BARYON ASYMMETRY IN THE UNIVERSE

— LEPTOGENESIS —

T. Yanagida

Los Houches, 2001

ONE OF THE MOST FUNDAMENTAL OBSERVATIONS :

OUR UNIVERSE IS COMPOSED OF MATTER , BUT NO ANTIMATTER .

IF $n_B = n_{\bar{B}}$ IN THE HOT THERMAL BATH IN THE EARLY UNIVERSE , THEY ANNIHILATE WITH EARCH OTHER WHEN THEY DECOUPLE TO THE BATH.

NO MATTER LEFT IN THE UNIVERSE.

NO STRUCTURE FORMATION.

BARYON - NUMBER ASYMMETRY

IS CRUCIAL FOR THE UNIVERSE TODAY.

THE ASYMMETRY PARAMETER IS ONE OF

THE MOST FUNDAMENTAL ONES IN NATURE.

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma}$$

THE BARYON-TO-PHOTON RATIO η_B IS DETERMINED

BY THE BIG-BANG NUCLEOSYNTHESIS.

$$\eta_B \simeq (1.5 - 6.3) \times 10^{-10}$$

CONSISTENT WITH

ASTROPHYSICAL OBSERVATIONS!

BIG CHALLENGE :

EXPLAIN THE BARYON ASYMMETRY.

CALCULATE THE PARAMETER η_B .

$$\eta_B \equiv n_B/n_\gamma \simeq 10^{-10}$$

CONDITIONS FOR BARYOGENESIS :

(i) BARYON – NUMBER NONCONSERVATION

(ii) C / CP VIOLATION

(iii) OUT-OF-EQUILIBRIUM PROCESSES

A. Sakharov (1967)

$\cancel{CP}$ IS OBSERVED IN K- DECAYS.

(i) → PROTON DCAYS !!

BUT, NO EVIDENCE OF THE PROTON DECAYS HAS BEEN FOUND.

Super K

THE PRESENCE OF B- ASYMMETRY

IN THE UNIVERSE STRONGLY SUGGESTS

VERY SMALL MASSES FOR NEUTRINOS !

AND

CP VIOLATION IN NEUTRINO SECTOR !!

Fukugita. T.Y. (1986)

RATHER THAN

proton Decays
$\cancel{CP}$ in quark sector

AND

Double β - Decays !!!

BARYON / LEPTON NUMBER NONCONSERVATION

IN THE ELECTROWEAK THEORY.

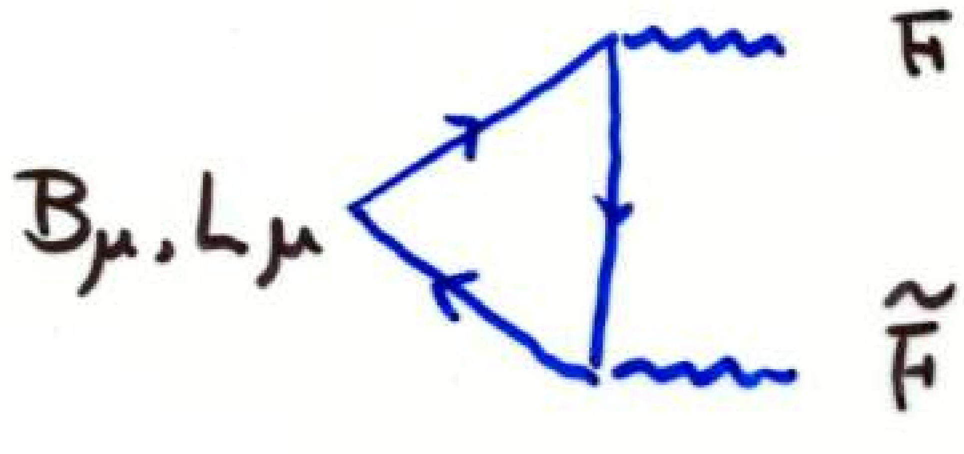
in Weinberg - Salam model

TWO GLOBAL SYMMETRIES :

- BARYON NUMBER B
- LEPTON NUMBER L

THESE ARE BROKEN AT QUANTUM LEVEL DUE TO ANOMALIES.

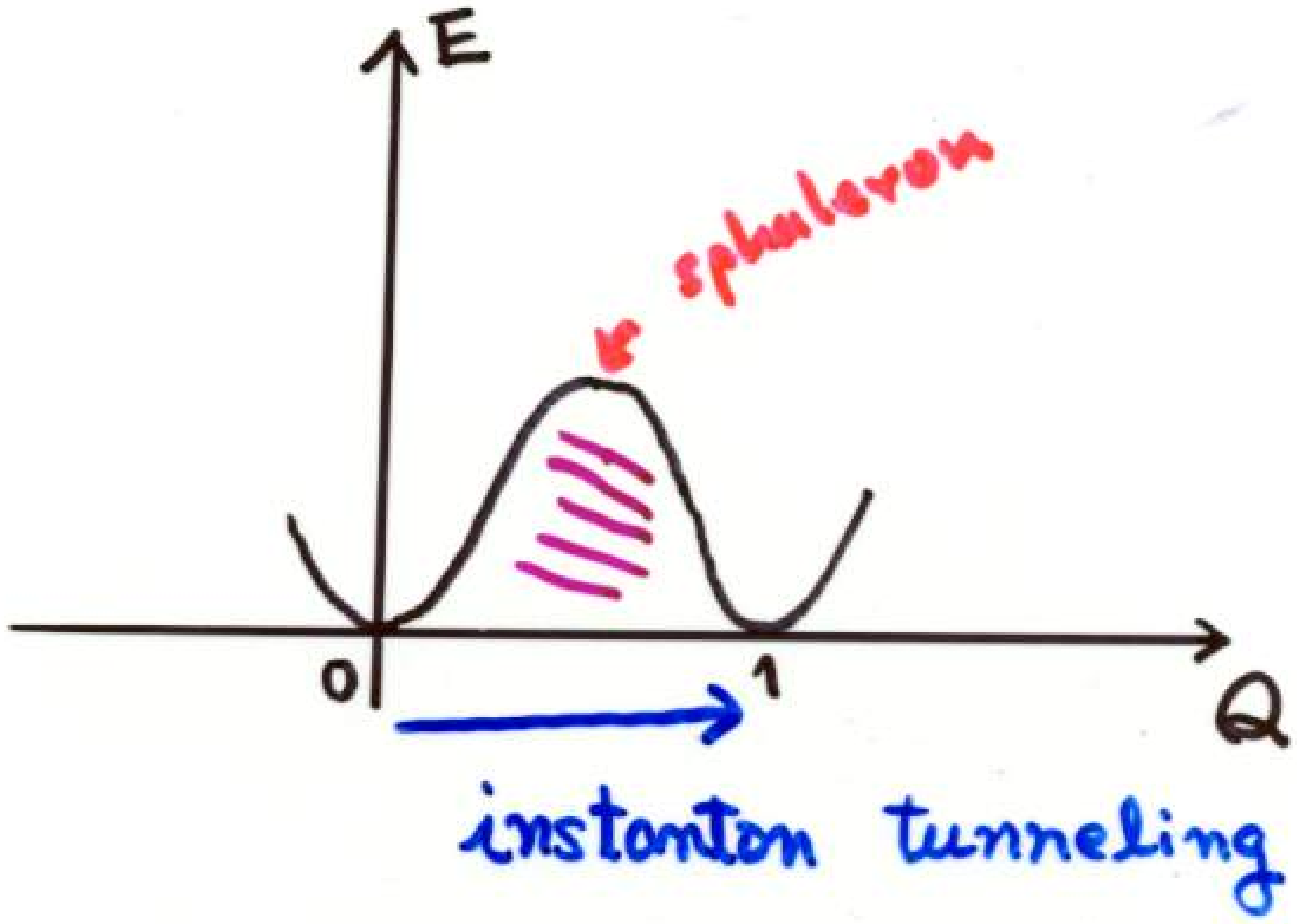
't Hooft (1976)



$$\partial_\mu J^\mu \neq 0$$

$$\dot{B} \neq 0 \quad , \quad \dot{L} \neq 0$$

BUT, $(B-L)$ IS CONSERVED.



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

AT $T \simeq 0$ THIS TUNNELING IS SUPPRESSED.

