

RENCONTRES DE MORIOND EW

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CAN LHC DISPROVE LEPTOGENESIS ?

BASED ON JHEP 0901(2009)051

IN COLLABORATION WITH J.M.FRÈRE & T.HAMBYE

G. VERTONGEN
(UNIVERSITÉ LIBRE DE BRUXELLES)



WHY LEPTOGENESIS ?

Ξ Neutrinos Oscillations

Paradigm : neutrinos

- are massives
- mix among each other

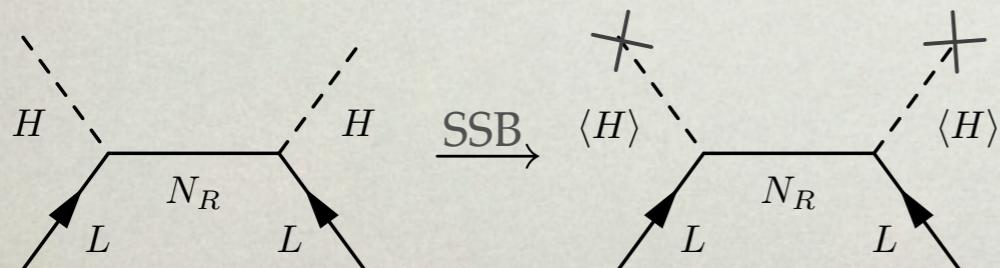
Q? How to explain such tiny masses ?

Ξ Elegant solution : *Seesaw mechanism* :

Add Majorana heavy fields to the SM

Ex: *Seesaw Type I*: Heavy Right-Handed neutrinos fields

$$\mathcal{L} \in -\overline{L} \tilde{H} Y_N^\dagger - \frac{1}{2} \overline{N} m_N N^c + h.c.$$



Ξ Baryon Asymmetry of the Universe

Assume :

1. production of symmetric Universe @ end of inflation.
2. free evolution untill now

$$Y_B^{sym} \equiv \frac{n_B - n_{\bar{B}}}{s} \sim \mathcal{O}(10^{-19})$$

But :

1. CMB acoustic peaks
2. BBN

$$Y_B^{obs} \simeq 8.10^{-11}$$

i.e. $\exists 10\ 000\ 000\ 001$ b for $10\ 000\ 000\ 000\ \bar{b}$

Q? Why something rather than (almost) nothing ?

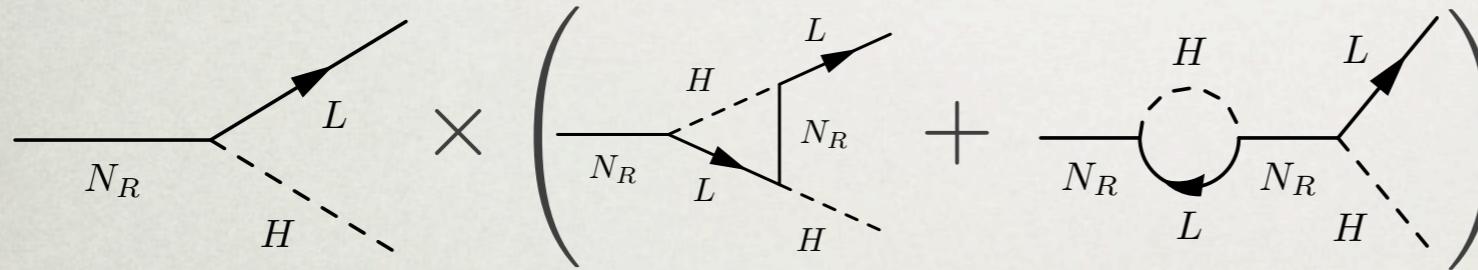
PLAIN VANILLA LEPTOGENESIS

Baryogenesis through Leptogenesis [Fukugita & Yanagida, 1986] :

↪ Using the N_R See-Saw fields, Leptogenesis fulfill the 3 **Sakharov's Conditions** [1967]

1. **L violation source**

2. **CP violating source**: $\Gamma(N_R \rightarrow LH) \neq \Gamma(N_R \rightarrow LH^*)$



Relevant parameters

$$\varepsilon_{CP}^i \equiv \frac{\Gamma_{N \rightarrow LH} - \Gamma_{N \rightarrow \bar{L}H^*}}{\Gamma_{\text{tot}}} \sim \sum_{j \neq i} \text{Im} \left[(m_D^\dagger m_D)_{ij} \right]^2$$

3. **Out-of-equilibrium decay**

4. Sphalerons: L asymmetry transferred to baryons
[Kuzmin, Rubakov, Shaposhnikov, 1985] [Harvey & Turner, 1986]

$$r_{\mathcal{L} \rightarrow \mathcal{B}} = -\frac{14 n_f + 9 n_\phi}{22 n_f + 13 n_\phi} = -\frac{28}{79}$$

Final Baryon asymmetry:

$$Y_{\mathcal{B}}^{\text{fin}} = Y_{\mathcal{L}}^{\text{fin}} r_{\mathcal{L} \rightarrow \mathcal{B}} = Y_N^{eq} \varepsilon_{CP} \eta r_{\mathcal{L} \rightarrow \mathcal{B}}$$

TESTING LEPTOGENESIS

Observing N_R ?

1. Hierarchical N_R

Leptogenesis ok if $m(N_R) > 10^8 \text{ GeV}$
[Davidson-Ibarra, 2002]

✗

2. Degenerate N_R

Leptogenesis ok @ low scales [Pilaftsis, 2002]
but $m(v_\alpha)$ require λ suppressed

✗

Linking CP violation ?

► Casas-Ibarra parameterization of Yukawa [NPB 618(2001)171]

$$\lambda = \sqrt{m_N} R \sqrt{m_\nu} U^\dagger \quad \text{PMNS}$$

\mathcal{CP} @ LE

$$f(U)$$

\mathcal{CP} @ HE

$$\varepsilon_{CP} \sim \sum_{j \neq i} \mathcal{Im} [\lambda^\dagger \lambda] \neq f(U)$$

✗

$\Rightarrow \nexists$ direct link between \mathcal{CP} [Branco et al. 2001, Rebelo 2002, Davidson et al. 2007]

If not testable, could leptogenesis at least be *falsified* ?

LEPTOGENESIS IN GAUGE FRAMEWORK

Proposition:

The observation of W_R @ LHC would disprove Leptogenesis

Why a W_R ?

1. Majorana neutrinos are *naturally* present in Grand Unified Theories:

$$SO(10) \rightarrow \dots$$

$$\rightarrow SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_Y$$

Left-Right Sym. Model

$$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

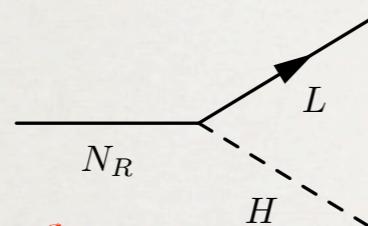
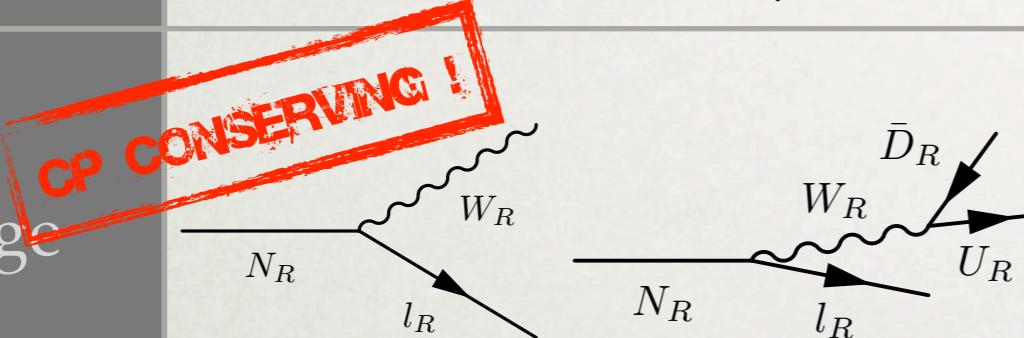
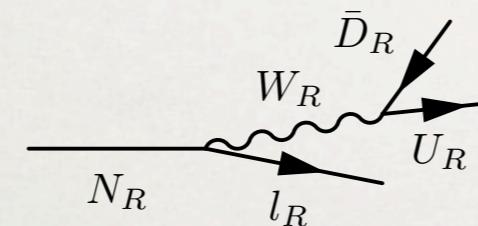
New gauge fields : W_R

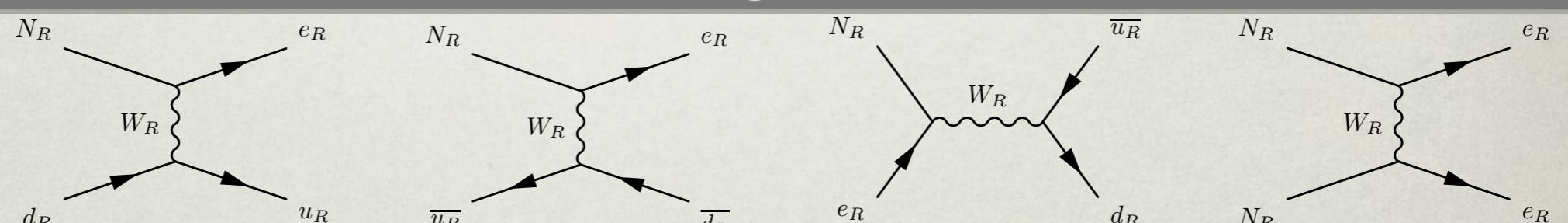
$$\mathcal{L} \ni \frac{g}{\sqrt{2}} W_R^\mu (\bar{u}_R \gamma_\mu d_R + \bar{N} \gamma_\mu l_R)$$

2. LHC arrival !

2. Tevatron fixed $m(W_R) > 800$ GeV [CDF Collaboration, note 8747 (2007)]
3. LHC will probe $m(W_R) < 3-4$ TeV [CERN-LHCC-2006-021]

