NEUTRINO MASS

AND

UNIVERSE'S BARYON ASYMMETRY

— LEPTOGENESIS —

T. Yanagida

ν 2002, —

NEUTRIO MASSES :

ATMOSPHERIC ν OSCILLATION.

$$|m^2_{\nu_3} - m^2_{\nu_2}| \simeq (2-3)\times 10^{-3}\,\mathrm{eV}^2.$$

SOLAR ν OSCILLATION.

$$|m^2_{\nu_2} - m^2_{\nu_1}| \simeq 10^{-5} - 10^{-4}\,\mathrm{eV}^2.$$

IF $m_{\nu_3} > m_{\nu_2} > m_{\nu_1}$, ONE GETS

$$m_{\nu_3} \sim 0.05\,\mathrm{eV}$$

$$m_{\nu_2} \sim 0.005\,\mathrm{eV}.$$

TWO THEORETICAL REASONS

TO BELIEVE SMALL NEUTRINO MASSES.

I. UNIFICATION OF QUARKS AND LEPTONS

$$\begin{array}{c} \uparrow \\ \text{GUT} \\ \downarrow \end{array}
\begin{array}{l}
\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ; \quad \begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix} \\[2ex]
\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L ; \quad \begin{matrix} e_R & \mu_R & \tau_R \end{matrix}
\end{array}$$

← Horizontal → ← Horizontal →
(Family) (Family)

MOST OF UNIFICATION MODELS REQUIRE

Right-Handed NEUTRINOS $\nu_R \equiv N$.

RIGHT-HANDED NEUTRINO N IS A KEY
INGREDIENT FOR UNIFICATION !!!

CONSIDER THE GUT DIRECTION AS AN EXAMPLE
TO SEE IT.

$SU(3) \times SU(2) \times U(1)_Y \Rightarrow$ RANK 4

CONSIDER A GAUGE THEORY BASED ON G.

UNIFICATION GROUP

RANK$\{G\} > 4$: $G \supset SU(3) \times SU(2) \times U(1)_Y$

$$G \longrightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1) \times U(1) \times \cdots$$

UNIFICATION SCALE

SOME STRING MODELS ARE EXAMPLES.

SO(10)
Pati-Salam
⋮

Valle
King at ν02

WHAT IS A POSSIBLE GAUGE U(1) ?

$$G \supset SU(3) \times SU(2) \times U(1)_Y \times \underset{?}{\underline{U(1)}} \times \cdots$$

TAKE THE SU(5) GUT FOR AN EXPLANATION:

QUARKS, LEPTONS $\subset 5^* + 10$

$$5^*_L = \begin{pmatrix} \bar{d}_R \\ \ell_L \end{pmatrix} \quad ; \quad \ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$$10_L = \left(q_L, \bar{u}_R, \bar{e}_R \right) \quad ; \quad q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

Higgs BOSON $\subset H(5)$

THREE GLOBAL U(1)'s:

$$5^*_L \longrightarrow e^{i\alpha} 5^*_L$$

$$10_L \longrightarrow e^{i\beta} 10_L$$

$$H(5) \longrightarrow e^{i\gamma} H(5)$$

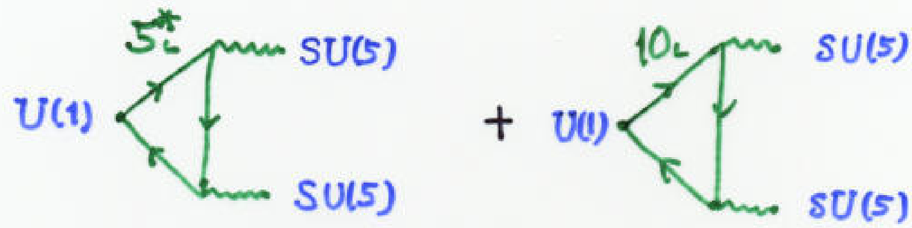
BUT, WE HAVE Yukawa COUPLINGS:

$$\mathcal{L}_Y = 5^*_L 10_L H^* + 10_L \cdot 10_L \cdot H .$$

ONLY ONE U(1) IS LEFT UNBROKEN!!