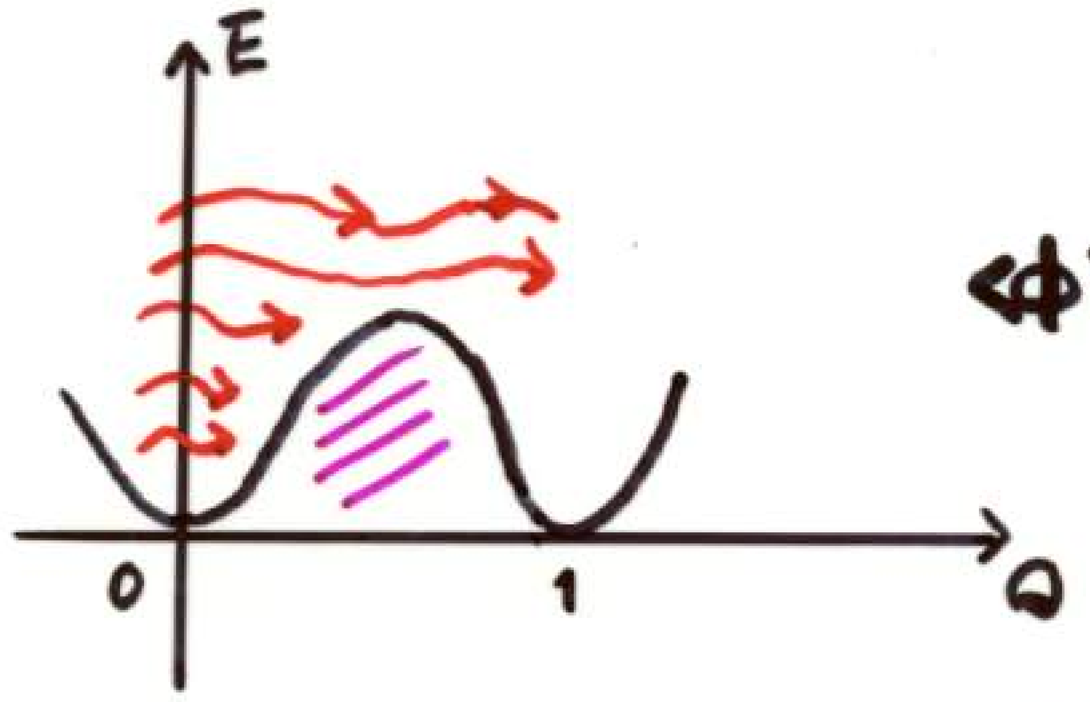
$$A \sim e^{-S} = e^{-8\pi^2/g^2} \simeq e^{-100} \ll 1$$

THE PROTON IS STABLE.

Susskind ('80)

THE SITUATION CHANGES DRASTICALLY AT HIGH TEMPERATURES.

Kuzmin, Rubakov, Shaposhnikov (1985)



$\langle \phi \rangle \propto 246$ GeV

THERMAL TRANSITION

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

NO SUPPRESSION OF B-VIOLATION AT HIGH TEMPERATURE.

B/L NUMBER VIOLATING PROCESSES ARE IN THERMAL EQUILIBRIUM IN THE EARLY UNIVERSE,

$T > O(100)$ GeV.

BIG IMPACT ON THE EVOLUTION OF B-ASYMMETRY.

ELECTROWEAK BARYOGENESIS :

THE STANDARD EW THEORY MEETS THE FIRST TWO CONDITIONS :

(i) B - VIOLATION ✓

(ii) CP - VIOLATION ✓

THE THIRD CONDITION, (iii) OUT-OF-EQUILIBRIUM, MAY BE SATISFIED IF THE ELECTROWEAK PHASE TRANSITION IS THE FIRST ORDER.

IT PREDICTS $m_H \lesssim 74$ GeV.

lattice simulations in the full 4D theory
Csikor, et al (1999)

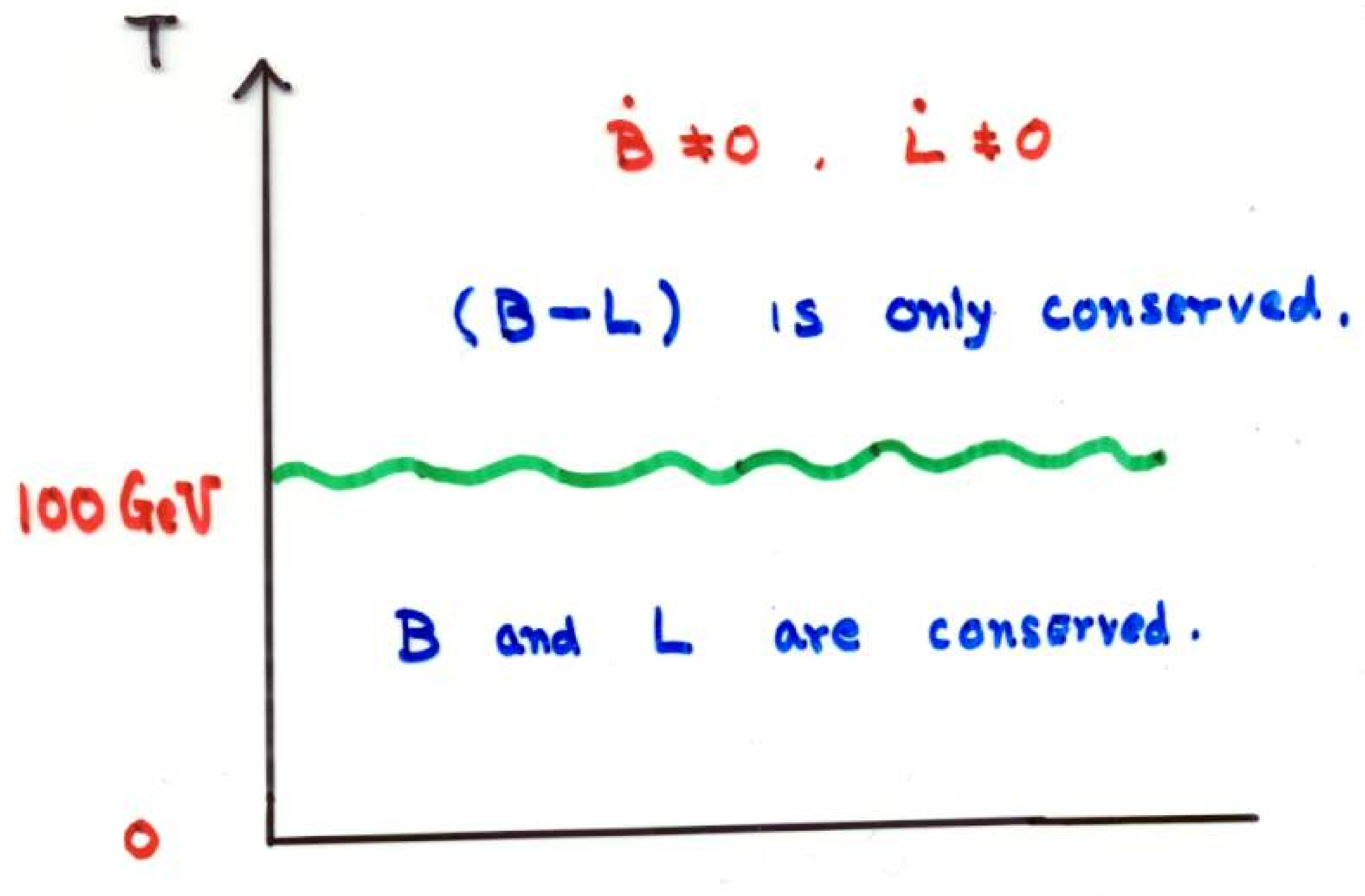
BUT LEP EXPERIMENTS SHOW

$$m_H > 108 \text{ GeV}$$

LEP (2000)

EW BARYOGENESIS IN THE STANDARD THEORY IS EXCLUDED.

IN SUSY, IF $m_{\tilde{t}} < m_t$
IT CAN BE THE 1st order, But...



$$n_B(\text{PRESENT}) \simeq \underset{0.35}{C}\,(n_{B-L})_0$$

$(n_{B-L})_0$ IS THE B−L NUMBER DENSITY PRODUCED IN MUCH EARIER EPOCH.

