

The Antimatter Mystery: From leptogenesis to electroweak baryogenesis

The Cosmic Enigma
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Thanks to my collaborators

On leptogenesis:

Sacha Davidson, Guy Engelhard, Yuval Grossman, Tamar Kashti,
Enrico Nardi, Juan Racker, Esteban Roulet

On EW baryogenesis:

Micha Berkooz, Nicolas Bernal, Kfir Blum, Cedric Delaunay,
Marta Losada, Sean Tulin, Tomer Volansky

Plan of Talk

1. Baryogenesis
2. Leptogenesis:
 - Basics
 - Implications
 - The future
3. Electroweak baryogenesis:
 - Basics
 - Implications
 - The future

Baryogenesis

Sakharov, 1967

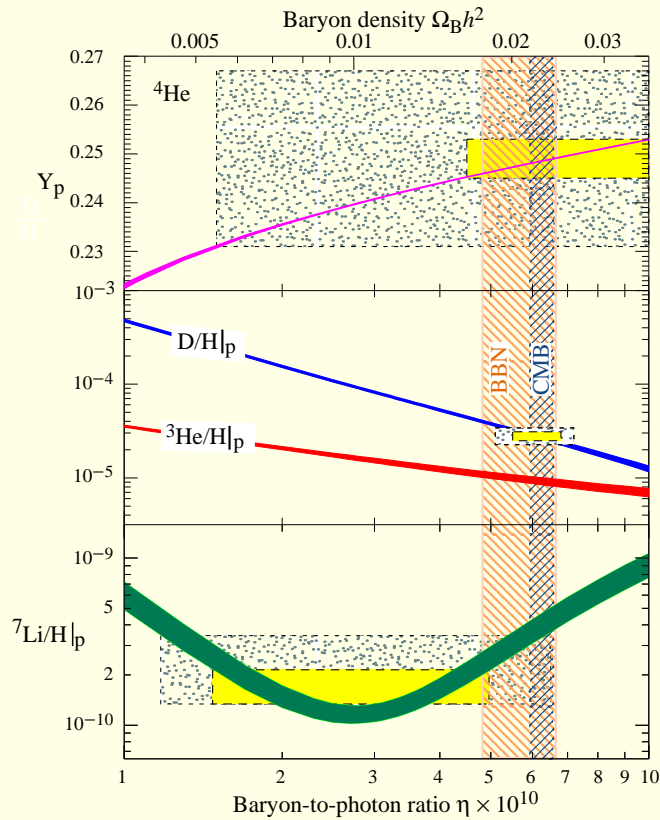
The Baryon Asymmetry

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

- b = protons and neutrons
- \bar{b} = antiprotons and antineutrons
- s = entropy density $\approx n_\gamma/7$

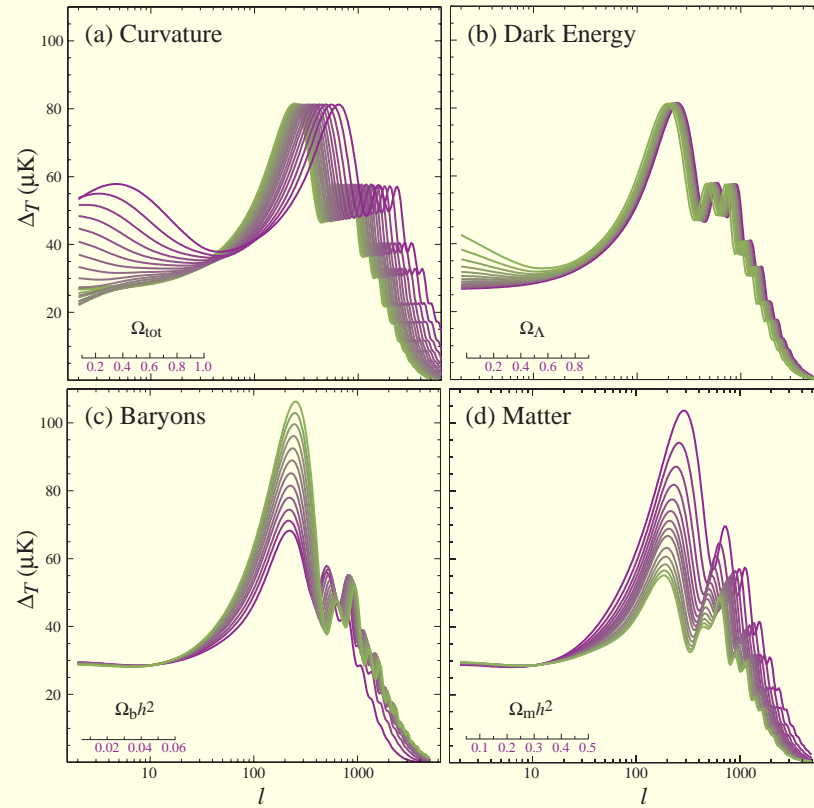
- $n_b/s \sim 10^{-10}$
- $n_{\bar{b}}/s \approx 0$