	5^*_L	10_L	$H(5)$
$U(1)$	-3	$+1$	-2

ANOMALY FREE: $A\{U(1)\cdot[SU(5)]^2\} = 0$

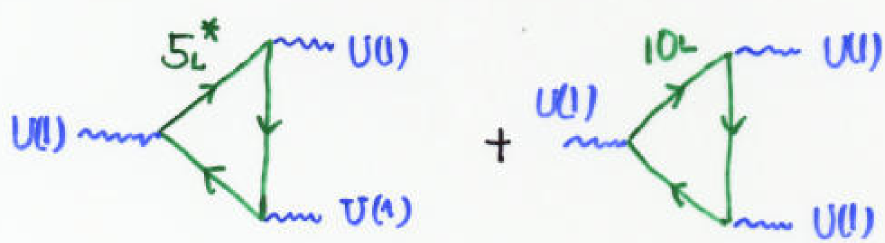


$= 0$

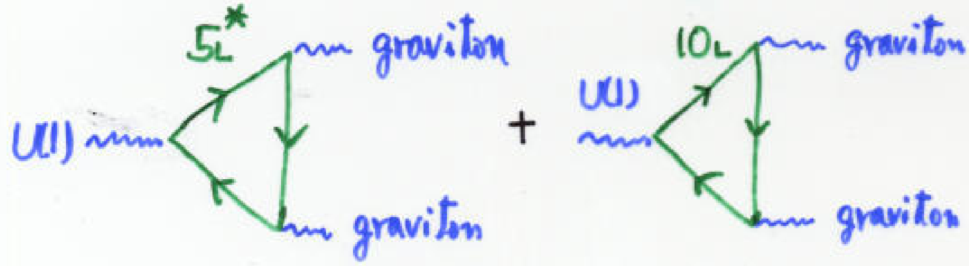
'tHooft

☆ CAN IT BE A GAUGE SYMMETRY?

NO! IT IS ANOMALOUS.



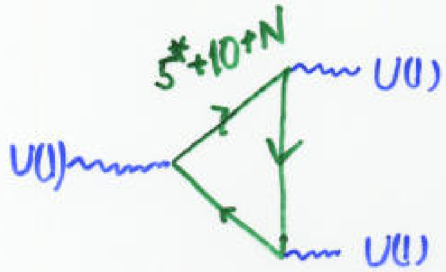
$\neq 0.$



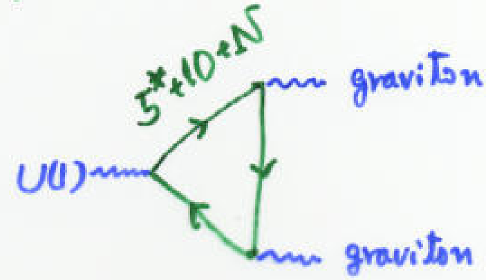
$\neq 0.$

BUT, THE TWO ANOMALIES ARE CANCELED OUT BY INTRODUCING ONE SINGLET FERMION N.

$$\mathcal{N}\ (+5)$$



$=0$;



$=0$

NO ACCIDENTAL GLOBA SYMMETRY IS LEFT, SINCE THE NEW N CAN HAVE Yukawa COUPLING:

$$\mathcal{L}_N = \underset{-3}{5^*_L}\ \underset{+5}{N}\ \underset{-2}{H}.$$

THE NEW U(1) GAUGE SYMMETRY MUST BE BROKEN AT VERY HIGH ENEGY, SINGE WE DO NOT HAVE ADDITIONAL GAUGE BOSON. THE N OBTAINS A LARGE MASS OF THE ORDER OF THE BREAKING SCALE.