B−L GENERATION IS IMPORTANT !!

EVEN IF B IS CREATED WITH $\Delta(B-L)=0$, ALL B−ASYMMETRY IS WASHED OUT BY THE EW NON-PERTURBATIVE EFFECTS.

THE FOURTH CONDITION SHOULD BE ADDED :

(iv) (B−L) NUMBER NONCONSERVATION.

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 !!

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

Weinberg
Wilczek-Zee
('79)

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)

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

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

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 !!!

NOW, WE HAVE STRONG EVIDENCE FOR

MASSIVE NEUTRINOS !!

ATMOSPHERIC NEUTRINO OSCILLATION :

$$\delta m^2_{23} \simeq 3 \times 10^{-3}\, eV^2$$

SOLAR NEUTRINO OSCILLATION :

$$\delta m^2_{12} \simeq 10^{-5}\, eV^2$$

ASSUMING THE HIERARCHY $m_3 > m_2 > m_1$,

$$m_{\nu_3} \sim 5 \times 10^{-2}\, eV \quad , \quad m_{\nu_2} \sim 3 \times 10^{-3}\, eV .$$

MAY BE ON THE RIGHT TRACK !

THE NEXT STEP IS

TO CALCULATE THE B-ASYMMETRY PARAMETER : $\eta_B = n_B / n_\gamma \simeq 10^{-10}$.

$$m_\nu \simeq \frac{f^2 \langle \phi \rangle^2}{M} \simeq 5 \times 10^{-2}\,\mathrm{eV}$$

$$f \langle \phi \rangle \simeq m_t$$

$$M \sim 10^{15}\,\mathrm{GeV}$$

THERE MUST BE SOME PHYSICS MUCH BELOW THE PLANCK SCALE !!

Gell-Mann, Ramond, Slansky ; Yanagida

THE SEESAW MODEL OF GRSY

(1979)

SM ⊕ RIGHT-HANDED NEUTRINOS N^i $(i = 1, 2, 3)$

real diagonal

$$\mathcal{L}_{lepton} = f_i \, e_R^i \, l_L^i \, \phi^*$$

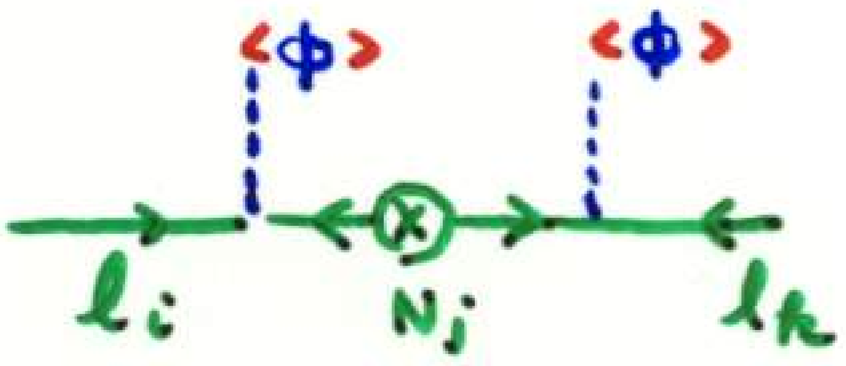
$$+ h_{ij} \, N^i \, l_L^j \, \phi \; + M_i \, N^i N^i \; + h.c.$$

$\cancel{CP}$ phases

real diagonal

INTEGRATION OF N^i GIVES NEUTRINO MASSES :

$$\mathcal{L}_{mass} \simeq \frac{h_{ij} \, h_{jk}}{M_j} \, l_i \, l_k \langle \phi \phi \rangle$$

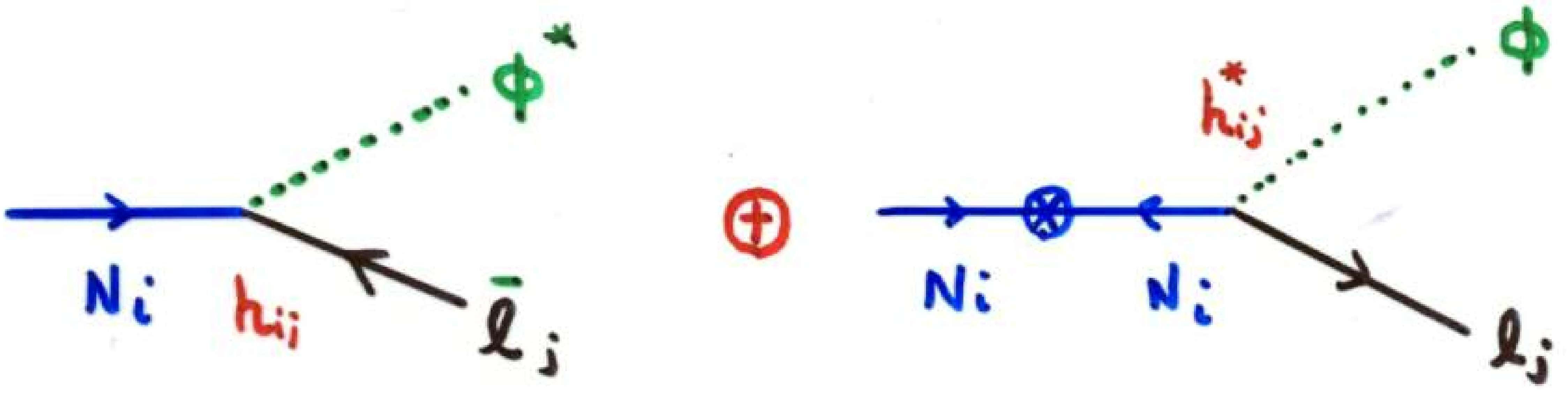


$$(m_\nu)_{ik} \simeq \frac{h_{ij} \, h_{jk}}{M_j} \, v^2$$

$\cancel{CP}$ PHASE COMES FROM THE PHASES IN THE YUKAWA COUPLING h_{ij} .

LEPTON NUMBER IS BROKEN BY THE MAJORANA MASS OF N^i.

→ L VIOLATION IN N^i DECAYS.



IF h_{jk} HAVE $\not{CP}$ PHASES N_i DECAYS PRODUCE THE LEPTON ASYMMETRY $\Delta L \neq 0$:

$$B_R(N \to \ell + \phi) \neq B_R(N \to \bar{\ell} + \phi).$$

THE (B−L) ASYMMETRY IS CREATED !!

OR

THE (L) ASYMMETRY IS CONVERTED TO THE (B) ASYMMETRY BY EW ANOMALY EFFECTS.

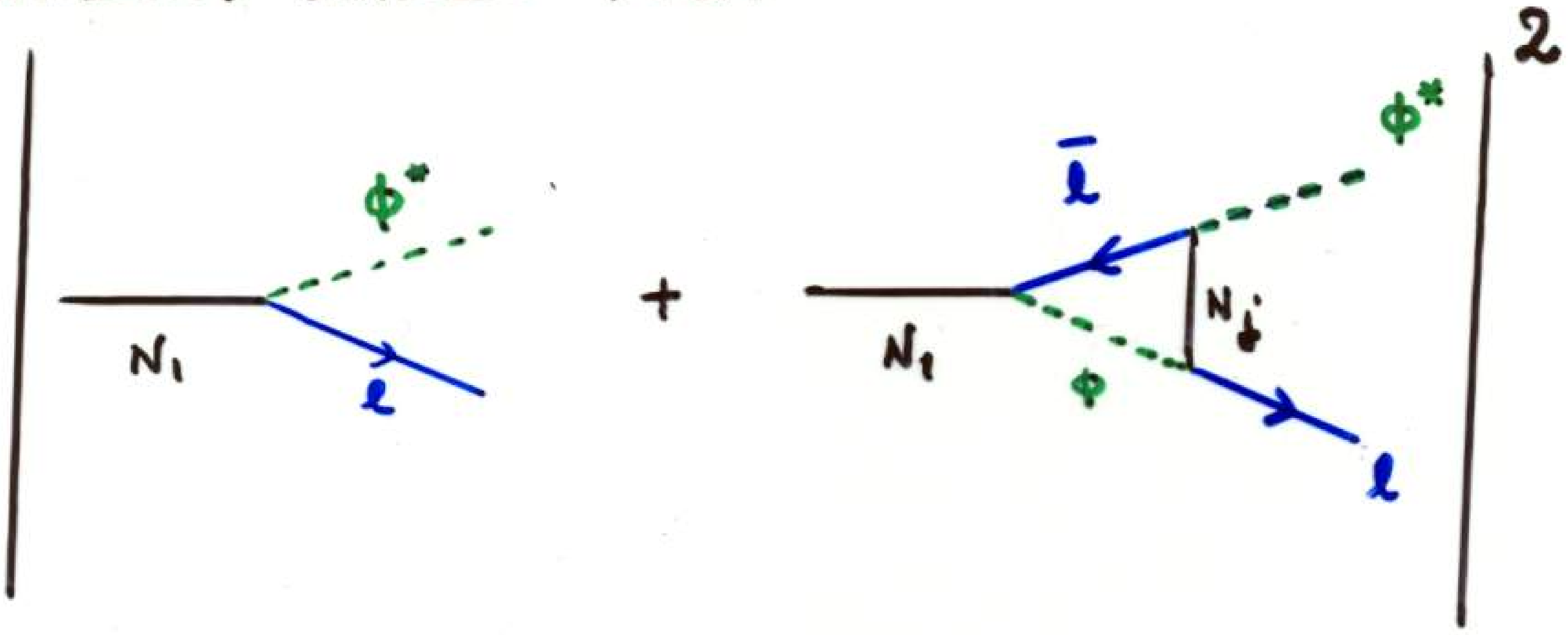
Fukugita . T.Y. ('86)