BBN + CMBR



Nucleosynthesis

$$\eta_{10} = 5.6 \pm 0.9$$



CMBR

$$\eta_{10} = 6.11 \pm 0.19$$

Initial Conditions?

- Fine tuning:

For every 6,000,000 antiquarks – 6,000,001 quarks

- Inflation:

Any initial asymmetry would be erased

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The baryon asymmetry was dynamically generated

BARYOGENESIS

Sakharov Conditions

The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

1. Baryon number is violated;
2. C and CP are violated;
3. Departure from thermal equilibrium.

SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by δ_{KM} ;
3. Departure from thermal equilibrium at the EWPT.

SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by δ_{KM} ;
3. Departure from thermal equilibrium at the EWPT.

The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT;
2. KM CP violation is too suppressed.

Alternative Scenarios

Should have:

- New sources of CP violation
- Either a new departure from TE and $B - L$ violation
- Or a modification of the EWPT

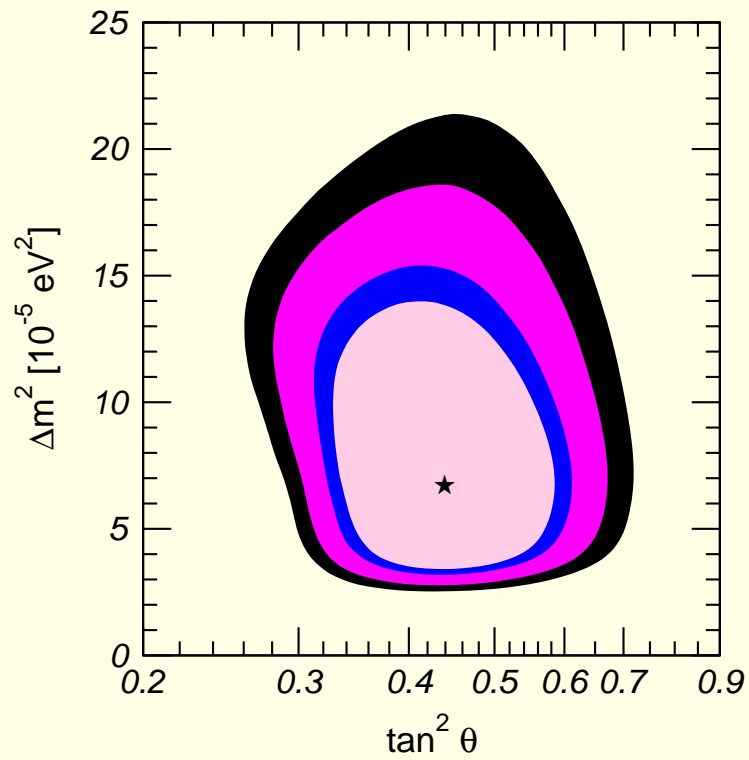
The most attractive scenarios:

- Leptogenesis
- Supersymmetric baryogenesis

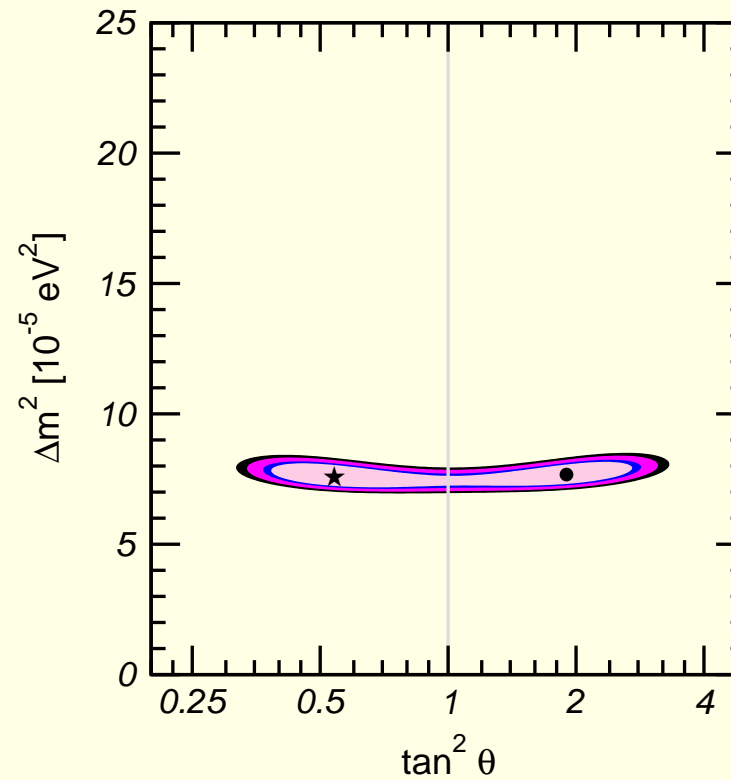
Leptogenesis

Fukugita and Yanagida, 1986

Solar + Kamland



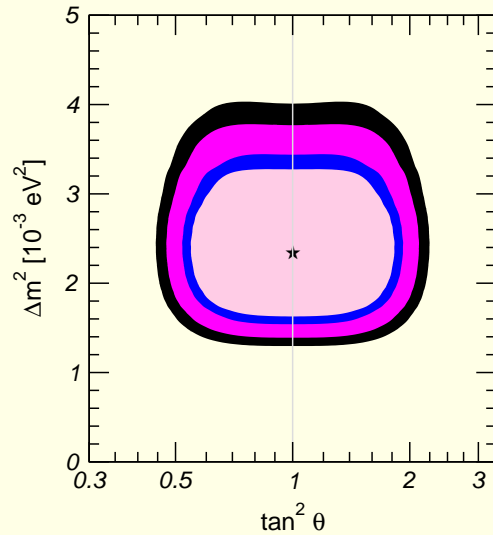
Solar



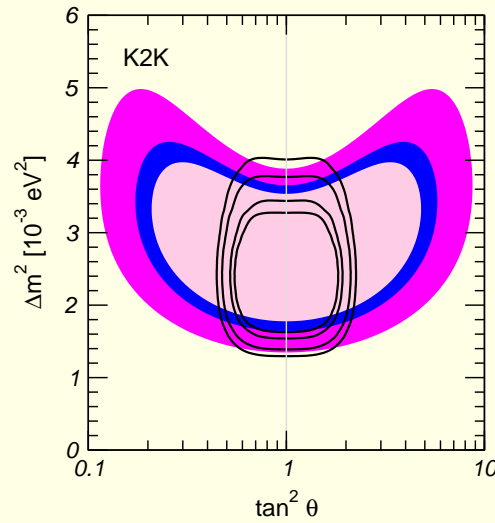
Kamland

$$\Delta m_{21}^2 = (7.9 \pm 0.3) \times 10^{-5} \text{ eV}^2, \quad \sin^2 \theta_{12} = 0.31 \pm 0.02$$

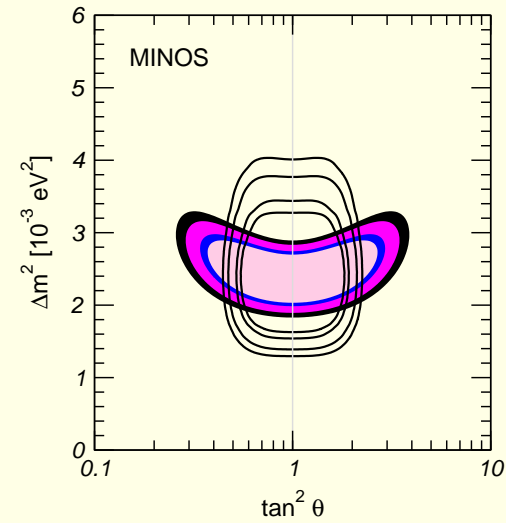
Atmospheric + K2K + Minos



Atmospheric



K2K



Minos

$$|\Delta m_{32}^2| = (2.6 \pm 0.2) \times 10^{-3} \text{ eV}^2, \quad \sin^2 \theta_{23} = 0.47 \pm 0.07$$