EFFECTS OF A LOW SCALE W_R

Decays	Diagrams	CP Violation	Efficiency
Yukawa		$\varepsilon_{CP}^{(0)} \equiv \frac{\Gamma_{N \rightarrow LH} - \bar{\Gamma}_{N \rightarrow \bar{L}H^*}}{\Gamma_{tot}^{(l)}}$ "Average ΔL produced per decay"	$\eta \leq 1$
Gauge	 	$\begin{aligned} \varepsilon_{CP} &= \frac{\Gamma - \bar{\Gamma}}{\Gamma_{tot}^{(l)} + \Gamma_{tot}^{(W_R)}} \\ &= \frac{\Gamma - \bar{\Gamma}}{\Gamma_{tot}^{(l)}} \frac{\Gamma_{tot}^{(l)}}{\Gamma_{tot}^{(l)} + \Gamma_{tot}^{(W_R)}} \end{aligned}$ <div style="border: 1px solid orange; padding: 5px; display: inline-block;"> Dilution! </div>	$\eta \leq \frac{\Gamma_{tot}^{(l)}}{\Gamma_{tot}^{(l)} + \Gamma_{tot}^{(W_R)}}$ <p style="text-align: center;">↑</p>

Scatterings	Diagrams
Gauge	

Strong Thermalization

- ⇒ Easier to produce neutrinos @ Reheating ✓
- ⇒ Harder decoupling @ Low T° (Washout) ✗

INCLUSION IN BOLTZMANN EQUATIONS

Boltzmann Input Parameters:

1. $m(N)$ \Rightarrow Yukawa interactions $\gamma_N^{(l)}$
2. $m(W_R)$
3. λ \Rightarrow Gauge interactions $\gamma_N^{(W_R)}, \gamma_{Nu,d,e}, \gamma_{NN}$

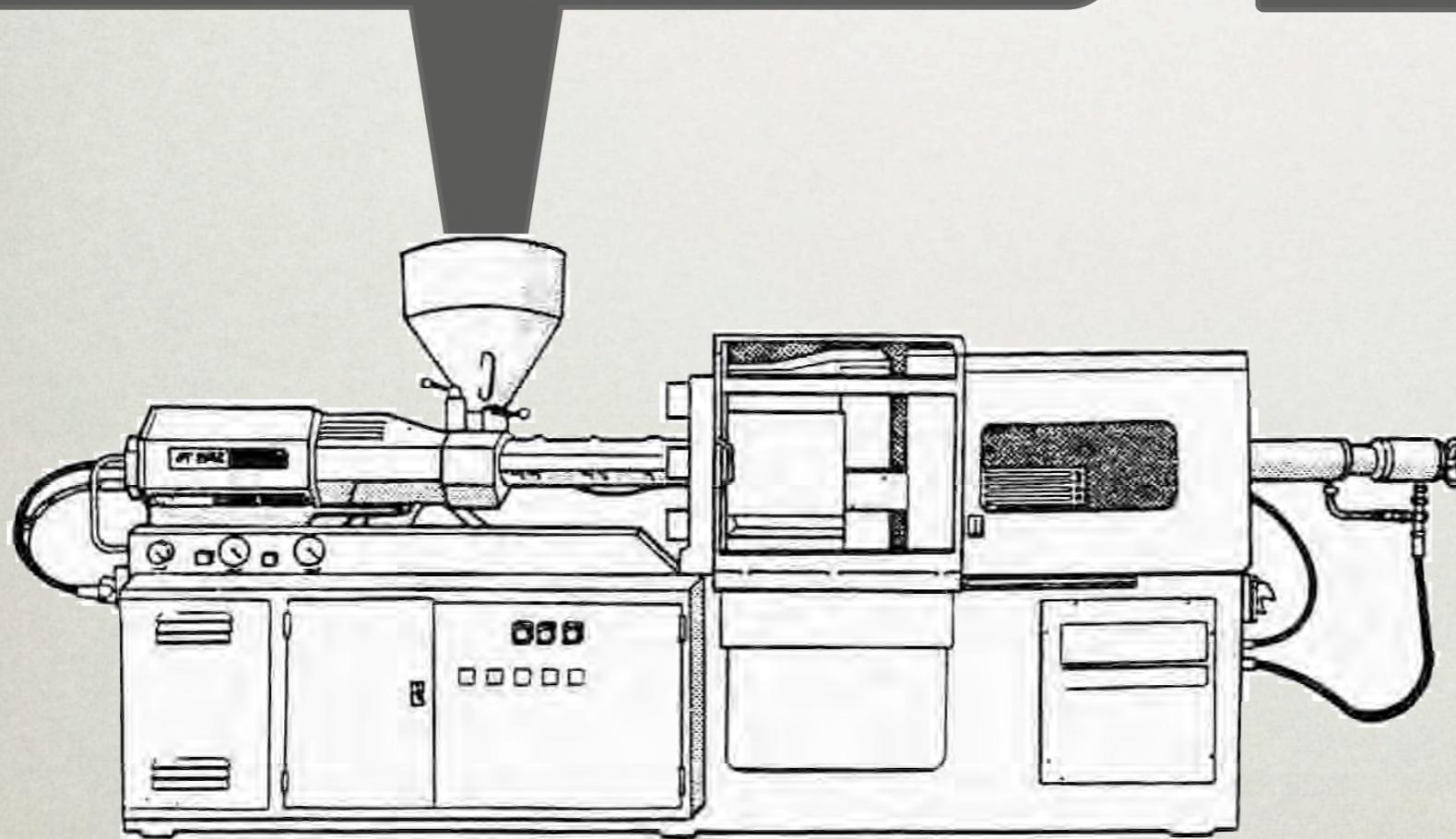


Degenerate N_i [Pilaftsis, 2002]

$$\varepsilon_{CP} \leq 1$$

Hierarchical N_R [Davidson-Ibarra, 2002]