CALCULATION OF THE ASYMMETRY PARAMETER ε.

ASSUME A MASS HIERARCHY : $M_3 > M_2 > M_1$

CONSIDER THE DECAY OF THE LIGHTEST N : N_1.

ASYMMETRY ARISES FROM



$$\varepsilon \equiv \frac{\Gamma(N_1 \to \phi^* + \ell) - \Gamma(N_1 \to \phi + \bar{\ell})}{\Gamma(N_1 \to \phi^* + \ell) + \Gamma(N_1 \to \phi + \bar{\ell})}$$

$$\simeq \frac{3}{16\pi} \frac{\sin(2\delta)}{(hh^\dagger)_{11}} \left| hh^\dagger \right|^2_{13} \frac{M_1}{M_3}$$

$$\simeq \frac{3}{16\pi} \sin(2\delta) \frac{|h_{33}|^2}{M_3} M_1 \qquad (h_{33} \gg h_{ij})$$

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

$$\because \; m_{\nu_3} \simeq \frac{(h_{33})^2 \langle\phi\rangle^2}{M_3}$$

$\cancel{C}P$ PHASE : $(hh^\dagger)_{13} \equiv e^{i\delta} |(hh^\dagger)_{13}|$

USING $\quad m_{\nu_3} \sim 5\times10^{-2}\,eV \;,\quad \langle\Phi\rangle \simeq 246\ GeV$

$$\varepsilon \simeq \sin(2\delta)\cdot 10^{-6}\cdot\left(\frac{M_1}{10^{10}\,GeV}\right)$$

$$\frac{n_L}{n_\gamma} \simeq \varkappa\cdot\left(\frac{N_f}{g_*}\right)\varepsilon$$

↖ degrees of freedom

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq -0.3\,\frac{n_L}{n_\gamma} \simeq \varkappa\cdot 10^{-8}\left(\frac{M_1}{10^{10}GeV}\right)\sin(2\delta)$$

Dynamical Factor

↕

OUT-OF-EQUILIBRIUM CONDITION

THE DELAYED DECAY MECHANISM

Weinberg ('79)
Wilczek et al ('79)

THE OUT-OF-EQUILIBRIUM CONDITION IS SATISFIED IF X PARTICLE DECAYS AFTER IT DECOPLED TO THE THERMAL BATH :

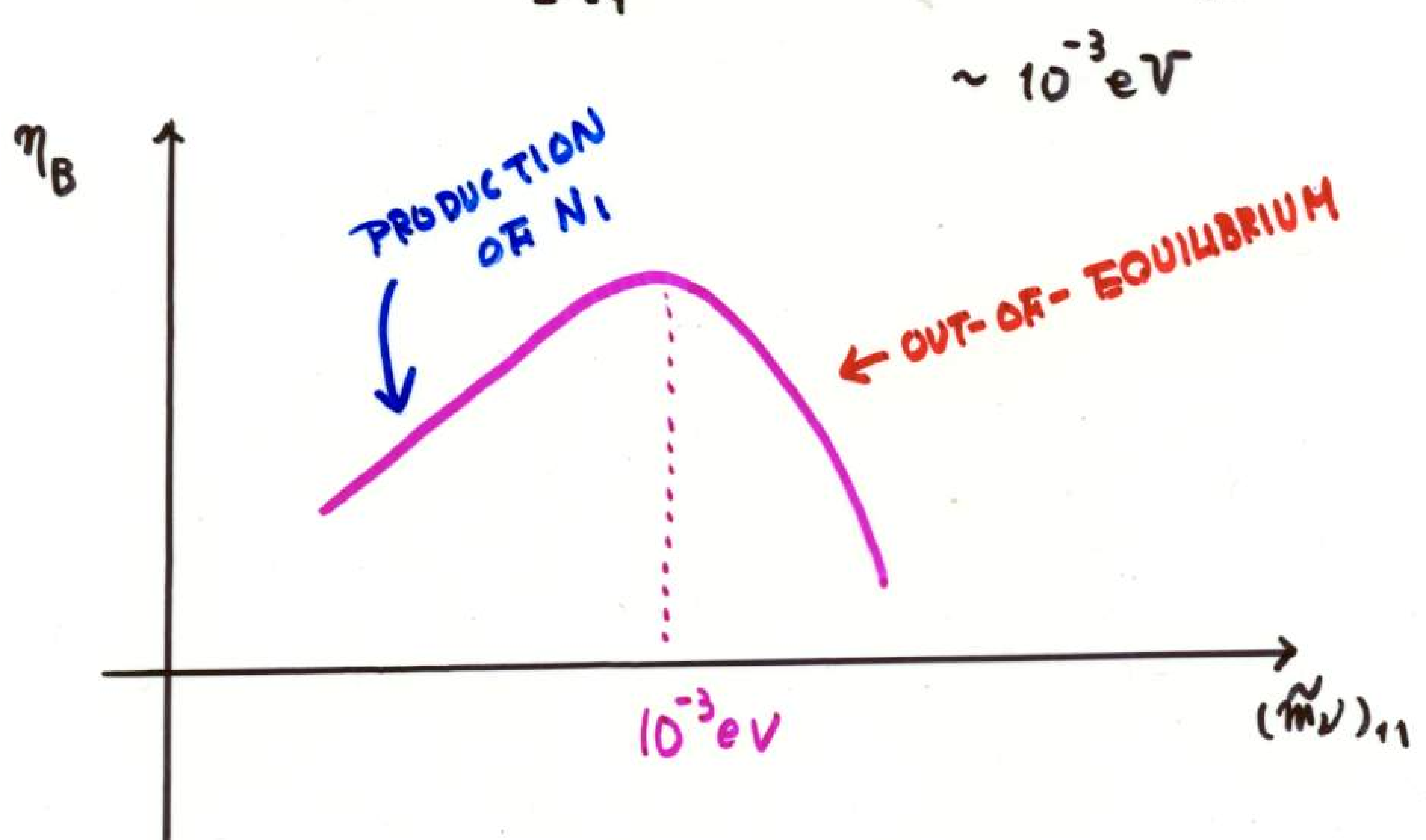
$$\Gamma_{DECAY} < \gamma_{exp}\,(T \simeq m_X)$$