The Seesaw Mechanism

- Atmospheric + Solar Neutrinos \implies $m_{\nu_3} \gtrsim 0.05 \text{ eV}$

- In the SM: $m_\nu = 0$

- Add SM singlets N : $\mathcal{L}_N = \lambda N H L + M N N$

- Assume $M \gg \langle H \rangle$

\implies Neutrinos are massive but very light

- “The Seesaw Mechanism:”

$$m_\nu \sim \frac{\lambda^2 \langle H \rangle^2}{M}$$

($\implies M/\lambda^2 \sim 10^{14} \text{ GeV}$)

The Seesaw \Leftrightarrow Leptogenesis Relation

$$\mathcal{L}_N = \lambda N H L + M N N$$

• Implications:

1. Lepton number is violated (M)

2. New sources of CP violation (λ)

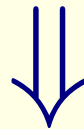
3. If $\Gamma_{N_1} \lesssim H(T = M_{N_1})$ ($\implies \tilde{m}_1 \equiv \frac{(\lambda^\dagger \lambda)_{11} v^2}{M_1} \lesssim 10^{-3} \text{ eV}$)
 $\implies N_1$ decays out of equilibrium

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LEPTOGENESIS

Calculating Y_B

$$Y_B = \left(\frac{135\zeta(3)}{4\pi^4 g_*} \right) \times C_{\text{sphal}} \times \eta \times \epsilon$$

1. $\frac{135\zeta(3)}{4\pi^4 g_*} \sim 0.004$

Equilibrium N_1 number density divided by s at $T \gg M_1$

2. $C_{\text{sphal}} \simeq 28/79$

The “price” for $B + L$ violation

3. $\eta \sim \frac{10^{-3} \text{ eV}}{\tilde{m}_1} \sim \text{few} \times 10^{-2}$

The “price” for departure from thermal equilibrium

4. $\epsilon \simeq -\frac{3}{16\pi} \sum_j \frac{M_1}{M_j} \frac{\text{Im}\{[(\lambda^\dagger \lambda)_{1j}]^2\}}{(\lambda^\dagger \lambda)_{11}}$

The “price” for CP violation

$$Y_B \sim 10^{-5} \epsilon$$

The relevant parameters

Ignoring flavor, the final Y_B depends on four parameters:

- $\epsilon \gtrsim 10^{-5}$
No model-independent bound on low energy phases
- $M_1 \gtrsim 10^9 \text{ GeV}$ ($\implies T_{RH} \gtrsim 10^9 \text{ GeV}$)
With supersymmetry: gravitino problem?
- $\tilde{m}_1 \lesssim 0.1 \text{ eV}$
- $\bar{m}^2 = m_1^2 + m_2^2 + m_3^2 \lesssim (0.15 \text{ eV})^2$

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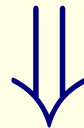
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Quantitatively - very plausible

More recent developments

- Spectator processes

Nardi, Nir, Racker, Roulet, JHEP 0601 (2006) 068

- Finite-temperature effects

- Flavor effects

Nardi, Nir, Racker, Rouley, JHEP 0601 (2006) 164

- N_2 leptogenesis

Engelhard, Grossman, Nardi, Nir, PRL 99 (2007) 081802

- Variations: Soft, Resonant, Dirac...

Grossman, Kashti, Nir, Roulet, PRL 91 (2003) 251801; JHEP 0411 (2004) 080

The future of leptogenesis

- N is heavy and $SU(3) \times SU(2) \times U(1)$ -singlet:

Direct tests are very unlikely

- Observation of $0\nu 2\beta$ decay:

Will establish L violation

- $\Gamma(\nu_\mu \rightarrow \nu_e) \neq \Gamma(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ in long baseline ν -experiments:

Will establish CPV in lepton interactions

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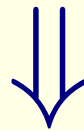
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- Leptogenesis is a very plausible explanation of Y_B
- It can be made even more plausible
- It probably cannot be directly probed and proven

Electroweak Baryogenesis

The basic picture

- EWSB via first order phase transition:
Bubbles of broken $SU(2)_L$ nucleate and expand
- CPV interactions within the bubble wall:
Production of CP-asymmetric charge density of LH fermions
- The charge diffuses ahead of the wall into the unbroken phase:
Non-perturbative sphaleron processes convert it into the BAU
- After EWSB, sphalerons become inactive:
The baryon density freezes out