$$\varepsilon_{CP} \leq (3/16\pi)(m_N/v^2)\sqrt{\Delta m_{atm}^2}$$

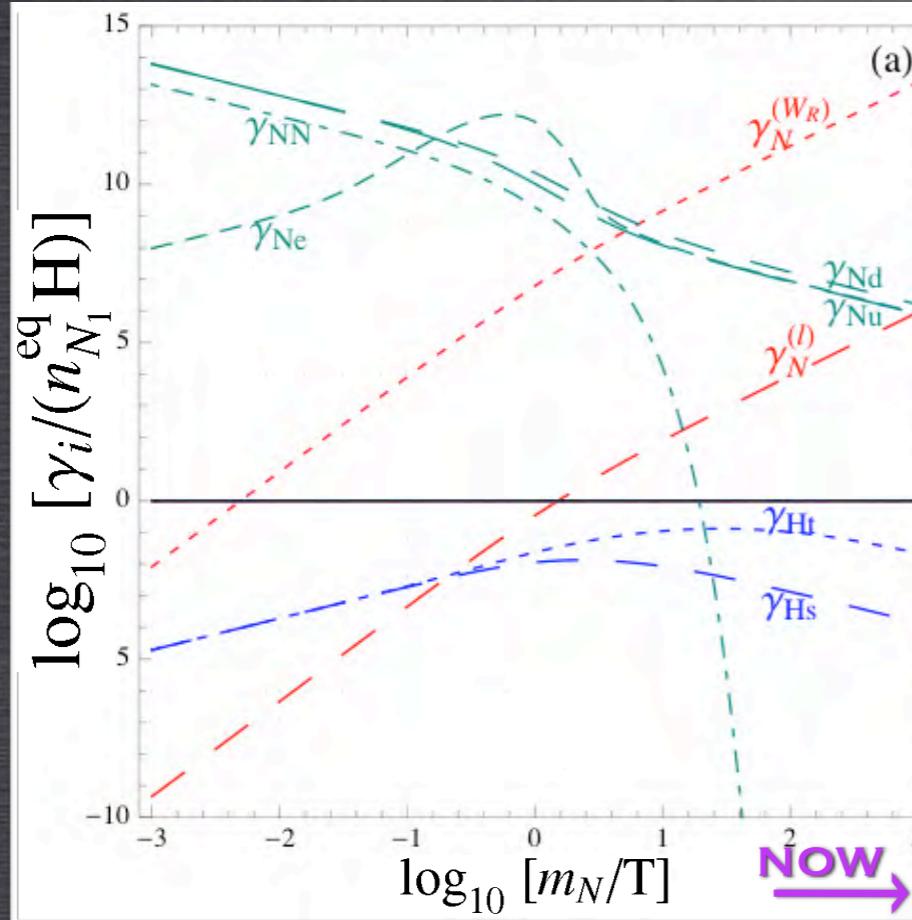


$\Rightarrow dY_L/dT^\circ$
 $\Rightarrow dY_N/dT^\circ$



EFFICIENCY η

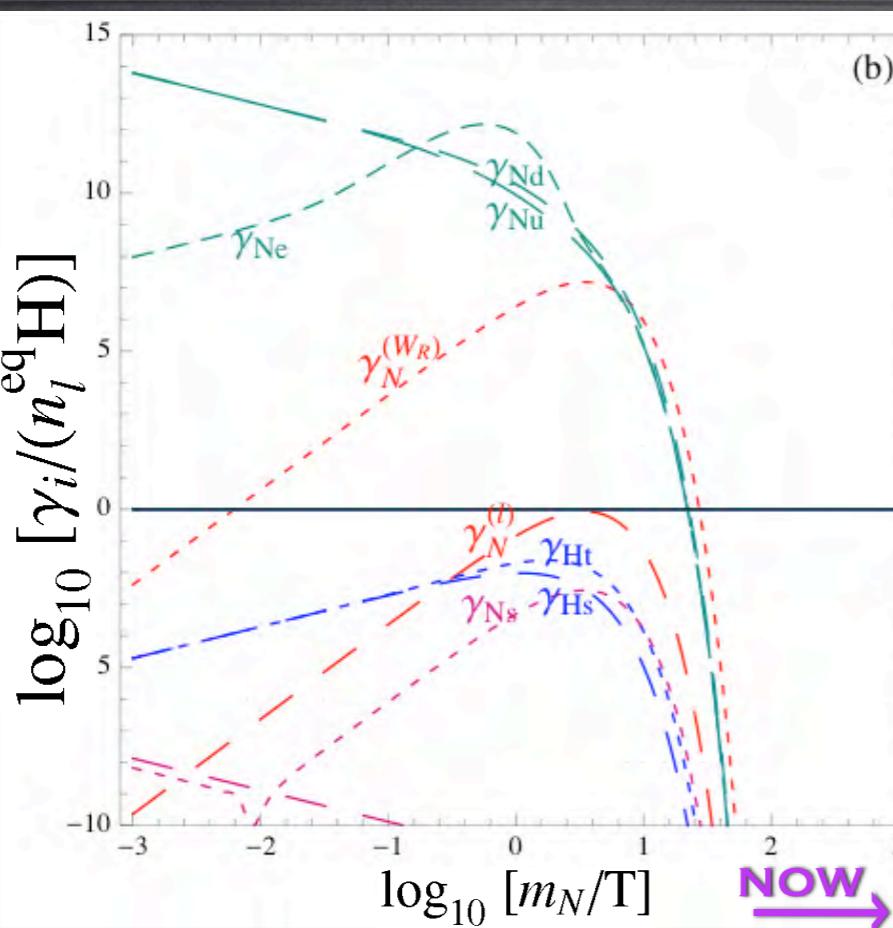
INTERACTION RATES



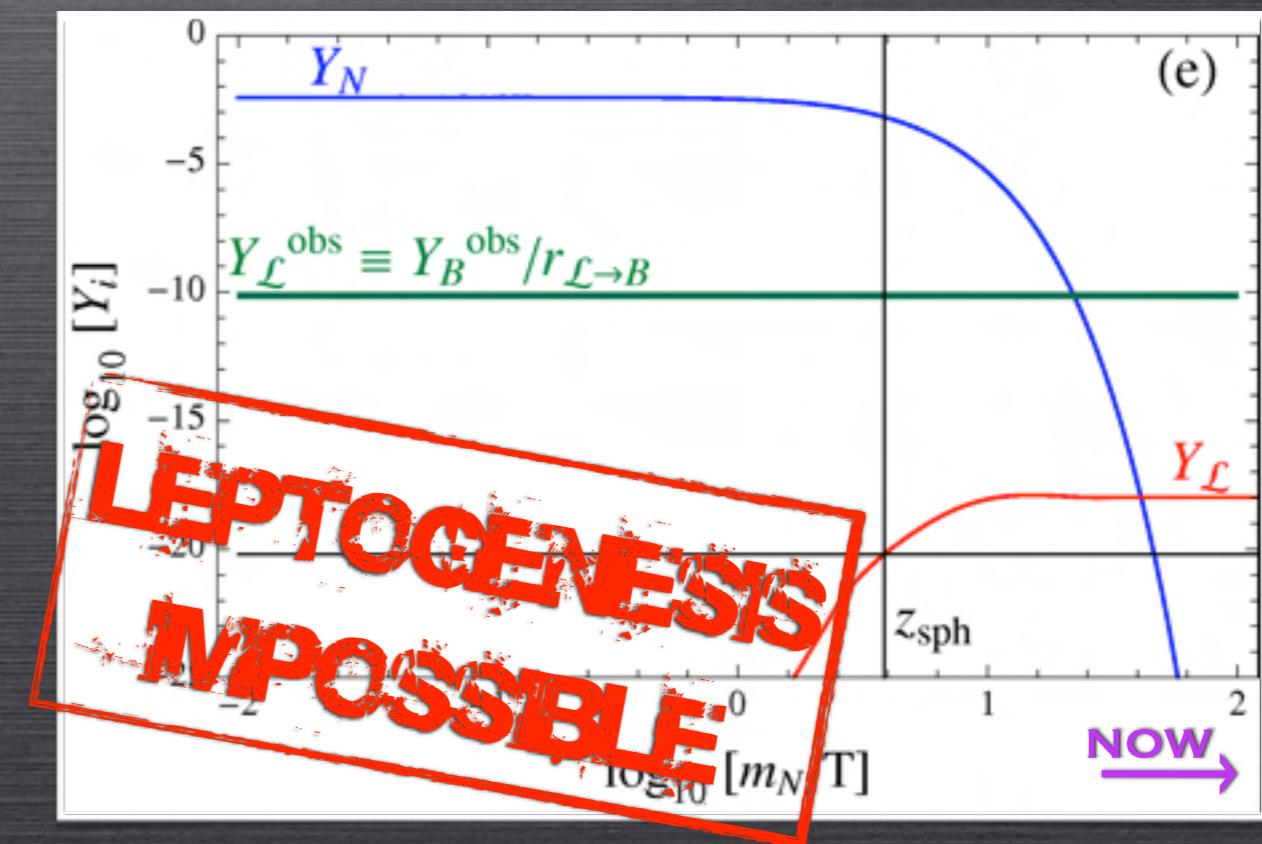
EXAMPLE OF GAUGE EFFECTS

$$m(N) = 500 \text{ GeV} \quad m(W_R) = 3 \text{ TeV} \quad \lambda = 10^{-3}$$

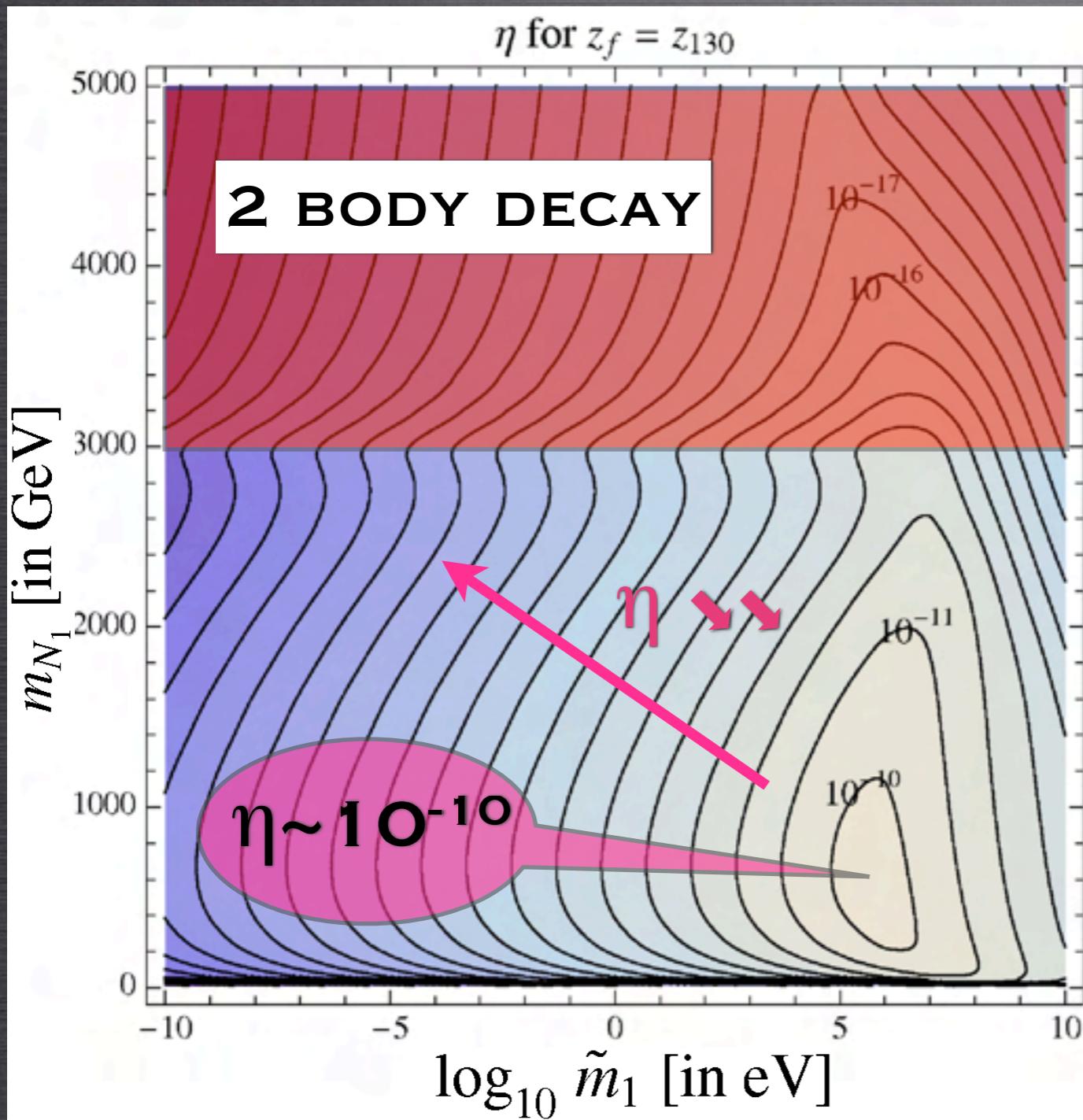
Case	Content	η	Y_B
(a)	Standard Leptogenesis	0, 5	6. 10 ⁻⁴
(b)	(a)+ W_R decays in Y_N	3. 10 ⁻⁸	4. 10 ⁻¹¹
(c)	(b)+ W_R scatterings in Y_N	2. 10 ⁻¹⁰	2. 10 ⁻¹³
(d)	(c)+ W_R scatterings in Y_L	2. 10 ⁻¹⁸	2. 10 ⁻²¹
(e)	(d)+ W_R decays in Y_L	2. 10 ⁻¹⁸	2. 10 ⁻²¹