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

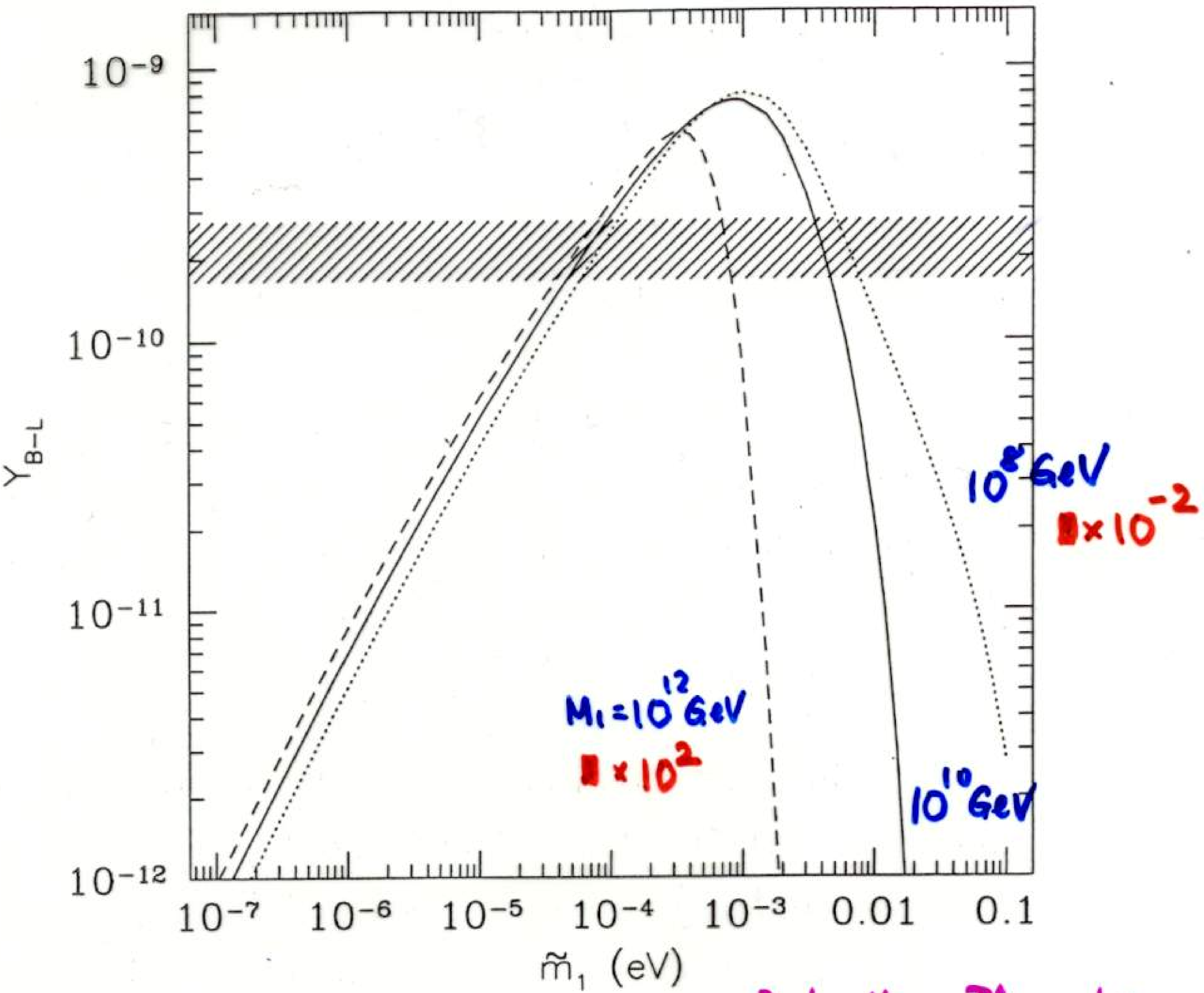
$$\gamma_{exp}\,(T \simeq M_1) \simeq \sqrt{g_*}\,\frac{M_1^2}{M_{Pl}}$$

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

$$(\tilde{m}_\nu)_{11} \equiv \frac{(h^+\langle\phi\rangle h\langle\phi\rangle)_{11}}{M_1} < \sqrt{g_*}\,8\pi\,\frac{\langle\phi\rangle^2}{M_{Pl}} \sim 10^{-3}\,eV$$



n_{B-L}/s



Buchmuller - Plumacher

e 6: *Generated* $B - L$ *asymmetry as a function of* $\widetilde{m}_1$ *for* $M_1 = 10^8$ *GeV (doi* $M_1 = 10^{10}$ *GeV (solid line) and* $M_1 = 10^{12}$ *GeV (dashed line). The shaded a* *s the measured value for the asymmetry.*

$\varepsilon = 10^{-6}$ fixed.

$$\varepsilon \simeq \sin(2\delta) \times 10^{-6} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}} \right)$$

$$\begin{cases} M_1 \gtrsim 3 \times 10^9 \text{ GeV} \\ (\tilde{m}_\nu)_{11} \lesssim 0.01 \text{ eV} \end{cases}$$

$$(\tilde{m}_\nu)_{11} \simeq \left(h_{11} \frac{1}{M_1} h_{11} + h_{21} \frac{1}{M_1} h_{12} + h_{31} \frac{1}{M_1} h_{13} \right) \langle\phi\rangle^2$$

$$(m_\nu)_{33} \simeq \left(h_{31} \frac{1}{M_1} h_{13} + h_{32} \frac{1}{M_2} h_{23} + h_{33} \frac{1}{M_3} h_{33} \right) \langle\phi\rangle^2$$

$$\sim \left(\frac{5}{2}\right) \times 10^{-2} \text{ eV}$$

NATURAL EXPECTATION : $(\tilde{m}_\nu)_{11} \sim 10^{-2}$ eV

THEN $M_1 \sim 10^{10}$ GeV

$\sin(2\delta) \simeq O(1)$

MASS HIERARCHY IN N^i SECTOR.

$$m_{\nu_3} \simeq \frac{(h_{33}\langle\phi\rangle)^2}{M_3} \simeq \frac{m_t^2}{M_3} \simeq 5\times10^{-2}\,\mathrm{eV}$$

$$M_3 \simeq 10^{15}\,\mathrm{GeV} \qquad \text{FOR } h_{33}\sim 1.$$

$$M_2 \simeq ?$$

$$M_1 \simeq 10^{10}\,\mathrm{GeV}$$

$$M_1 : M_3 \simeq m_u : m_t$$

VERY INTERESTING

THE MINIMAL MODEL OF GRSY EXPLAINS THE OBSERVED BARYON-NUMBER ASYMMETRY IN THE PRESENT UNIVERSE

$$\eta_B \equiv n_B/n_\gamma \simeq (1.6-6.4)\times10^{-10}.$$

⊕ SUSY

THE CONCLUSION DOES NOT CHANGE MUCH.

$$M_1 \simeq 10^9 - 10^{10}\ \mathrm{GeV}.$$

MAY BE

THE GRAVITINO PROBLEM.