$$\mathcal{L} = \tfrac{1}{2} M\ N \cdot N$$

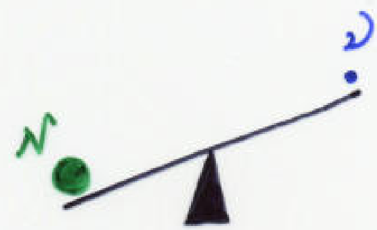
Majorana MASS

NEUTRINO $\underline{\nu}$ AND THE HEAVY Majorana $\underline{N}$ FORM 2×2 MASS MATRIX:

$$(\nu, N) \begin{pmatrix} 0 & \langle H \rangle \\ \langle H \rangle & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

$$m_\nu \simeq \frac{\langle H \rangle^2}{M} \ll m_{\ell, q}$$

$$m_N \simeq M$$



Seesaw

Gell-Mann, Ramond, Slansky
Yanagida (1979)

☆ THE SMALL MASS OF NEUTRINO IS A KEY INGREDIENT FOR THE UNIFICATION.

THE FURTHER UNIFICATION INCLUDING FAMILY STRUCTUR $G \supset SU(5) \times U(1) \times \underbrace{U(1)' \times U(1)'' \times \cdots\cdots}_{\text{FAMILY STRUCTURE}}$.

IT MAY EXPLAIN THE MASS MATRICES OF QUARKS AND LEPTONS. Nielsen, Takanishi

II. THE BARYON ASYMMETRY IN THE UNIVERSE

$\Downarrow$ PREDICTS

SMALL NEUTRINO MASSES !!

Fukugita . TY (1986)

BUT NOT PROTON DECAY.

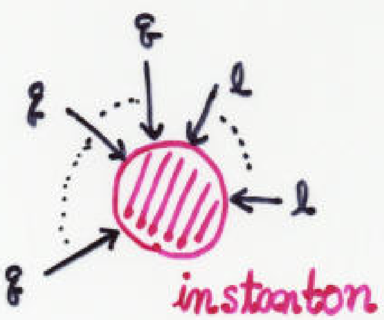
BARYON NUMBER NONCONSERVATION
IN THE STANDARD GAUGE THEORY.

TWO GLOBAL CHARGES :

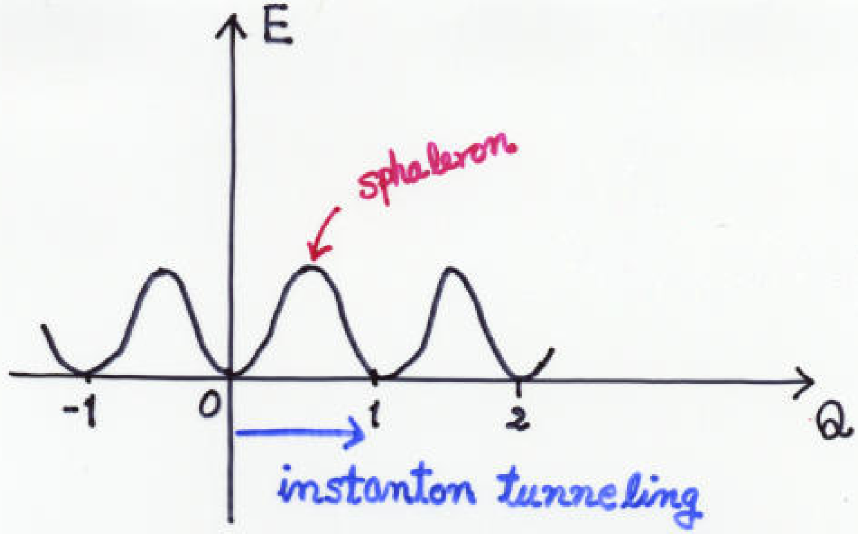
- BARYON NUMBER B
- LEPTON NUMBER L

THEY ARE BROKEN BY QUANTUM EFFECTS.
(ANOMALIES)

't Hooft (1976)



BUT, (B−L) IS CONSERVED !!