ASYMMETRY EVOLUTION



EFFICIENCY RESULTS



$M(W_R) = 3 \text{ TeV}$

$$\tilde{m}_1 = \frac{\lambda^\dagger \lambda v^2}{M_1}$$

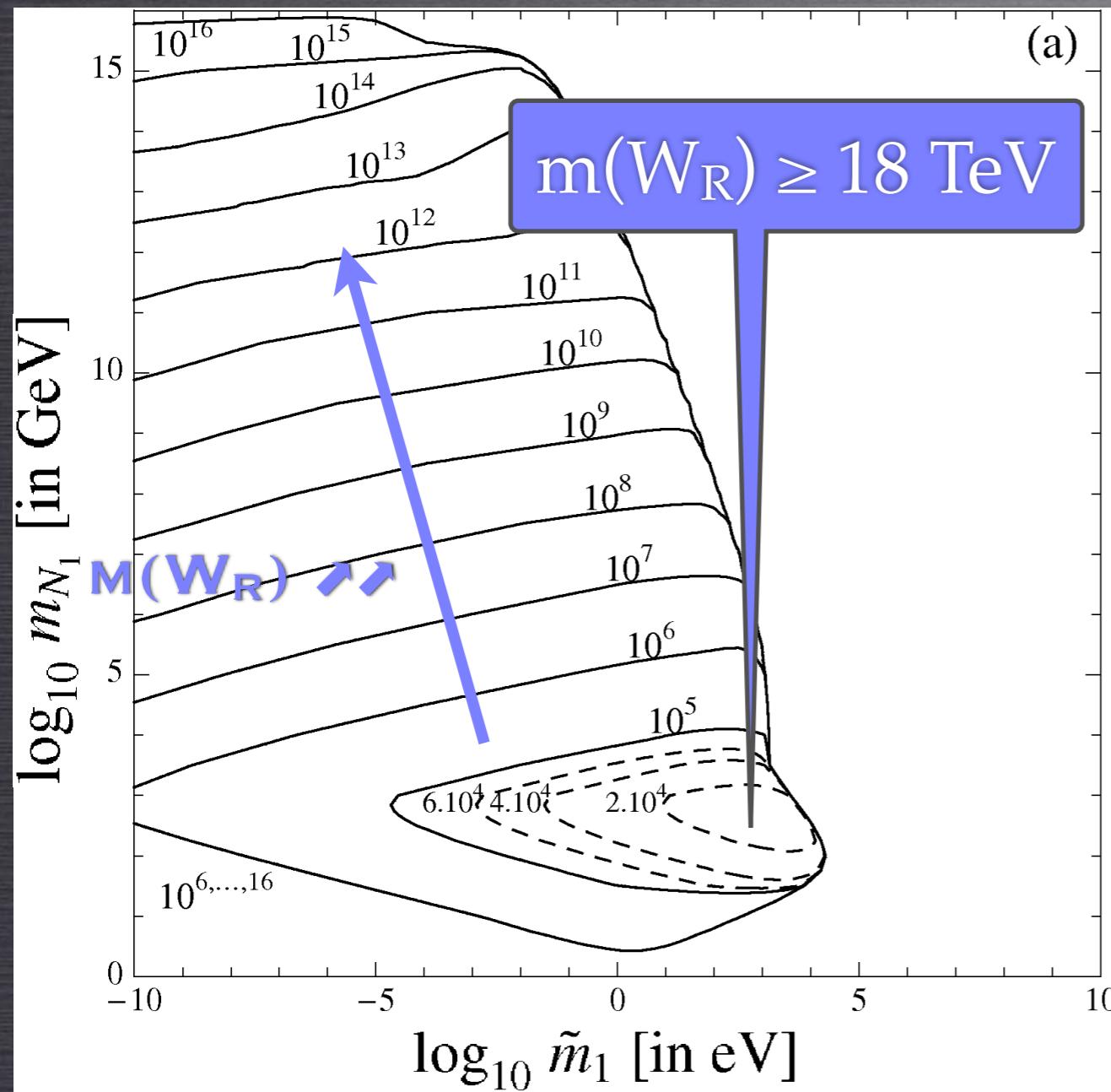
IN ANY CASE :

$$\eta < \eta_{\text{MIN}} = 7.10^{-8}$$

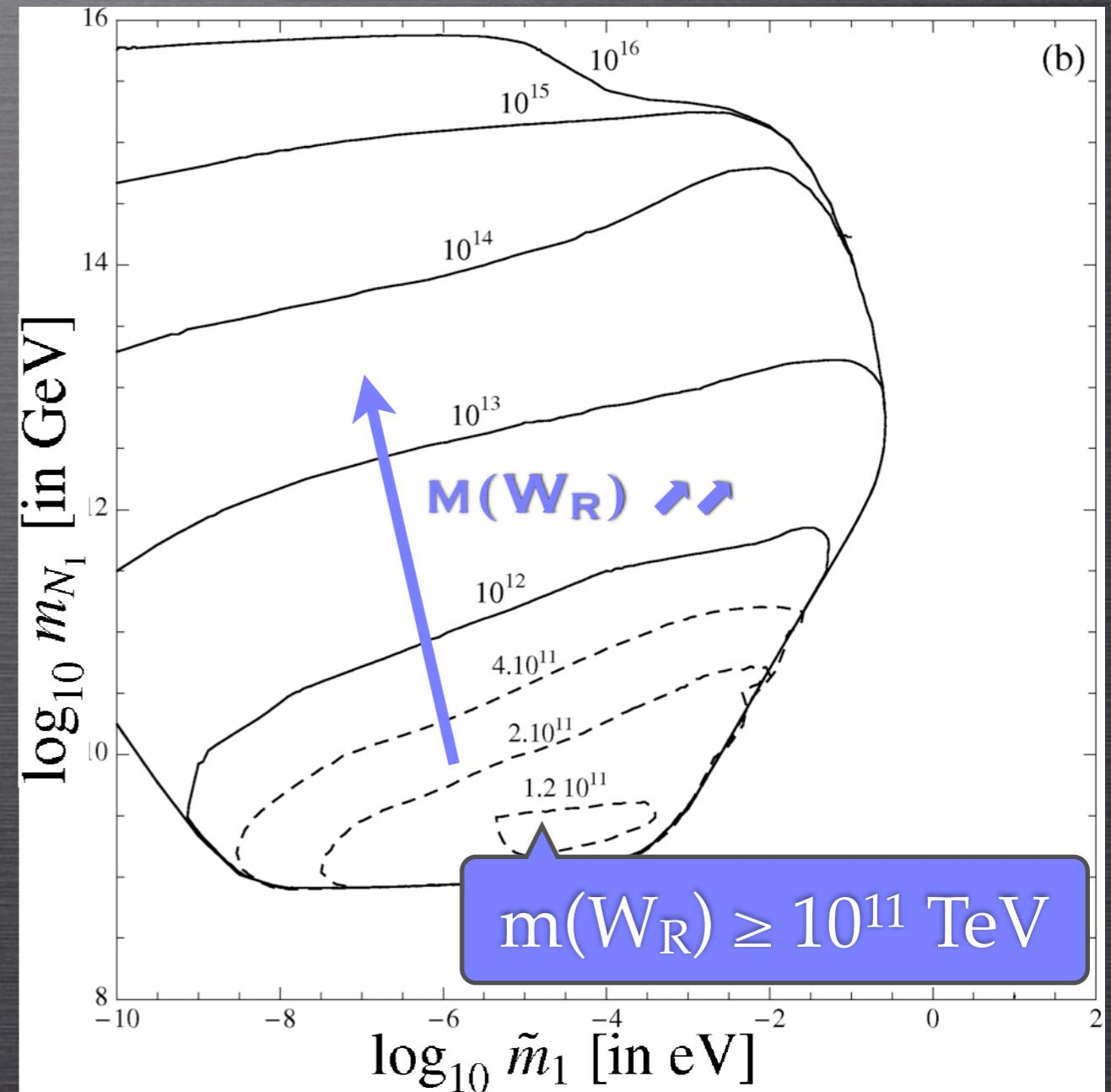
Type I Leptogenesis
Disproved if W_R
Discovered @ LHC

BOUNDS ON $M(W_R)$ & $M(N_R)$

FOR $\epsilon_{CP} = 1$



FOR $\epsilon_{CP} = |\epsilon_D|$



SUMMARY

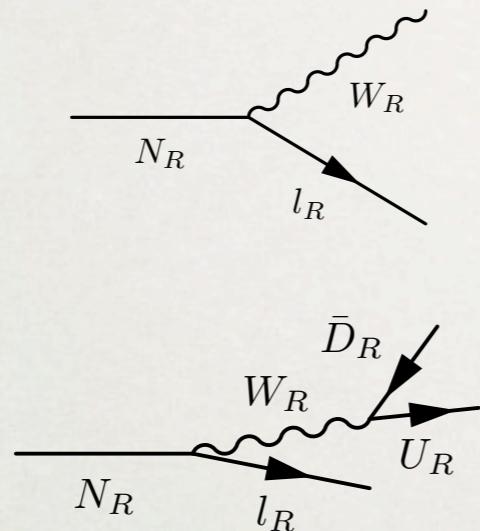
- ♦ We consider Type I Leptogenesis in its *natural* gauge framework
- ♦ Strong Gauge Dilution & Scatterings do play an important role in the lepton asymmetry creation
- ♦ Type I Leptogenesis
 - could be disproved if W_R observed @ LHC
 - could work if $m(W_R) > 18 \text{ TeV}$

BACKUP

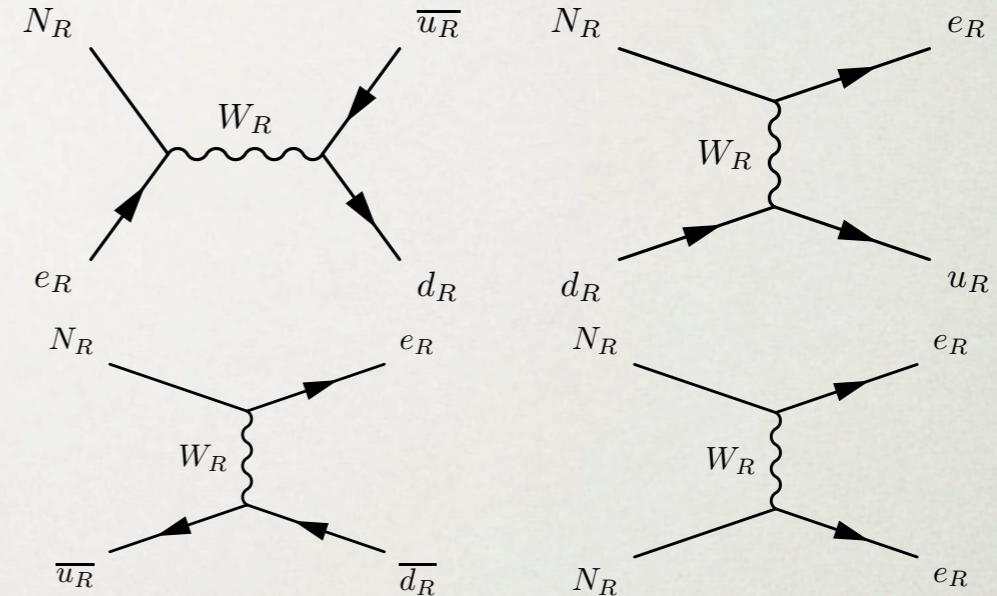
BOLTZMANN EQUATIONS

New Effects:

W_R Decays



W_R Scatterings



$$\begin{aligned}
 zH(z)sY' &= -\left(\frac{Y}{Y^{\text{eq}}} - 1\right) \left(\gamma^{(\text{g})} + \gamma^{(\square_R)} + 2\gamma_{\text{A}} + 4\gamma_{\text{AA}} + 2\gamma_{\text{A}\bar{A}} + 2\gamma_{\text{B}} + 2\gamma_{\text{B}\bar{A}} \right) \\
 &\quad - \left(\left(\frac{Y}{Y^{\text{AA}}} \right)^2 - 1 \right) \gamma \\
 zH(z)sY'_L &= \gamma^{(\text{g})} \varepsilon \left(\frac{Y}{Y^{\text{eq}}} - 1 \right) - \left(\gamma^{(\text{g})} + \gamma^{(\square_R)} \right) \frac{Y_L}{2Y^{\text{eq}}} \\
 &\quad - \frac{Y_L}{Y^{\text{eq}}} \left(2\gamma_{\text{A}}^{\text{sub}} + 2\gamma_{\text{B}} + 2\gamma_{\text{AA}} + 2\gamma_{\text{A}\bar{A}} + 2\gamma_{\text{B}\bar{A}} + \gamma_{\text{A}\bar{A}} + \gamma_{\text{B}} + \gamma_{\text{B}\bar{A}} \right)
 \end{aligned}$$

INTERACTION RATES EVOLUTION

$$\gamma(ab \leftrightarrow 12)(T) \sim \iint d\bar{p}_a d\bar{p}_b f_a^{eq} f_b^{eq} |\mathcal{M}|^2 \leftrightarrow \mathcal{H}(T) \leftrightarrow n_i^{eq}(T)$$

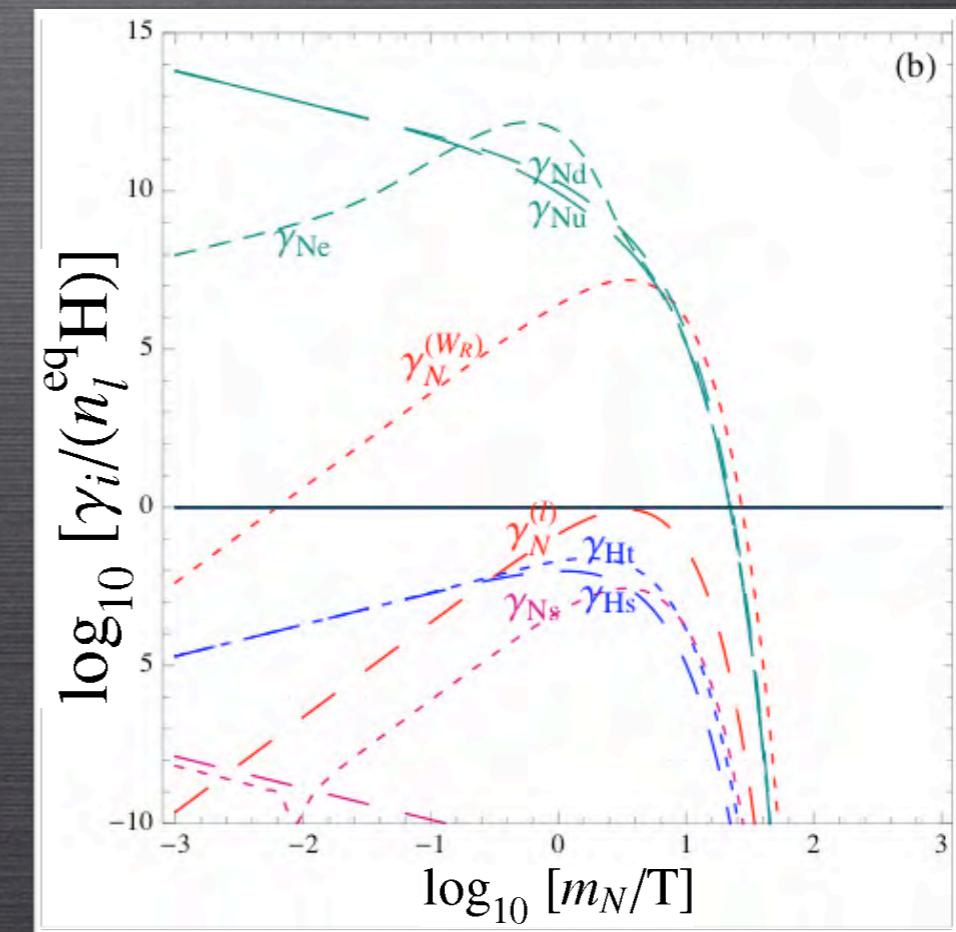
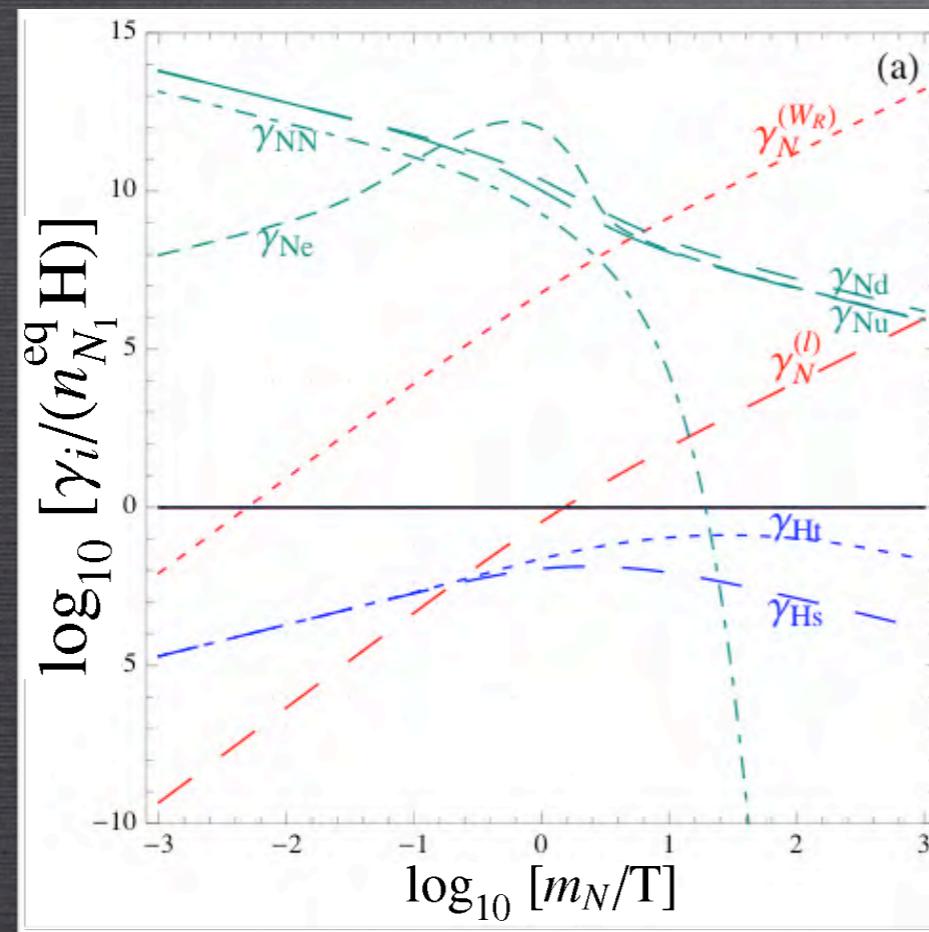
$\frac{\gamma_i}{\mathcal{H} n_i^{eq}}(T)$

at $T \ll m_N$

$$f_N^{eq} \sim e^{-m_N/T}$$

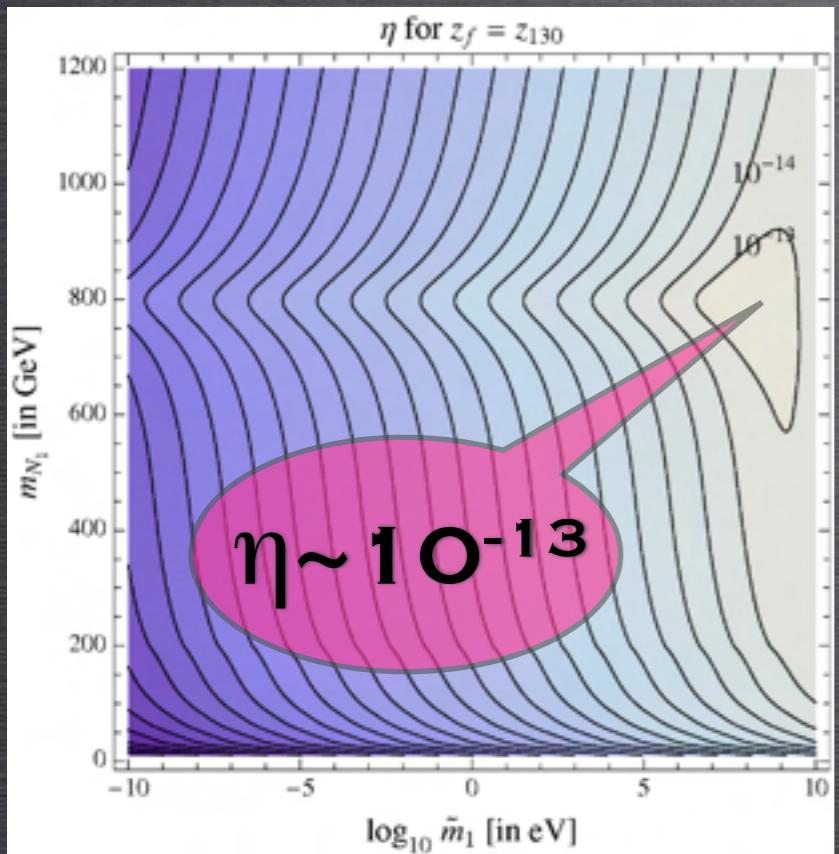
$$n_N^{eq} \sim e^{-m_N/T}$$

$$\frac{\gamma_{Ne,u,d}}{\mathcal{H} n_N^{eq}}(T) \quad \text{NOT Boltzmann suppressed !}$$