⇩

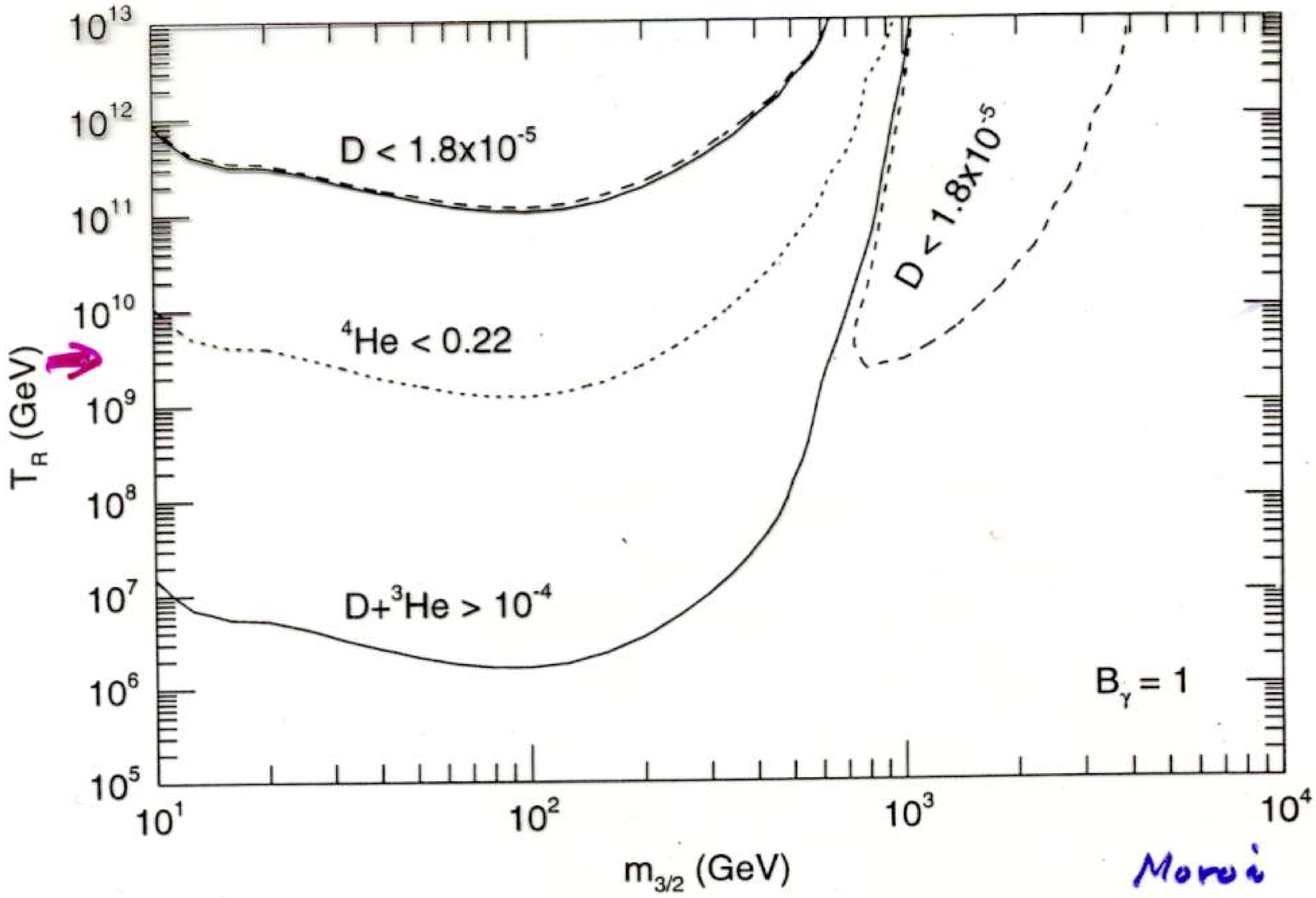
$$m_{3/2} \lesssim 1\ \mathrm{keV}$$

OR

$$m_{3/2} \gtrsim 500\ \mathrm{GeV}$$

IF THE GRAVITINO IS LSP, NO PROBLEM!

Buchmuller, Plumacher ..



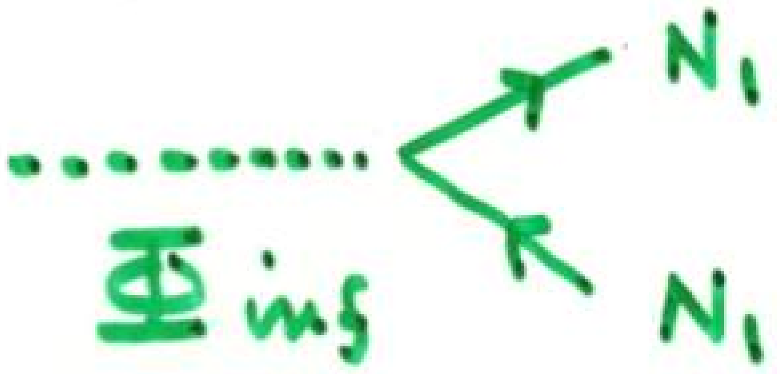
gure 6.6: Upperbound on T_R as a function of $m_{3/2}$. Here, we take $B_\gamma = 1$. In the region ove the solid curve ^{3}He and D are overproduced, the abundance of ^{4}He is less than 0.22 ove the dotted curve and the abundance of D is less than 1.8×10^{-5} above the dashed rve.

$$T_R \lesssim 10^{9-10}\ \text{GeV}$$

FOR $m_{3/2} \simeq O(1)$ TeV.

INFLATON DECAY

PRODUCTION OF N_1



$$\frac{n_L}{s} \simeq B_R(\Phi \to N_1 \bar{N}_1) \times \varepsilon \times \frac{T_R}{M_\Phi}$$

$$\simeq B_R \times 10^{-6} \left(\frac{T_R}{10^{10}\,GeV} \right) \cdot \frac{M_{N_1}}{M_\Phi}$$

FOR $\quad B_R \simeq 10^{-2} \quad , \quad m_\Phi \sim m_{N_1}$

$$n_{B/s} \simeq 0.3\,\frac{n_L}{s} \simeq 3 \times 10^{-11} \left(T_R/10^8\,GeV \right)$$

$T_R \simeq 10^8\,GeV$: NO $(3/2)$ PROBLEM

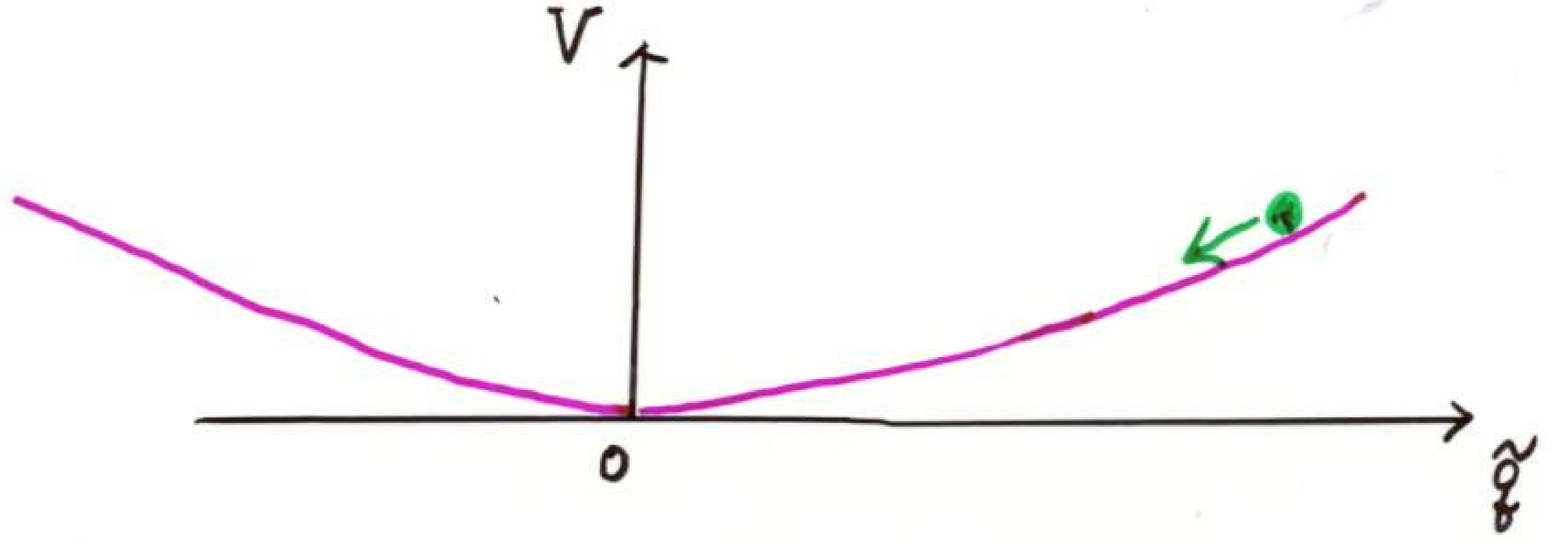
Asaka et al

Giudice et al ('99)

AFFLECK-DINE BARYOGENESIS :

Affleck - Dine (1985)

THERE ARE MANY FLAT DIRECTIONS IN SUSY THEORY.



SQUARKS MAY HAVE LARGE VALUES :

$$\langle \tilde{q} \rangle \simeq M_{Planck} \quad :$$

IN THE EARLY UNIVERSE.

WHEN THE EXPANSION RATE H BECOMES $\sim m_{\tilde{q}}$

THE FLAT DIRECTION $\tilde{q}$ STARTS TO OSCILLATE.

IF $\cancel{B}$, THE PHASE φ of $\tilde{q}$ ($\tilde{q} \equiv |\tilde{q}| e^{i\varphi}$)

ROTATES : $\dot{\varphi} \neq 0$, PRODUCING THE ΔB .