MSSM baryogenesis

1. Need to modify the EWPT into a first-order one
 2. Need new sources of CPV
-
1. \tilde{t}_R, \tilde{t}_L couple strongly (y_t^2) to the Higgs
 - \implies The finite-T cubic term in the Higgs potential modified
 - \implies First-order EWPT if $m(\tilde{t}_R) \lesssim m_t$
 2. At least two new, flavor-diagonal, CPV phases (ϕ_A, ϕ_B)
 - \implies CPV in the $\tilde{H}, \tilde{W}_1, \tilde{W}_2$ interactions

MSSM-BG pushed to a corner

- 1st order EWPT $\implies m(\tilde{t}_R) \lesssim 125 \text{ GeV}$
 $+ m_h > 114 \text{ GeV} \implies m(\tilde{t}_L) \gtrsim 6.5 \text{ TeV}$
 Fine tuning!
- Large enough CPV for baryogenesis $\implies \phi \gtrsim 0.1$
 Experimental constraints on EDMs $\implies \phi \lesssim 0.1$
 The viable range for CPV phases is very narrow
- Also $m_h, m_A, m_{\tilde{W}_{1,2}}, m_{\tilde{H}}, \tan \beta$ constrained
- Highly fine-tuned
- Very predictive, testable by LHC and EDMs in the near-future

BMSSM

$$W_{\text{BMSSM}} = W_{\text{MSSM}} + \frac{\lambda}{M} (H_u H_d)^2$$

- Allows $m_h > 114$ GeV with light stops
No little hierarchy problem
- Both stops can be light
1st order EWPT without fine tuning
- New CPV phases
Possibility of “spontaneous baryogenesis”
Still, EDMs within order of magnitude of experimental bounds

Blum, Nir, PRD 78 (2008) 035005

Bernal, Blum, Nir, Losada, JHEP 0908 (2009) 053

Blum, Delaunay, Nir, Losada, Tulin, JHEP (2010)

The LHC will explore the unknown

Energy $0.6 \rightarrow 4 \text{ TeV}$

Distance $10^{-19} \rightarrow 10^{-20} \text{ m}$

“Time” $10^{-11} \rightarrow 10^{-13} \text{ s}$

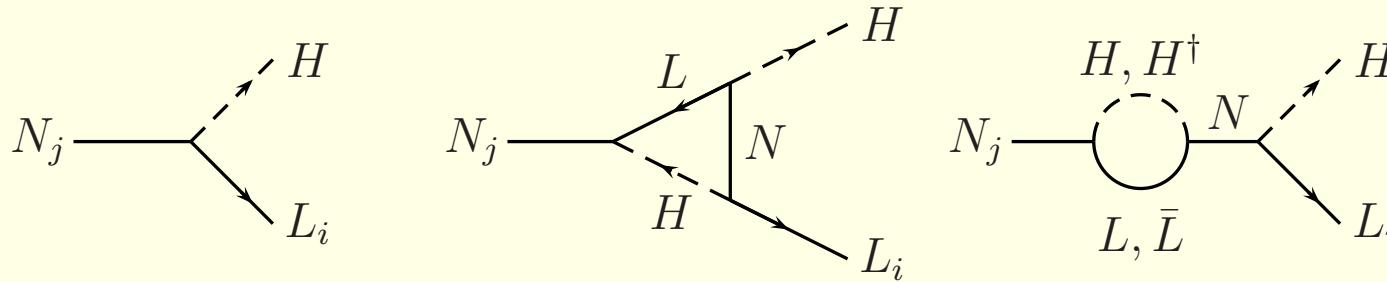
The LHC will explore the unknown

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What are the dark matter particles?
- What happened at the electroweak phase transition (10^{-11} second after the big bang)?
- Was the baryon asymmetry generated by TeV scale physics?