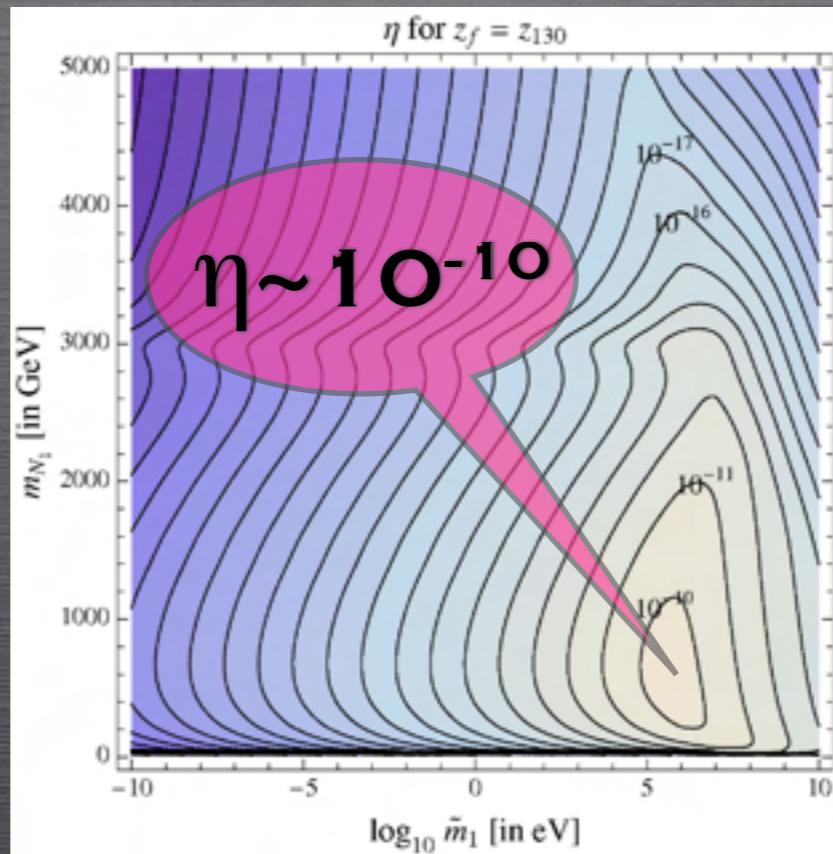


EFFICIENCY RESULTS (FOR DIFFERENT W_R MASSES)

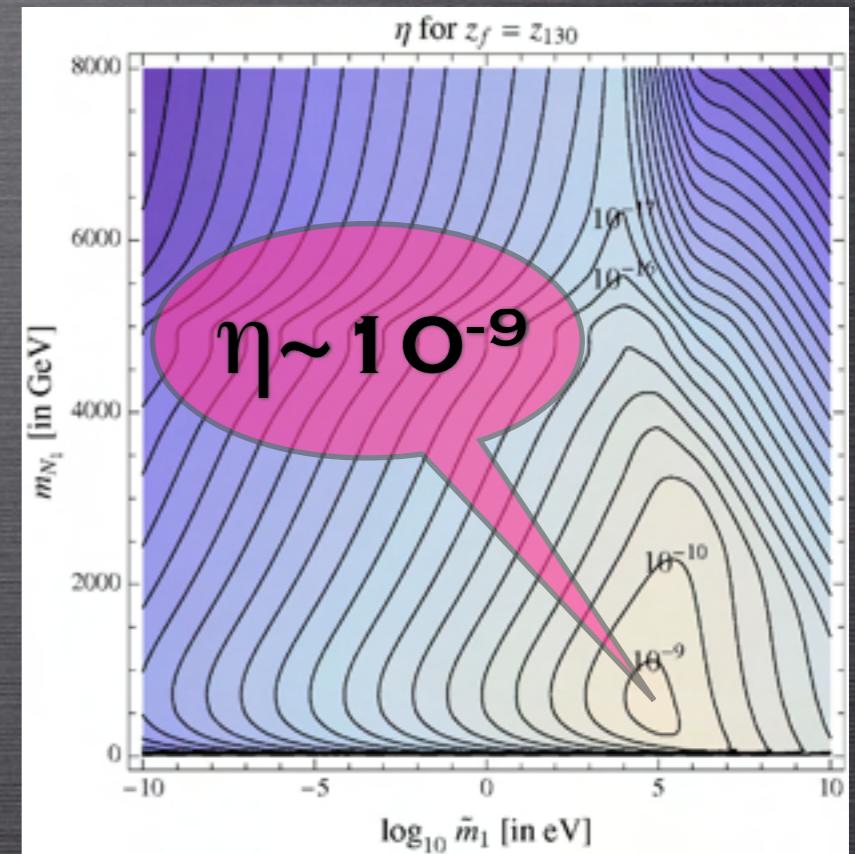
$M(W_R) = 0.8 \text{ TeV}$



$M(W_R) = 3 \text{ TeV}$



$M(W_R) = 5 \text{ TeV}$

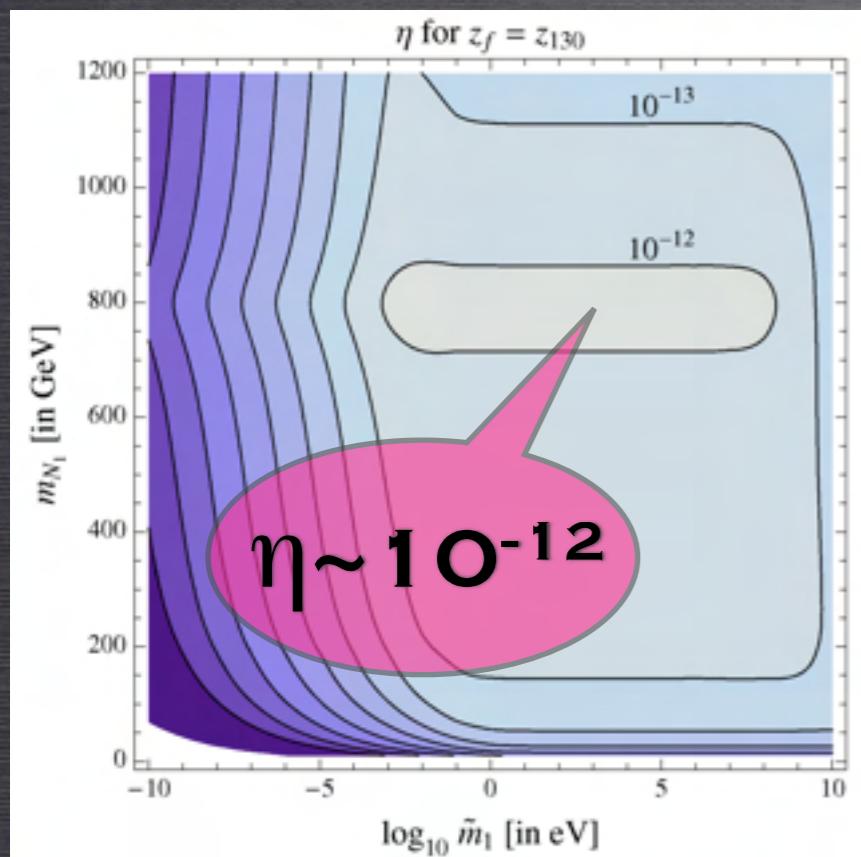


IN ANY CASE : $\eta < \eta_{\text{MIN}} = 7.10^{-8}$

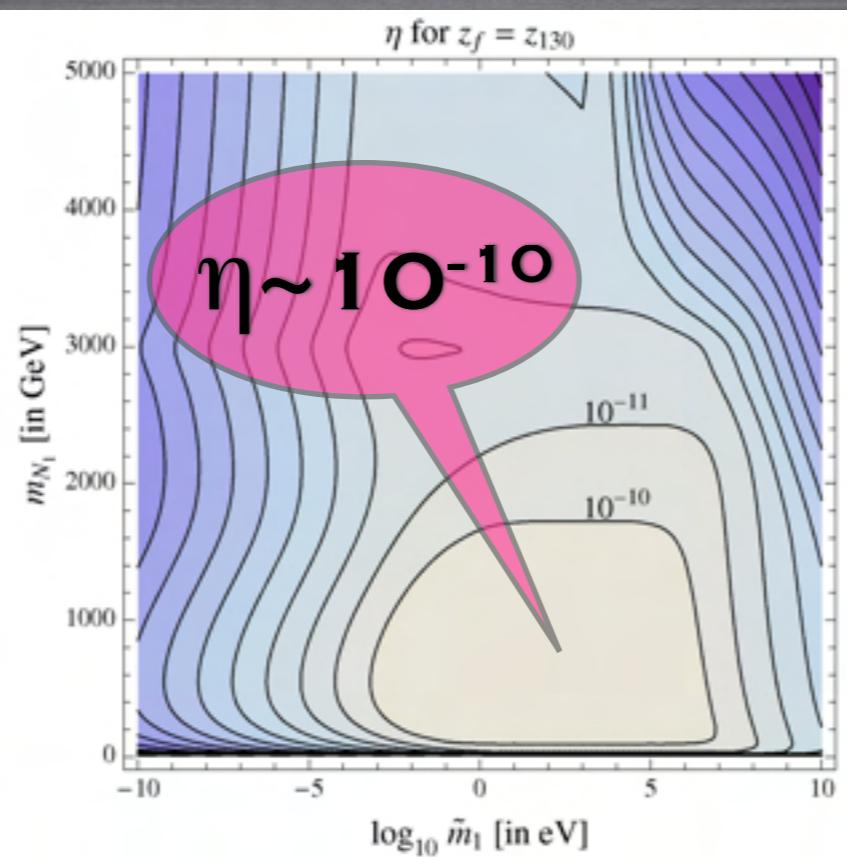
⇒ TYPE I LEPTOGENESIS DOES NOT WORK

EFFICIENCY RESULTS (FOR W_R EFFECTS IN Y_N ONLY)