THE QUANTUM TUNNELING FROM ONE VACUUM TO ANOTHER CAUSES BARYON-NUMBER VIOLATION.

BUT, THE TUNNELING IS SUPPRESSED AS

$$A \sim e^{-S_{in}} \simeq e^{-8\pi^2/g^2} \simeq e^{-100} \ll 1 .$$

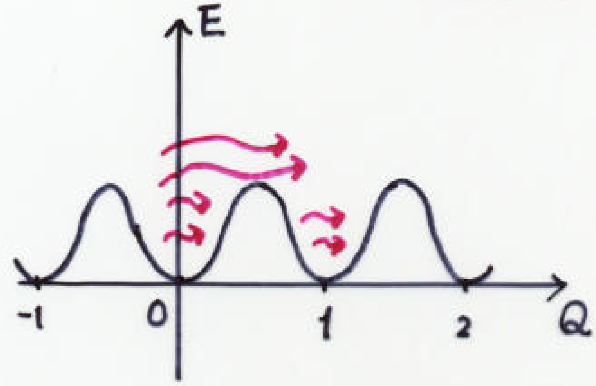
THE PROTON IS STABLE.

WHAT HAPPENS IN THE EARLY UNIVERSE ?

THE B-NUMBER VIOLATION IS NOT SUPPRESSED AT HIGH TEMPERATURE.

Kuzmin, Rubakov, Shaposhnikov (1985)

Susskind (1980)

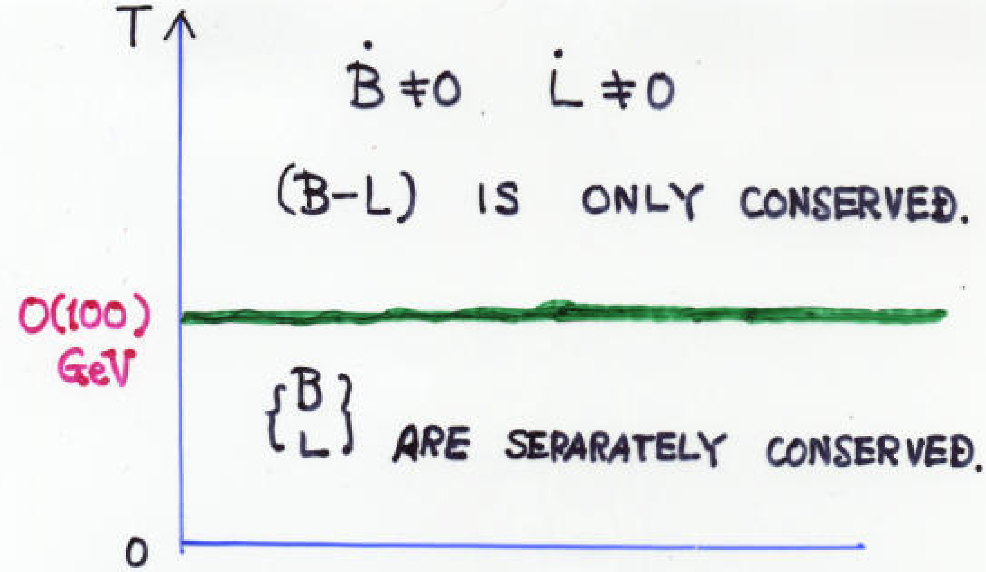


THERMAL TRANSITION

IF THE ENERGY OF THERMAL FLUCTUATION IS LARGER THAN THE BARRIER HEIGHT, THE SYSTEM PASSES OVER THE BARRIER FREELY.

B-VIOLATING PROCESSES ARE IN THERMAL EQUILIBRIUM IN THE EARLY UNIVERSE $T > O(100)$ GeV.