THE $\tilde{q}$ DECAY INTO PARTICLES CREATES THE BARYON NUMBER DENSITY IN THE THERMAL BATH.

AD LEPTOGENESIS :

Murayama, T.Y. ('94)

A FLAT DIRECTION :

$$L_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \varphi \\ 0 \end{pmatrix} \quad , \quad H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \varphi \end{pmatrix}$$

$\not{L}$ OPERATOR

$$W = \frac{f_1^2}{2M_1}(L_1 H_u)(L_1 H_u) = \frac{f_1^2}{8M_1}\varphi^4$$

$$m_{\nu_1} = \frac{f_1^2}{M_1}\langle v_u \rangle^2 \qquad \leftarrow \text{Seesaw}$$

DURING THE INFLATION :

$$\langle \varphi \rangle \simeq \sqrt{M H_{inf}}$$

$$\left(M = \frac{M_1}{f_1^2} \right)$$

WHEN φ STARTS OSCILLATION φ^4 TERM GENERATES THE PHASE ROTATION AND ΔL IS PRODUCED.

$\Delta L \to \Delta B$

SPHALERON PROCESSES.

SINCE $\varphi_I \sim \sqrt{MH} \ll M_{PLANCK}$ WE CAN NOT NEGLECT THE THERMAL EFFECTS.

Dine et al
Ellis et al

$$\delta V_{THERM.} \simeq \sum_n c_n f_n^2 T^2 |\varphi|^2 + a\,\alpha_s^2 T^4 \log\left(\frac{|\varphi|^2}{T^2}\right)$$

$$H_{osc.} \simeq m_\phi^2 + \sum_n c_n f_n^2 T^2 + a\,\alpha_s^2 \frac{T^4}{|\varphi|^2}$$

$$\frac{n_B}{s} \simeq 0.03\ \frac{M\ T_R}{M_{PLANCK}^2} \left(\frac{m_{3/2}}{H_{osc.}}\right) \cdot \delta_{eff}$$

T_R $\qquad$ $\delta_{eff} \simeq 1$

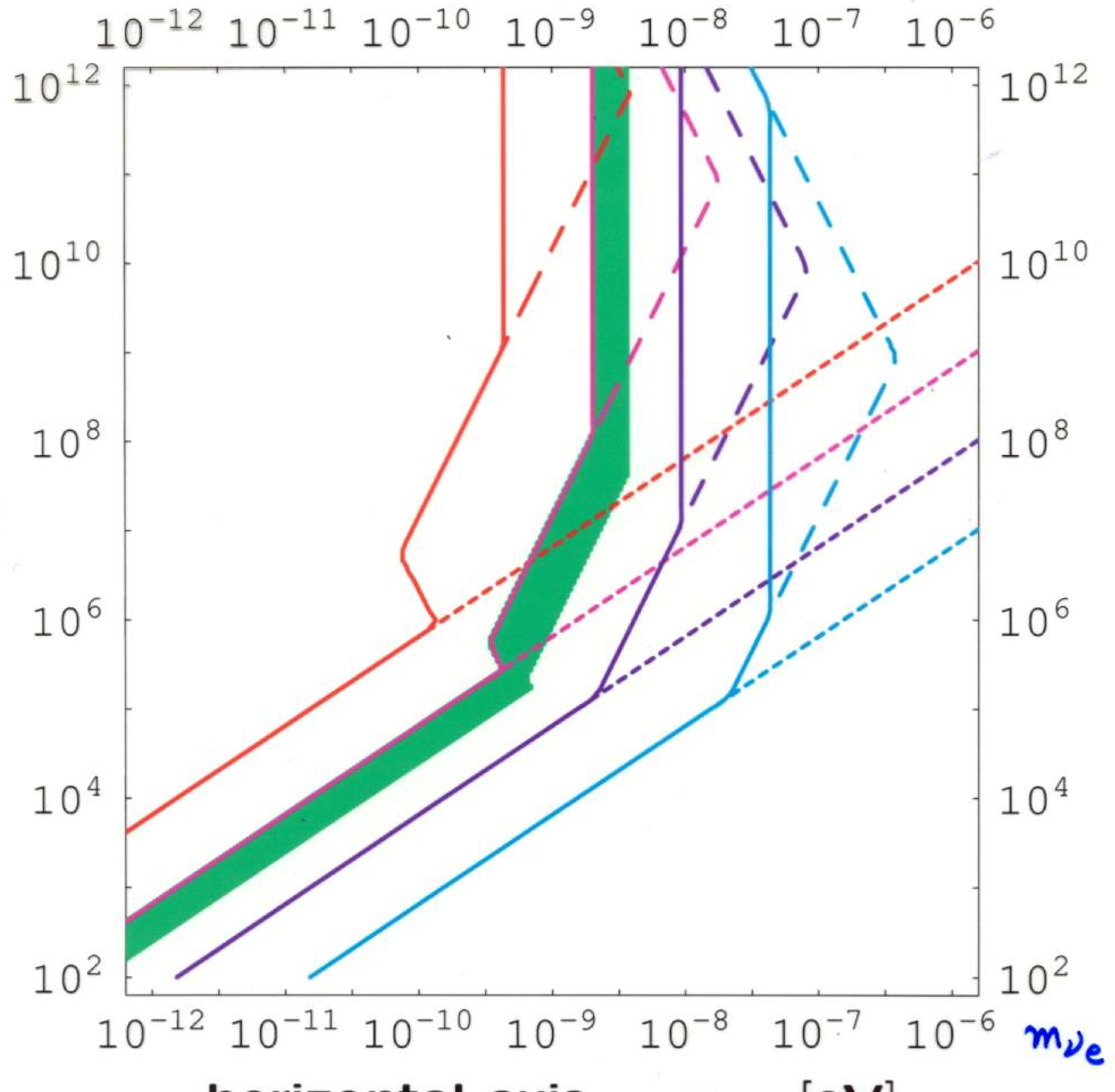
Fujii et al (2001)

$\Downarrow$

$m_{\nu_1} \simeq 10^{-9}\,\mathrm{eV}$!!!

⊙ Contour plot of baryon asymmetry

$$n_B/s = 10^{-9},\ 10^{-10},\ 10^{-11},\ 10^{-12}$$



horizontal axis $\rightarrow m_{\nu 1}$ [eV]
vertical axis $\rightarrow T_{RH}$ [GeV]

$$\frac{n_B}{s} = \frac{2}{69}\frac{MT_R}{M_*^2}\left(\frac{m_{3/2}}{H_{osc}}\right)\delta_{eff}$$

Fujii, Hamaguchi, T. Y.

With $m_{\nu_1} \simeq 10^{-9}$ eV WE CAN DRIVE

" m_{ee} " CONTRIBUTING 2β DECAY.