Conclusions

- The SM fails to explain Y_B
- Leptogenesis
 - If seesaw explains $m_\nu \neq 0 \implies$ qualitatively unavoidable
 - Given $m_\nu \sim 10^{-2} \text{ eV} \implies$ quantitatively plausible
 - Direct tests: probably impossible
- Electroweak baryogenesis
 - MSSM-BG: highly constrained and highly fine-tuned
 - 1st order EWPT: testable at LHC
 - CP violation: testable via EDMs

Leptogenesis at Work



- Lepton number violation at tree level,
- Direct CP violation at one loop,
- Requires at least 2 N's.

$$\epsilon \equiv \frac{\Gamma(N \rightarrow LH) - \Gamma(N \rightarrow \bar{L}H^\dagger)}{\Gamma(N \rightarrow LH) + \Gamma(N \rightarrow \bar{L}H^\dagger)} = \frac{1}{8\pi} \sum_k \frac{\text{Im}[(Y^\dagger Y)_{k1}^2]}{(Y^\dagger Y)_{11}} \times f \left(\frac{M_k^2}{M_1^2} \right)$$

$$\frac{n_B}{s} = -1.38 \times 10^{-3} \eta \epsilon.$$

Implications

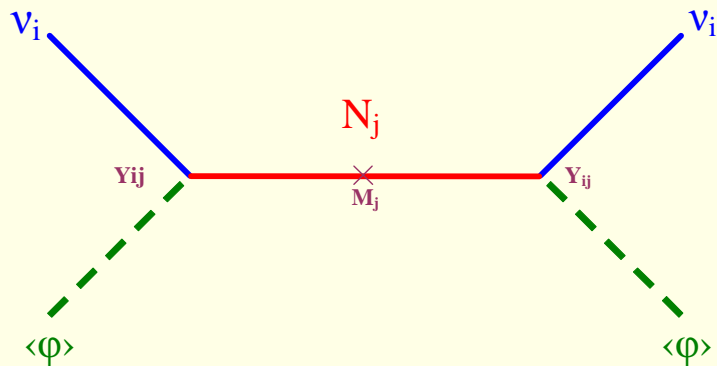
$$\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} \langle \phi \rangle^2}{M_1} \sim 10^{-3} \text{ eV}$$

- N_1 Decay rate: $\Gamma_1 = \frac{M_1 (Y^\dagger Y)_{11}}{8\pi}$
- The expansion rate: $H(T) = 1.66 g_*^{1/2} \frac{T^2}{M_{\text{Pl}}}$
- The out of equilibrium decay condition: $\Gamma_1 \lesssim H(T = M_1)$
- Equivalently: $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} \langle \phi \rangle^2}{M_1} \lesssim 10^{-3} \text{ eV}$
- \tilde{m}_1 determines almost all washout effects: $\eta \sim (10^{-3} \text{ eV} / \tilde{m}_1)$
- \tilde{m}_1 always larger than the lightest ν mass, $\tilde{m}_1 \geq m_1$

$$\implies \boxed{m_1 \leq \tilde{m}_1 \lesssim 10^{-1} \text{ eV}}$$

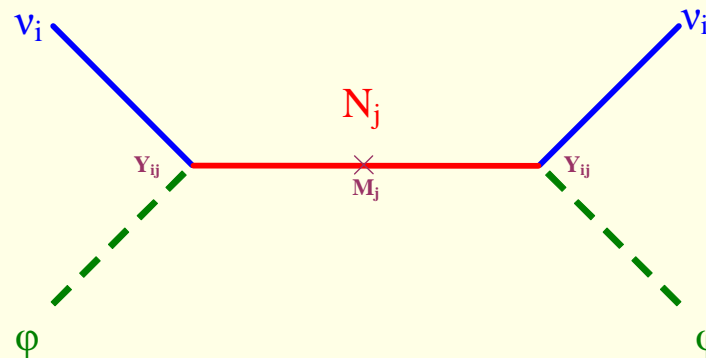
Implications

$$\underline{m_1^2 + m_2^2 + m_3^2 \lesssim (0.15 \text{ eV})^2}$$



Light Neutrino Masses

$$m_i \propto \sum_j Y_{ij}^2 / M_j$$



L -changing $2 \rightarrow 2$ Scattering

$$\sigma \propto \sum_i \left| \sum_j Y_{ij}^2 / M_j \right|^2$$

- Require that $\Delta L = 2$ washout effects are not too strong:

$$m_1^2 + m_2^2 + m_3^2 \lesssim (0.15 \text{ eV})^2$$

Buchmuller, Plumacher; Giudice et al.