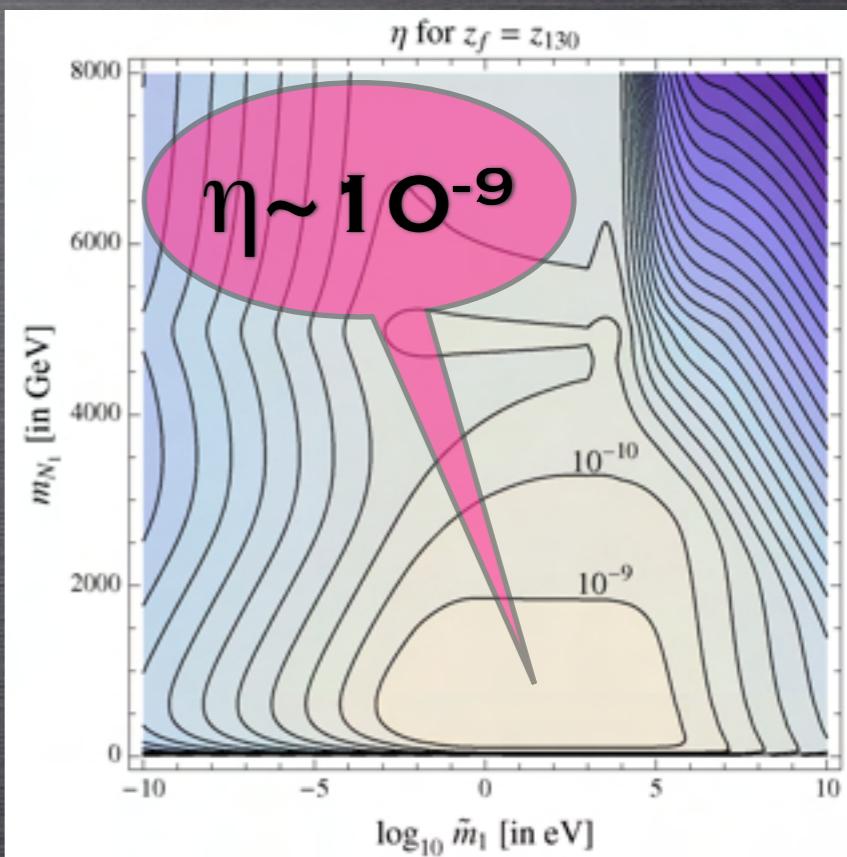
$M(W_R) = 0.8 \text{ TeV}$



$M(W_R) = 3 \text{ TeV}$



$M(W_R) = 5 \text{ TeV}$

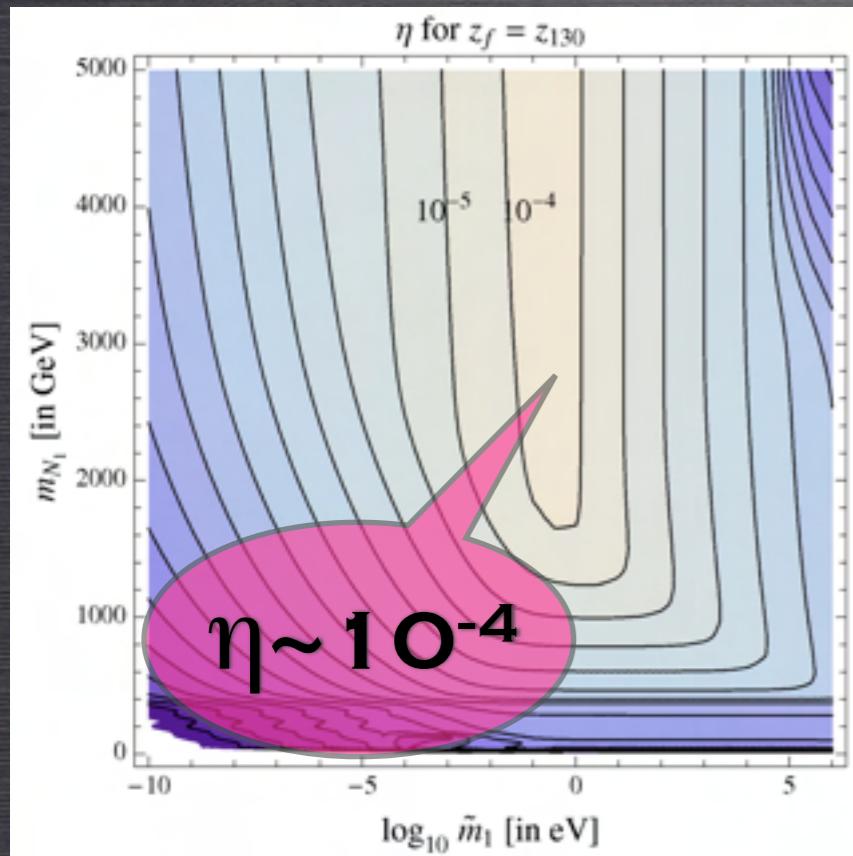


IN ANY CASE : $\eta < \eta_{\text{MIN}} = 7.10^{-8}$

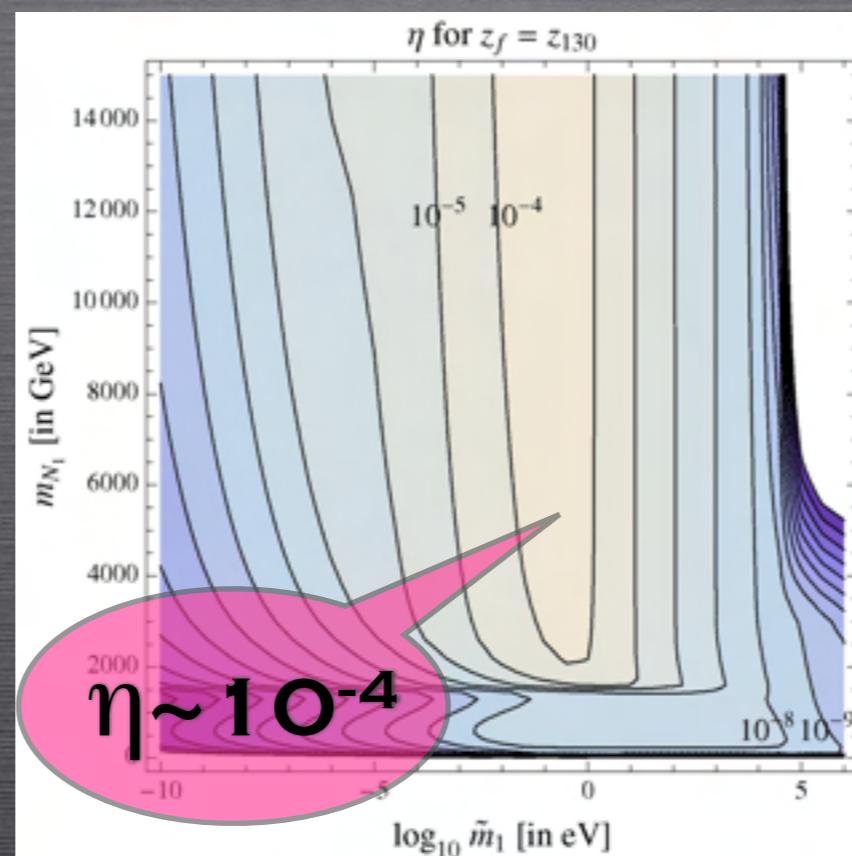
⇒ TYPE I LEPTOGENESIS STILL DOES NOT WORK

EFFICIENCY RESULTS (FOR Z' EFFECTS ONLY)