BIG IMPACT ON THE EVOLUTION OF BARYON-NUMBER ASYMMETRY.



$$n_B\,(\text{PRESENT}) \simeq \frac{8N_f + 4N_H}{22N_f + 13N_H}\,(n_{B-L})_0$$

$$\simeq 0.35\,(n_{B-L})_0$$

B-L GENERATION IS IMPORTANT.

B-L MUST BE BROKEN AT VERY HIGHT ENERGIES.

$\cancel{B-L}$

IF B-L IS BROKEN IN THE EARLY UNIVERSE, IT IS MOST LIKELY THAT (B-L) VIOLATING EFFECTIVE OPERATORS ARE INDUCED AT LOW ENERGIES.

BUT, ALL OPERATORS FOR PROTON DECAYS CONSERVE B-L !!

$$\mathcal{O} = q \cdot q \cdot q \cdot l \quad : \quad \Delta(B-L) = 0$$

Weinberg
Wilczek, Zee, ..
(1979)

THE PROTON DECAY IS NOT A PREDICTION OF THE BARYOGENESIS.

$\cancel{CP}$ IN THE QUARK SECTOR IS NOT RESPONSIBLE FOR B-ASYMMETR.

WHAT IS (B-L) VIOLATING OPERATOR AT LOW ENERGIES ?

THE LOWEST DIMENSIONAL OPERATOR IS

$$\mathcal{L} = \frac{1}{M}\, l \cdot l \cdot \phi \phi$$

Weinberg ('79)

$$\Delta(B-L) = -2$$

$$l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \; : \; \text{Higgs } \phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} .$$

THIS PRODUCES A NEUTRINO MASS :

$$\mathcal{L}_{mass} \simeq \frac{\langle \phi \rangle^2}{M}\, \nu \cdot \nu$$

SEESAW MECHANISM

$$m_\nu \simeq \frac{\langle \phi \rangle^2}{M}$$

THE SMALL NEUTRINO MASS IS A NATURAL PREDICTION OF THE BARYOGENESIS !!!

LEPTOGENESIS

Fukugita – T.Y. (1986)

THE SEESAW MODEL OF GRS;Y.

$$SM \oplus N_i \quad (i = 1-3)$$

real diagonal

$$\mathcal{L} = f_i \, \bar{e}_R^i \, l_L^i \, H^* + h_{ij} \, \bar{N}^i \, l_L^j \, H + M_i \, N^i N^i + \text{h.c.}$$

$\cancel{CP}$ phases

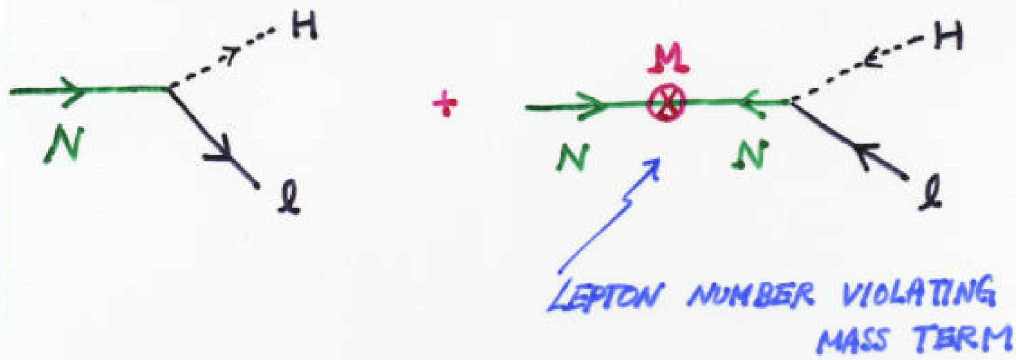
real diagonal

NEUTRINO MASSES :

$$(m_\nu) \simeq h^T \frac{1}{M} h \, \langle H \rangle^2$$

$\cancel{CP}$ PHASES ARE IN THE Yukawa COUPLING CONSTANTS h_{ij}.