- $T_{\text{LG}} < 10^{12} \text{ GeV} + \text{Flavor effects} \implies m_\nu \lesssim 4 \text{ eV} (10^{10} \text{ GeV} / T_{\text{LG}})^{1/2}$

Spectator Processes

- Fast, $B - L$ conserving processes:
Gauge, (Heavy) Yukawa, Sphaleron
 \implies T-dependent relations among chemical potentials

- $T > 10^{13}$ GeV:
Higgs asymmetry enhances washout-effects
 \implies Suppression of Y_{B-L} by $\sim 40\%$

Buchmuller, Plumacher, PLB 511 (2001) 74

- $T < 10^8$ GeV:
Lepton asymmetry transferred into baryons and into SU(2)-singlets
 \implies Enhancement of Y_{B-L} by $\sim 20\%$

Nardi, Nir, Racker, Roulet, JHEP 0601 (2006) 068

Flavor Issues

- $N_1 \rightarrow H\ell_1$: Define $K_i = |\langle \ell_i | \ell_1 \rangle|^2$ ($i = e, \mu, \tau$)
- $\epsilon_i \sim \epsilon K_i^0 + (K_i - \bar{K}_i)$
- For generic flavor structure ($K_i = \mathcal{O}(1), \neq 0, 1$):
 $\eta_i \sim \eta K_i \implies Y_{B-L} \propto \sum_{i=1}^{n_f} \eta_i \epsilon_i \sim n_f (\eta \epsilon)$
 $n_f = 1_{T > 10^{13} \text{ GeV}}, 2_{10^{11} < T < 10^{13} \text{ GeV}}, 3_{T < 10^{11} \text{ GeV}}$
- For non-generic flavor structure ($K_i \ll 1, \neq 0$):
 Large (order of magnitude) effects are possible
- Qualitatively new effects from $K_i \neq \bar{K}_i$
- $M_1 \gtrsim 10^9 \text{ GeV}$ but $m_\nu \lesssim eV$

Barbieri et al, NP B575 (2000) 61

Abada et al, JCAP 0604 (2006) 004; Nardi et al, JHEP 0601 (2006) 164

N_2 Leptogenesis

- Common wisdom:
Pre-existing lepton asymmetry washed-out by N_1 interactions
Consequence: $\epsilon_{N_{2,3}}$ can be ignored

- Obviously, not true in the N_1 -decoupling regime

$$\tilde{m}_1 \ll 10^{-3} \text{ eV}$$

Vives, PR D73 (2006) 073006; Blanchet, Di Bari, JCAP 0606 (2006) 023

- Surprisingly, not true in the strong N_1 -coupling regime

$$\tilde{m}_1 \gg 10^{-3} \text{ eV}$$

Barbieri et al, NP B575 (2000) 61; Engelhard et al, PRL 99 (2007) 081802

- $N_2 \rightarrow \ell_2 + H, \quad N_1 \rightarrow \ell_1 + H, \quad \ell_2 = s\ell_1 + c\ell_o$

$$\implies N_1 \text{ interactions project } \epsilon_2 \rightarrow s^2\epsilon_1 + c^2\epsilon_o$$

$$\implies \boxed{Y_L \sim (3/2)c^2 Y_{\ell_2}}$$

Finite Temperature Effects

- Finite temperature effects modify masses and couplings
⇒ Decay and scattering rates depend on temperature

- The most dramatic effect: $\frac{m_H^2}{T^2} = \frac{3}{16}g_2^2 + \frac{1}{16}g_Y^2 + \frac{1}{4}y_t^2 + \frac{1}{2}\lambda$

- $N \rightarrow LH$ blocked above $T \sim 2m_N$

- $H \rightarrow LN$ opened above $T \sim 7m_N$

⇒ $\mathcal{O}(1)$ corrections to final asymmetry

Giudice, Notari, Raidal, Riotto, Strumia, NP B685 (2004) 89

Soft Leptogenesis

- The framework: Supersymmetric Standard Model + N's
- Soft SUSY breaking terms ($A, B, m_{\tilde{w}}$)
 - \implies New sources of lepton number violation
 - \implies New sources of CP violation
- The lepton asymmetry is generated by sneutrino decays
- Indirect CP violation can play a major role
(Similar to ϵ or to $S_{\psi K_S}$)
- Particularly significant for low M
(No gravitino problem)

Grossman, Kashti, Nir, Roulet, PRL 91 (2003) 251801; JHEP 0411 (2004) 080

D'Ambrosio, Giudice, Raidal, PL B575 (2003) 75