\pi)^2} \frac{M_{N_i}^5}{m_{S_1}^2 m_{S_2}^2} \cdot \sum_{j,m,n}$$

$$\cdot \Big[\mathrm{Im}\big[h_{R_{ij}}^{2*} h_{R_{ij}}^{1} \lambda_S^{1*} \lambda_S^{2} \big] \left(\frac{|f_{mn}^1|^2}{m_{S_1}^2} - \frac{|f_{mn}^2|^2}{m_{S_2}^2} \right)$$

$$+ \mathrm{Im}\big[h_{R_{ij}}^{2} h_{R_{ij}}^{1*} f_{mn}^{1} f_{mn}^{2*} \big] \left(\frac{|\lambda_S^1|^2}{m_{S_1}^2} - \frac{|\lambda_S^2|^2}{m_{S_2}^2} \right)$$

$$+ \mathrm{Im}\big[f_{mn}^{2} f_{mn}^{1*} \lambda_S^{1} \lambda_S^{2*} \big] \left(\frac{|h_{R_{ij}}^1|^2}{m_{S_1}^2} - \frac{|h_{R_{ij}}^2|^2}{m_{S_2}^2} \right) \Big]$$

$$\Rightarrow \varepsilon_{N_i} \sim \frac{1}{16\pi} \frac{\lambda_S^2 f^2}{\lambda_S^2 + f^2 M_{N_i}^2} \frac{M_{N_i}^2}{m_S^2}$$

WITH:

$$\Gamma_{N_i} \sim \frac{1}{(2\pi)^3} \frac{1}{48} h_R^2 \left(\lambda_S^2 + f^2 M_{N_i}^2\right) \frac{M_{N_i}^3}{m_{S_1}^2 m_{S_2}^2}$$

$\Rightarrow$ IT IS EASY TO GET $\Gamma < H$ AND $\frac{n_L}{s} \sim 10^{-10}$:

EXAMPLE OF A SET OF VALUES WHICH GIVES:

$m_{\nu_1} = 0.1$ eV , δm^2_{atmos} , $\delta m^2_{SOLAR-LMA}$, $n_L/s \sim 10^{-9}$:

$M_N = 1$ TeV , $m_{S_1} = 4$ TeV , $m_{S_2} = 5$ TeV

$\lambda_S = 50$ GeV , $h_R = 10^{-4}$, $f_{e\mu} = 0.2$ $(= 3 \cdot 10^2 f_{e\tau} = 3 \cdot 10^5 f_{\mu\tau})$

SUMMARY

- IN CONSTRAINED MODELS (SUSY SEESAW WITH UNIVERSALITY, GUT WITH TEXTURES) WE MIGHT GET A CHANCE TO TEST LEPTOGENESIS
  - ↳ FROM ν MASS CONSTRAINTS, e^- AND μ^- EDM...

- THE OBSERVATION OF A Z' OR W' WOULD PROVIDE ⚠ INFORMATION FOR UNDERSTANDING THE ORIGIN OF LEPTOGENESIS

- WE ARE NOT OBLIGED TO GO TO A HIGH SCALE
  - ↳ IF THE LAST L-VIOLATING DECAY WAS A 3-BODY DECAY AT 1-10 TeV, LEPTOGENESIS COULD OCCUR NATURALLY AND BE TESTED AT THIS SCALE
  - ↳ THIS PROVIDES A WAY TO RECONCILE THE RADIATIVE ν MASS MODELS WITH LEPTOGENESIS