N DECAY HAS LEPTON NUMBER VIOLATION.



IF h_{ij} HAVE $\not{CP}$ PHASES, N DECAY PRODUCES THE LEPTON ASYMMETRY:

$$BR(N \to \ell + H) \neq BR(N \to \bar{\ell} + H^*)$$

PRODUCED L ASYMMETRY $\xrightarrow[\text{CONVERTED}]{}$ B ASYMMETRY !!!

BARYON ASYMMETRY

$$\frac{n_B}{s} \simeq -0.35\,\frac{n_L}{s}$$

$$\frac{n_L}{s} \simeq \kappa\,(1/g_*)\,\varepsilon$$

degrees of freedom

Dynamical Factor From out-of-equilibrium condition

$$\frac{n_B}{s} \simeq \kappa \cdot 10^{-3}\,\varepsilon$$

ESTIMATION OF ε PARAMETER :

$M_3 > M_2 > M_1$

CONSIDER N_1 DECAY.

$$\varepsilon_{(1)} \equiv \frac{\Gamma(N_1 \to l + H) - \Gamma(N_1 \to \bar{l} + H^*)}{\Gamma(N_1 \to l + H) + \Gamma(N_1 \to \bar{l} + H^*)}$$

$$\simeq \frac{3}{16\pi}(\sin\delta)\,\frac{m_{\nu_3}\,M_1}{\langle H\rangle^2}$$

Flanz, Paschos, Sarkar, Covi, Roulet, Vissani, Buchmuller, Plumacher, Pilaftsis, ...
⋮

$$\simeq (\sin\delta) \times 10^{-6}\left\{\frac{M_1}{10^{10}\,\mathrm{GeV}}\right\}$$

FOR $m_{\nu_3} \simeq 0.05\,\mathrm{eV}$: $\langle H\rangle \simeq 246\,\mathrm{GeV}$

$$\frac{n_B}{s} \simeq \varkappa \cdot (\sin\delta) \cdot 10^{-9} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

CP VIOLATING PHASE

$\varkappa$ SHOULD BE DETERMINED BY SOLVING THE Boltzmann EQUATIONS :

$$\varkappa = f(\tilde{m}_\nu, M_1)$$

OUT-OF-EQUILIBRIUM CONDITION

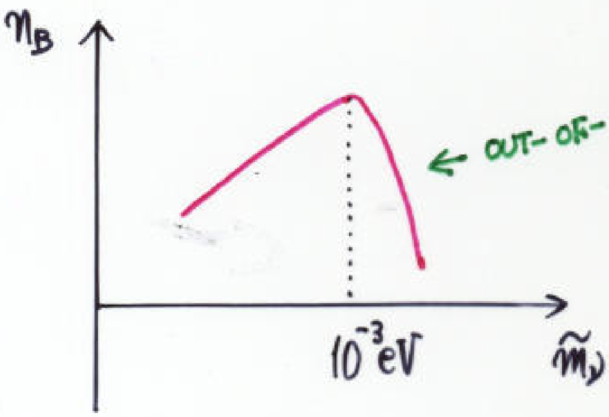
$$\Gamma_{DECAY} < \gamma_{exp}(T \sim m_{N_1})$$