FOR LAMSW SOLUTION, WE GET

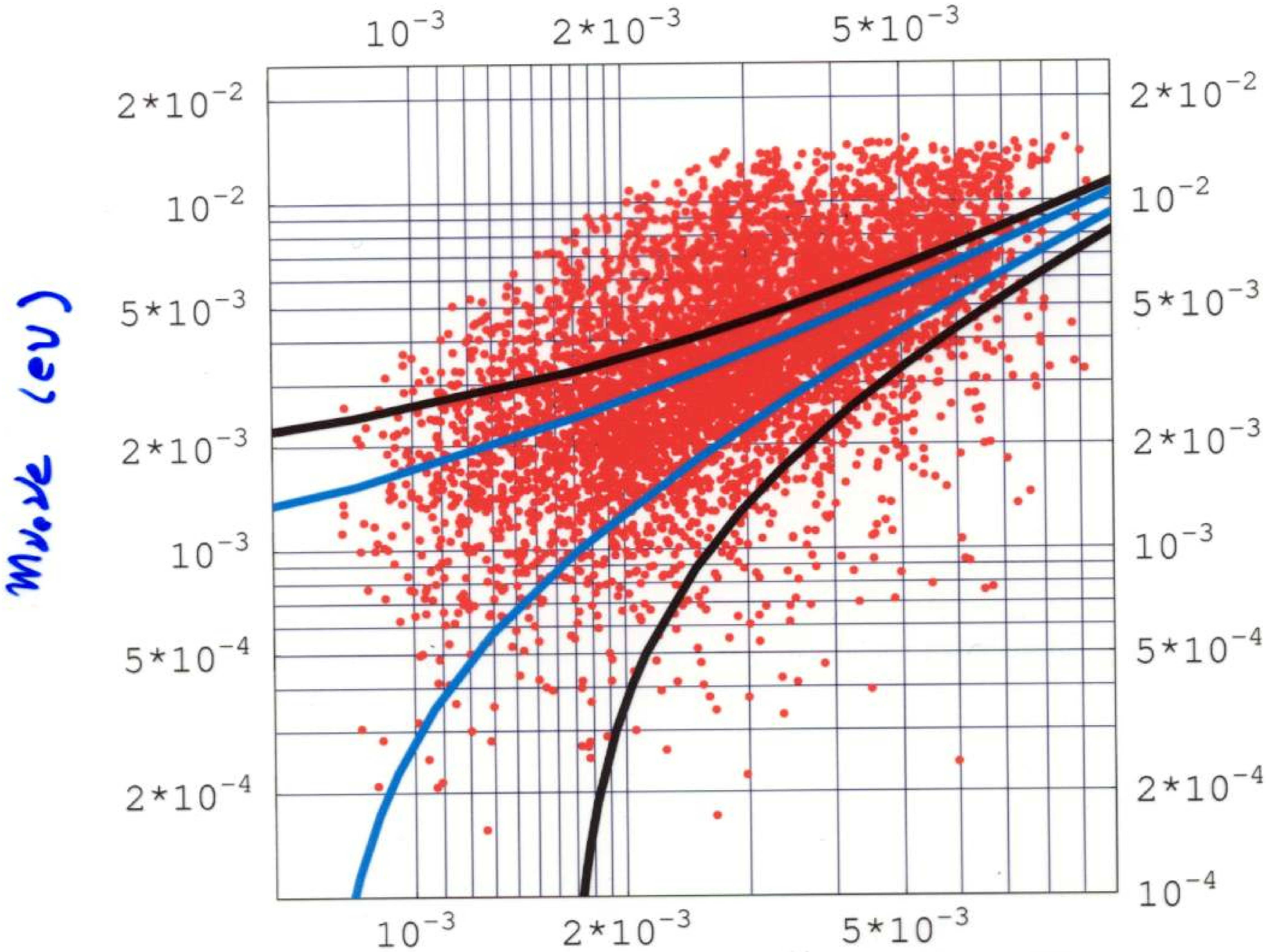
$$m_{ee} \simeq 0.5 \times 10^{-3} - 10^{-2} \text{ eV} \ !$$

Fujii et al
Vissani
Klapdor-Kleingrothaus,
Pas, Smirnov

⊙Prediction on $0\nu\beta\beta$ decay

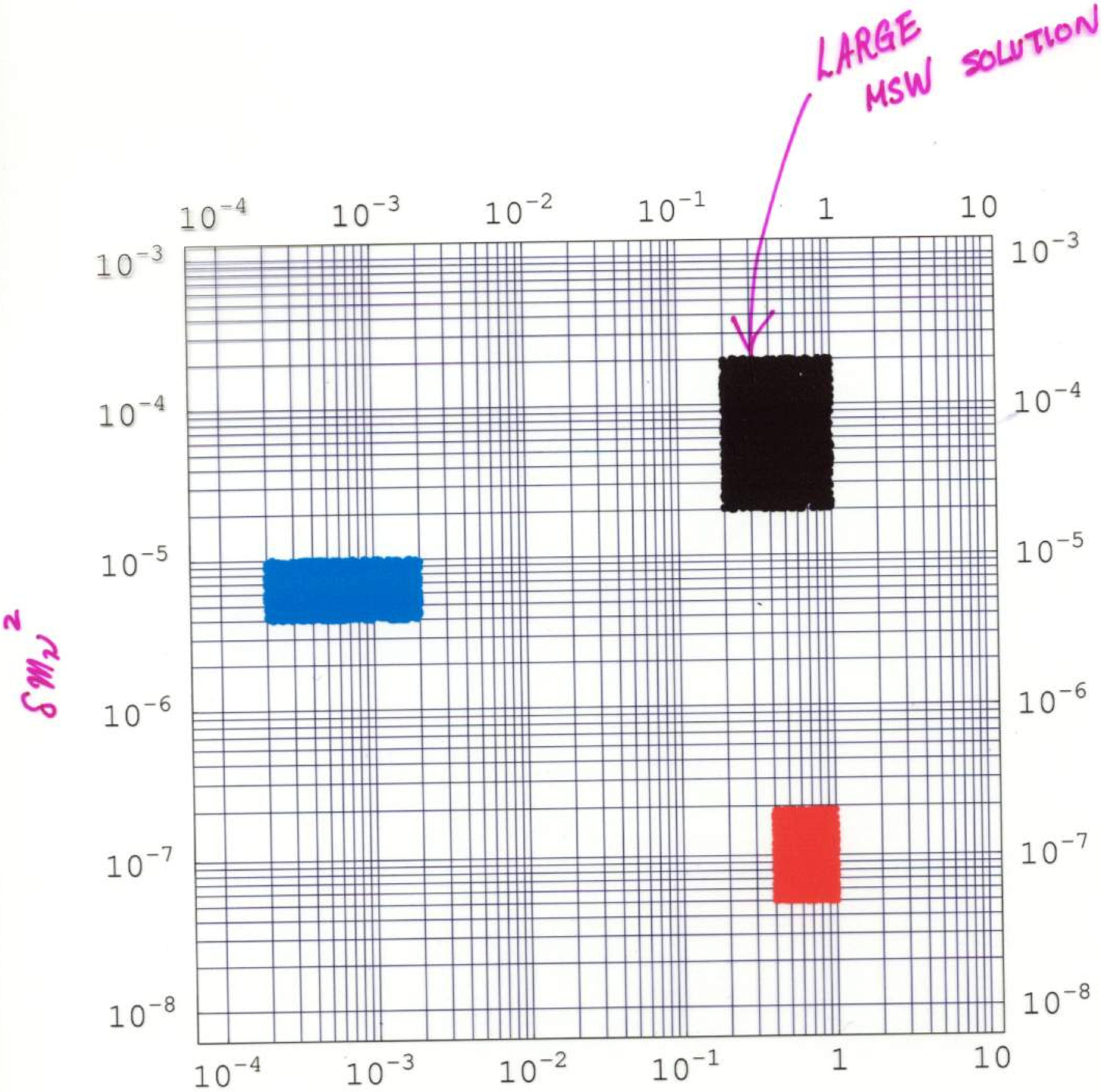
$e^{i\varphi}$

$$\begin{aligned} |m_{\nu e \nu e}| &= |U_{e1}^2 m_{\nu 1} + U_{e2}^2 m_{\nu 2} + U_{e3}^2 m_{\nu 3}| \\ &\simeq |(1-|U_{e3}|^2)\sin^2\theta_{sol}\sqrt{\delta m_{sol}^2} \\ &\quad +|U_{e3}|^2 e^{i\alpha}\sqrt{\delta m_{atm}^2}| \end{aligned}$$



horizontal axis→ $\sin^2\theta_{sol}\sqrt{\delta m_{sol}^2}$ [eV]
vertical axis→ $|m_{\nu e \nu e}|$ [eV]
$|U_{e3}| < 0.15,\ 0.1$

Fujii, Hamaguchi, T.Y.



horizontal axis⇒ $\tan^2\theta_{sol}$

vertical axis⇒ δm^2_{sol} $(\equiv m^2_{\nu 2} - m^2_{\nu 1})$ [eV^2]

CONCLUSION

NEUTRINO MASS IS RELATED TO THE BARYON ASYMMETRY IN THE UNIVERSE.

A BIG LONG-STANDING PROBLEM IN NATURE MAY BE SOLVED BY NEUTRINO PHYSICS.

i. IT PREDICTS A SMALL NEUTRINO MASS OF ORDER $\sim 10^{-2}-10^{-1}$ eV. ✓

ii. IT PREDICTS A LARGE CP VIOLATING PHASE IN NEUTRINO SECTOR.

iii. IT PREDICTS 2β DECAY.

THE NEXT STEP :

OBSERVATION OF CP VIOLATION

IN THE NEUTRINO SECTOR.

AND 2β DECAYS OF NUCLEUS.