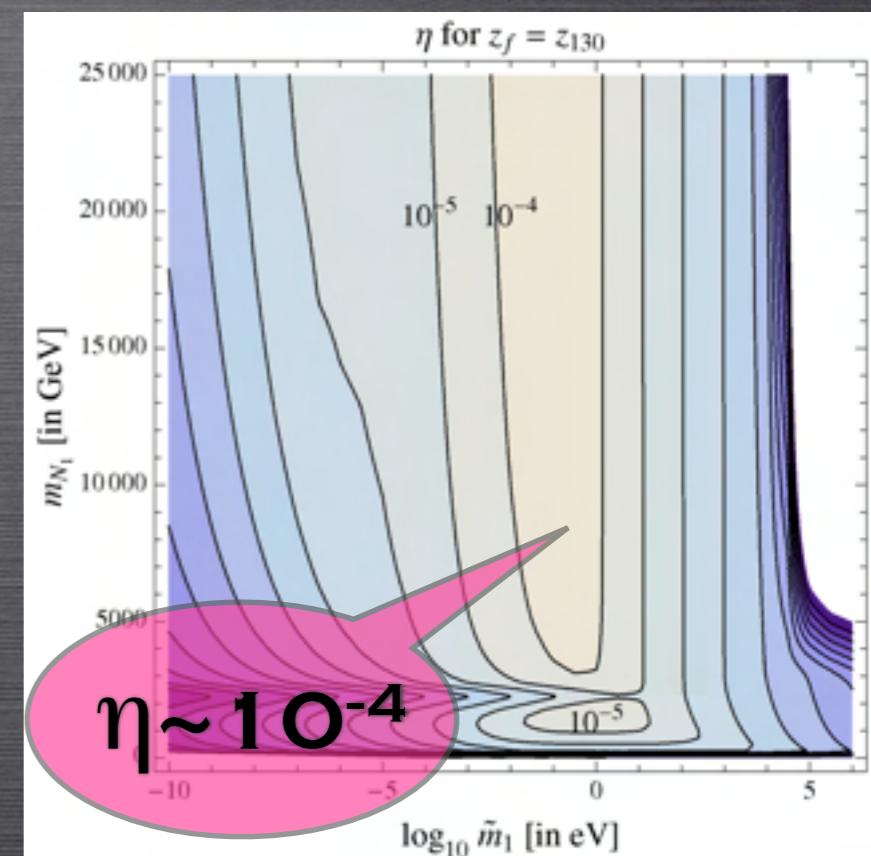
$M(Z') = 0.8 \text{ TeV}$



$M(Z') = 3 \text{ TeV}$



$M(Z') = 5 \text{ TeV}$

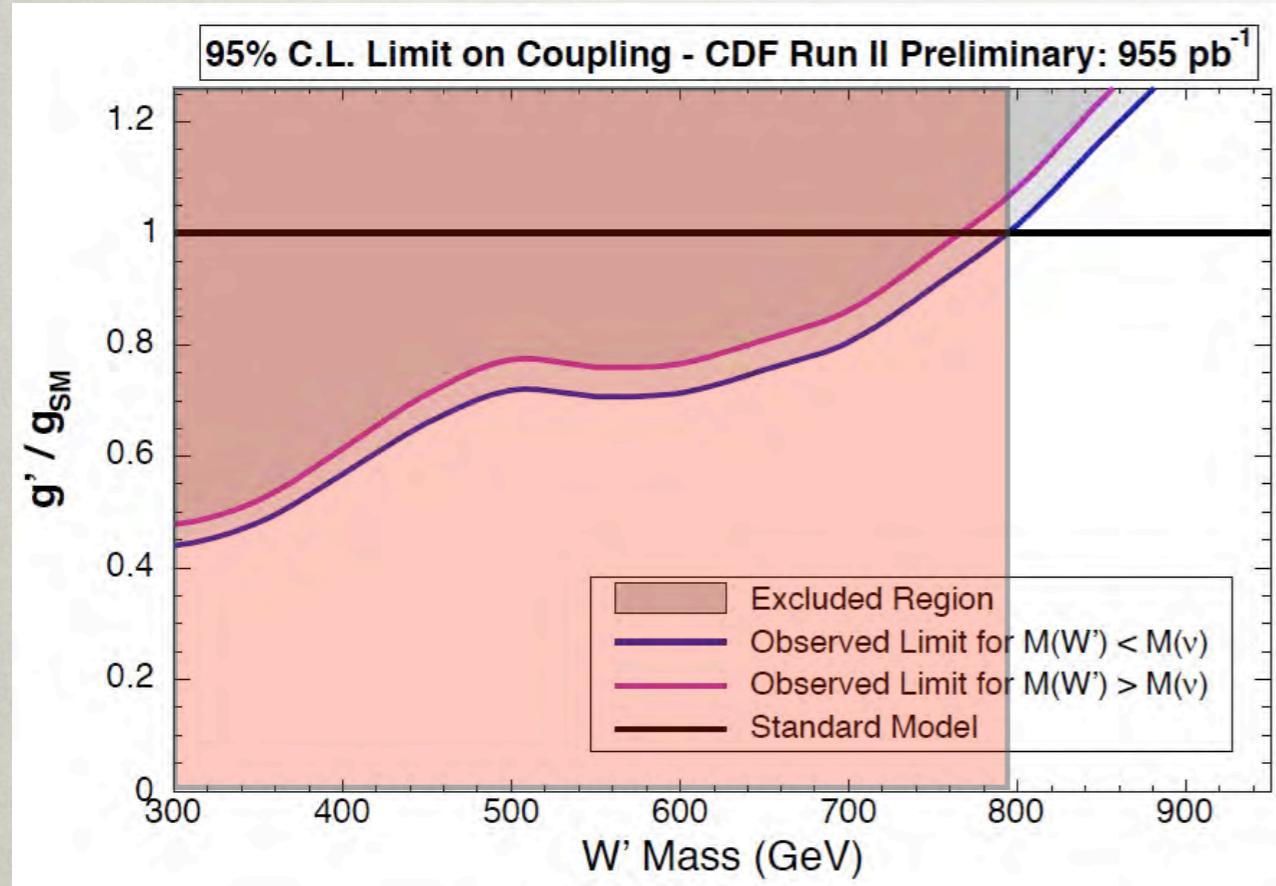


IN THIS CASE : η COULD BE $> \eta_{\text{MIN}} = 7.10^{-8}$

\Rightarrow TYPE I LEPTOGENESIS COULD WORK

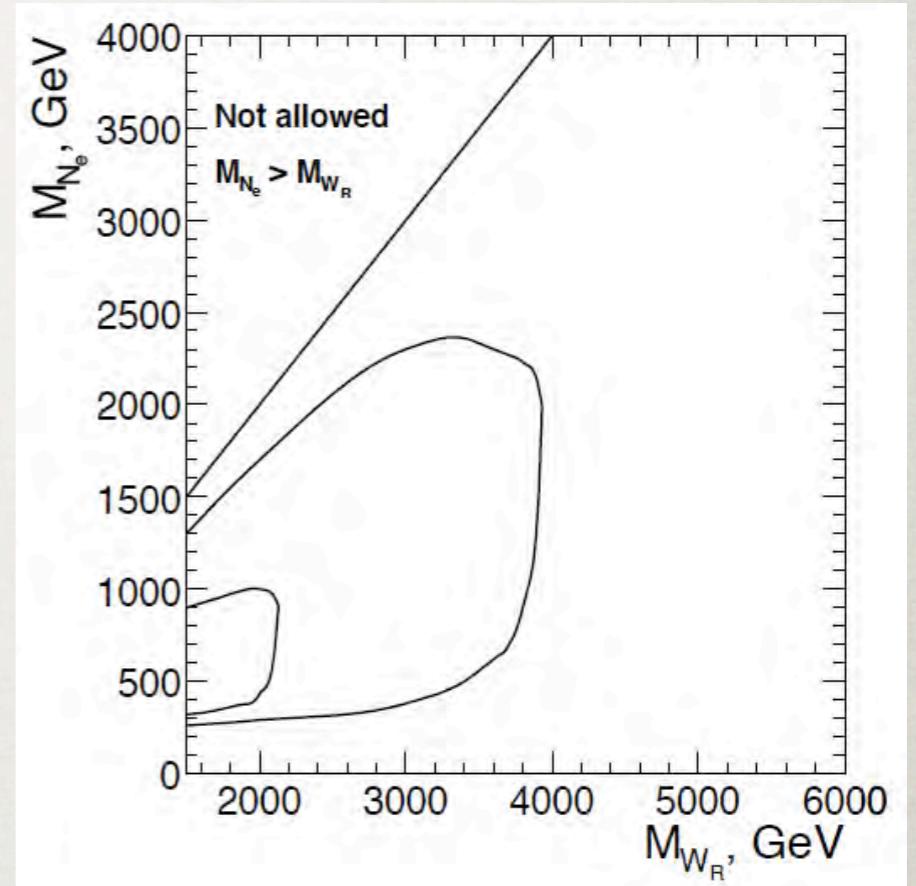
W_R @ COLLIDERS

Current Bounds



[CDF Collaboration, note 8747 (2007)]

LHC Expectations



[CERN-LHCC-2006-021]

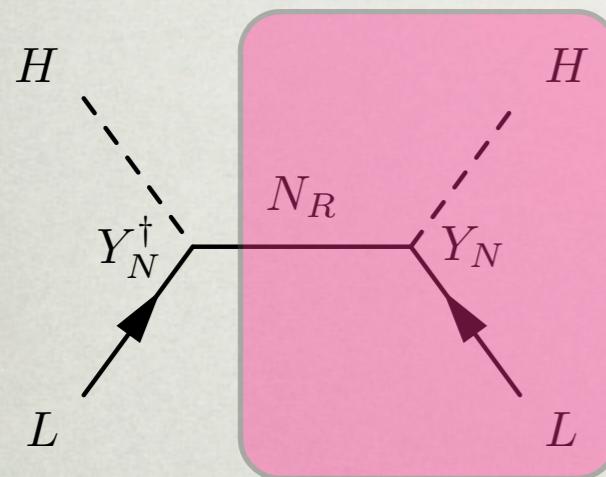
[CMS-TDR-008-2]

if $m(N) < m(W_R)$: $pp \rightarrow X + W_R \rightarrow X + l^- + N$ (N on-shell) $\rightarrow X + l^- + l^{(+,-)} + u + d$ [resonance @ $m(N)$]

if $m(N) > m(W_R)$: $pp \rightarrow X + W_R \rightarrow X + l^- + N$ (N off-shell) $\rightarrow X + l^- + l^{(+,-)} + u + d$ [resonance @ $m(W_R)$]

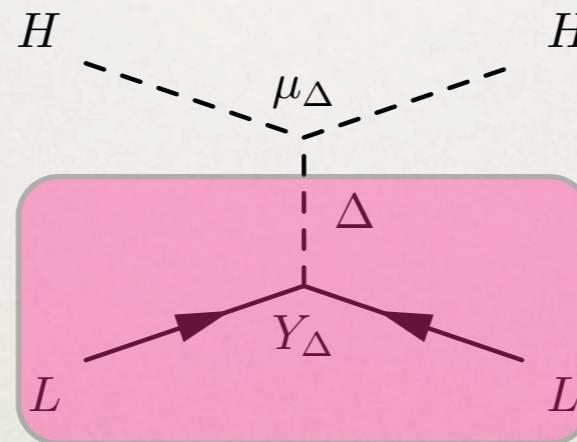
THE 3 SEESAW MODELS

Right-handed singlet:
(Type I)



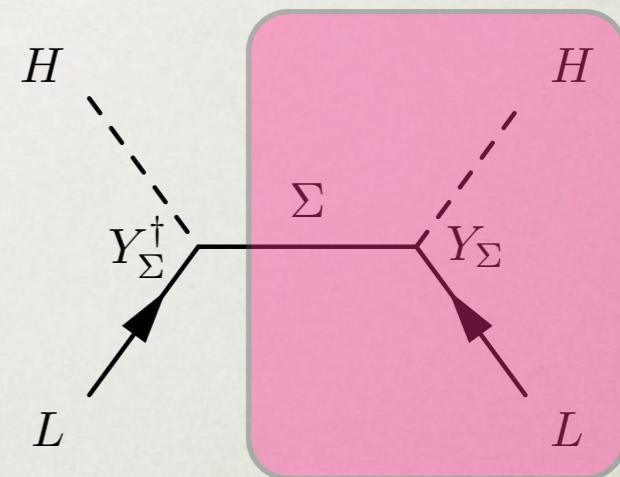
$$m_\nu = v^2 Y_N^T \frac{1}{M_N} Y_N$$

Scalar Triplet:
(Type II)



$$m_\nu = v^2 Y_\Delta \frac{1}{M_\Delta^2} \mu_\Delta$$

Fermion Triplet:
(Type III)



$$m_\nu = v^2 Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$