$$\Gamma_{DECAY} \simeq \frac{1}{8\pi} (h h^\dagger)_{11} M_1$$

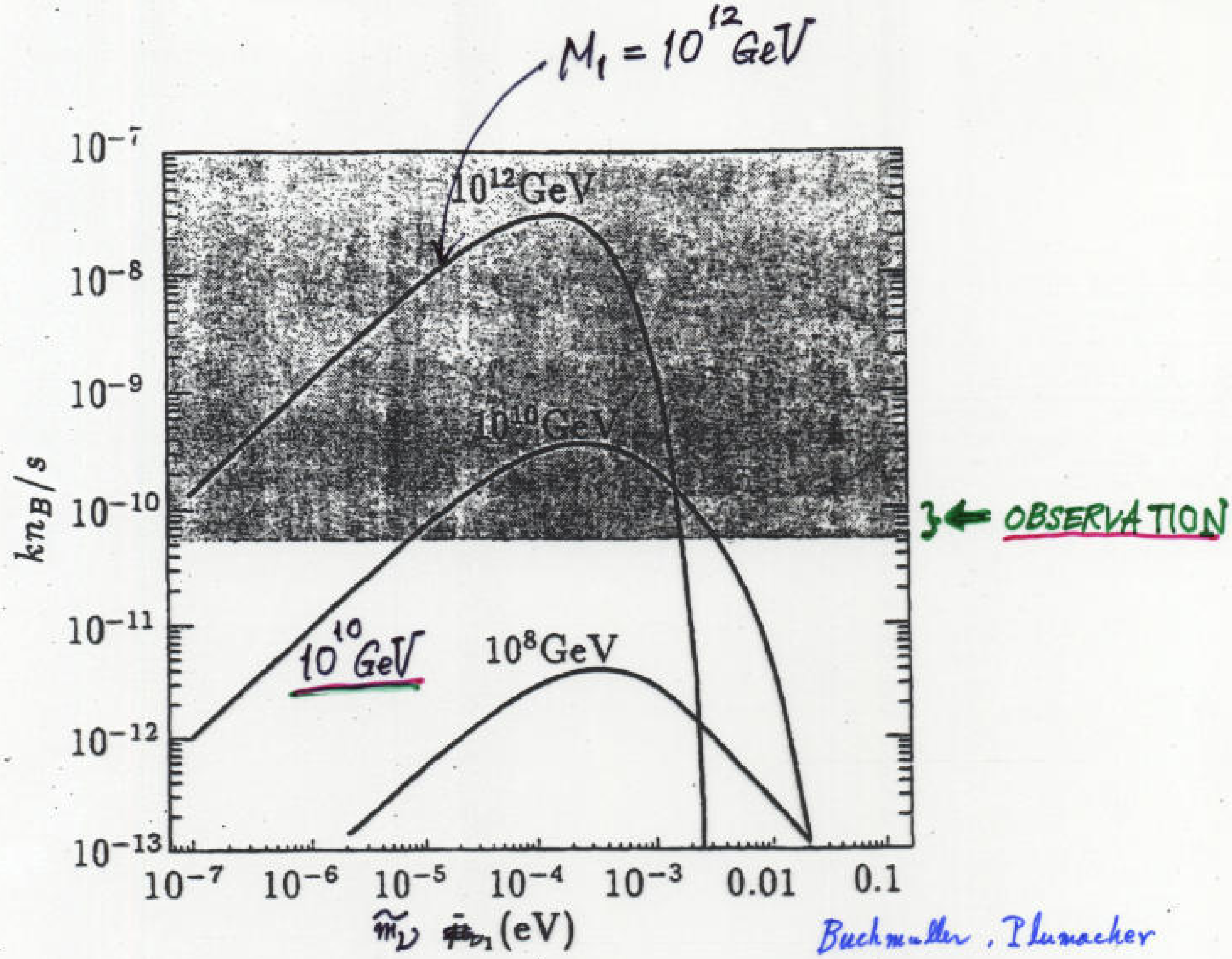
$$\gamma_{exp}(T = M_1) \simeq \sqrt{g_*} \frac{M_1^2}{M_{Pl}}$$

$$\frac{(h h^\dagger)_{11}}{M_1} < \frac{\sqrt{g_*}\, 8\pi}{M_{Pl}}$$

$$(\tilde{m}_\nu)_{11} < \frac{\sqrt{g_*}\, 8\pi}{M_{Pl}} \langle H \rangle^2 \sim 10^{-3}\,\mathrm{eV}$$



$$\tilde{m}_\nu \not\gg 10^{-3}\,\mathrm{eV}$$



Buchmuller, Plumacher

08: Baryon abundance represented in units of kn_B/s as a function of 'neutrino for an assumed right-handed neutrino mass $M = 10^8$, 10^9 and 10^{10} GeV and [1513]. The allowed region ($\delta \leq 1$) is shown by shading.

$\sin\delta = 1.$

Hirsch, King
Ellis et al

THE MINIMUM SEESAW MODEL EXPLAINS THE OBSERVED BARYON ASYMMETRY IN THE PRESENT UNIVERSE, $\frac{n_B}{s} \simeq 10^{-11}-10^{-10}$,

IF $M_1 \approx 10^{10}$ GeV, $\tilde{m}_\nu \simeq 10^{-3}-10^{-2}$ eV.

$\tilde{m}_\nu$ SHOULD NOT BE TOO SMALL AND TOO LARGE !!

THIS IS VERY CONSISTENT WITH THE OBSERVATION :

$$\begin{cases} m_{\nu_3} \simeq 0.05\,\text{eV} \\ m_{\nu_2} \simeq 0.005\,\text{eV} \end{cases}$$

Seesaw : $m_D^2/M = m_\nu$ $\quad M_3 \simeq 10^{15}$ GeV FOR $m_D \simeq m_t$

If $M_3 : M_2 : M_1 \simeq m_t : m_c : m_u$, $M_1 \simeq 10^{10}$ GeV. !!

IS THE MODEL OF ALMOST DEGENERATE NEUTRINOS INCONSISTENT WITH LEPTOGENESIS ?

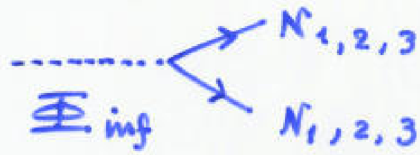
$$m_{\nu_1} \simeq m_{\nu_2} \simeq m_{\nu_3} \simeq 0.1 \text{ eV}$$

NO !! Fujii, Hamaguchi, T.Y. (2002)

NON-THERMAL PRODUCTION OF N^i's.

NO OUT-OF-EQUILIBRIUM CONDITION.

INFLATON DECAY



$$\frac{n_L}{s} \simeq BR(\Phi \to NN)\ \varepsilon\ \left(\frac{T_R}{M_\Phi}\right)$$

$$\varepsilon \simeq 10^{-8} \left(\frac{M}{10^{10}\,\mathrm{GeV}}\right)$$

Asaka et al
Giudice et al

$$\frac{n_B}{s} \simeq 3\times 10^{-9}\ BR\cdot\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{M}{M_\Phi}\right)$$

$BR \simeq 1\ \%$, $T_R \simeq 10^{10}$ GeV $\quad M_\Phi \sim M$

ONE GETS $n_B/s \simeq 3\times 10^{-11}$.

CONCLUSION

THE SEESAW MODEL OF GRSY EXPLAINS

TWO INDEPENDENT OBSERVATIONS:

1. SMALL NEUTRINO MASSES.

2. UNIBERSE'S BARYON ASYMMETRY.

IT HAS TWO GENERIC PREDICTIONS:

I. $0\nu 2\beta$ DECAY,

KDHK

⋮

II. CP VIOLATION IN NEUTRINO SECTOR.

$\not{CP}$ IN ν OSCILLATION.

Question 1. : CP VIOLATION by Petcov

Leptogenesis :

$$CP \text{ phase} \sim \mathrm{Im}\left(h\, m_\nu^\dagger\, h\right)$$

Hamaguchi (PhD thesis)

Mjorana phase Petcov et al
Valle et al (1980)
Doi et al

ν oscillation

$$CP \text{ phase} \sim \mathrm{Im}\left(m_\nu^\dagger m_\nu\right)$$

They are independent phases.

But origin of $\not{CP}$ is in the Yukawa Coupling h_{ij}. We expect visible $\not{CP}$ in ν oscillation as long as there is no accidental cancellation.