Recent Issues in Leptogenesis

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OUTLINE

- Why Leptogenesis?
- Leptogenesis Basics on the run
- Flavoured vs Unflavoured (leptogenesis)
- Purely Flavoured Leptogenesis
- Lepton Flavour Equilibration: implications and examples
- Color Octet Leptogenesis
- Recent Highlights/Questions in Leptogenesis
- Summary

Why Leptogenesis??

- Explain within a consistent theoretical model the mechanism for Baryogenesis.
- Need a dynamical mechanism that will start out with $Y_B = 0$ and lead to $Y_B \neq 0$.
- Can this observable be related to other physics, such as neutrinos?
- Neutrino masses and mixings consistent with recent neutrino data can successfully give the right $\frac{n_B}{s} \sim 10^{-10}$.
- Need extension of the Standard Model (SM) and large enough CP violation in lepton sector is allowed.
- Fully exploits effects of departures from thermal equilibrium in the evolution of the early Universe!!!!!
- Focus has moved from understanding the qualitative features to detailed quantitative analysis.

Leptogenesis Basics

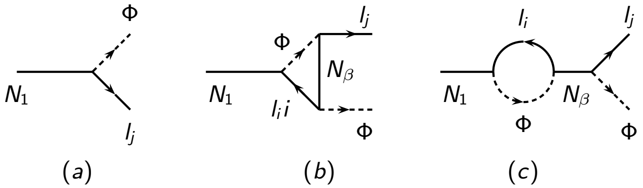
1. Need mixing/interference between (at least) two different states (typically flavour, CP-eigenstates,...)
2. All possible mechanisms of CP-violation can generically be implemented.
3. Important to carefully consider the dynamics in the background of an expanding Universe, then $n_B \neq n_{\bar{B}}$
4. Relevance of L and B-L conserving processes to determine the (asymmetric) densities of the different species.
5. Hard to test,....easier to falsify
6. B, C and CP violation is model dependent.

Which Model?

- (S)SM + Hierarchical Right-handed neutrinos
- Resonant Leptogenesis
- Soft Leptogenesis
- Dirac Leptogenesis
- Scalar/Fermion Triplet
- Electromagnetic Leptogenesis
- .....

Leptogenesis Mechanism

Fukugita, Yanagida



Based on standard out-of-equilibrium decay of a heavy particle....(e.g. RH neutrino):

1. CP violating decay of a heavy particle through a Lepton number -violating interation can produce a lepton asymmetry.
2. This lepton asymmetry is transformed into a *baryon asymmetry* through sphaleron interactions.

Spectator effects

Consider all processes that conserve B-L. For a given T, from chemical equilibrium considerations we solve the system of equations that are derived from requiring/having:

- Total isospin, hypercharge and color must be zero
- Flavor changing interaction in the quarks are in equilibrium
- Yukawa interactions in equilibrium
- Electroweak and QCD sphalerons in equilibrium
- With SUSY additionally particles in same multiplet have $\tilde{\phi} = \phi$

Solve for B, L, $B - L$ in terms of a chemical potential, say ℓ. However, in SUSY there are relevant mass-dependent effects from sparticles.

Chung,Garbrecht,Tulin

CP Asymmetry

- CP violation through phases in lepton sector.
- CP asymmetry produced through interference of tree and one-loop contribution of decay rate. The loop must also violate lepton number.
- CP asymmetry determined by the particle physics model that produces couplings and masses for ν_R. Connection with low scale CP violating observables is model dependent.

$$\epsilon = \frac{\Gamma(N_1 \to \phi + \bar{\ell}) - \Gamma(N_1 \to \ell + \bar{\phi})}{\Gamma(N_1 \to \phi + \bar{\ell}) + \Gamma(N_1 \to \ell + \bar{\phi})}$$

Basics of CP violation in See-saw Lepton Sector

Parameter counting...low energy : $\mathcal{L} = -\frac{1}{2}\nu^T m_\nu \nu + h.c.$

- 12 parameters in lepton sector: 6 masses, 3 mixing angles, 3 phases
- Have measured 7, 1 upper limit, 1 unknown mass and 3 unknown phases
- At low energy 1 Dirac phase related to flavour à la CKM. This CP violation in leptons NOT related to lepton number violation!!

Parameter counting...high energy:
$\mathcal{L}_{NP} = \lambda_{\alpha i} \ell_\alpha \phi N_i + h.c. + M_i N_i N_i$

- 3 charged fermion masses, 3 RH neutrino masses + 15 parameters from complex Yukawa matrix!!!
- Cannot easily disentangle LH and RH contributions at low energy....

Boltzmann Equations General Case

Interactions are too slow to catch up with expanding Universe. So n_X start to become overabundant.

$$\begin{aligned}\frac{dn_X}{dt} &+ 3Hn_X = \sum_{j,l,m} \int \Pi f_l f_m \cdots (1 \pm f_X)(1 \pm f_j) \cdots W(l + m \to X + j\\ &- f_X f_j \cdots (1 \pm f_l)(1 \pm f_m) \cdots W(X + j + \cdots \to l + m \cdots)\end{aligned}$$

R.H.S. n_X variation due to all elementary processes for X, inverse decays, scatterings, annihilations.....
Initially done with many simplifying assumptions on:

- kinetic equilibrium
- thermal and chemical equilibrium
- lepton flavour properties

Relevant processes

Coupled system for n_X and n_{B-L},

$$\frac{dn_X}{dt} + 3Hn_X = [\frac{n_X}{n_X^{eq}} - 1](\gamma_D + \gamma_a)$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \epsilon \left[\frac{n_X}{n_X^{eq}} - 1\right] \gamma_D - \frac{n_{B-L}}{n_L^{eq}} \gamma_W$$

$\epsilon \to$ CP Asymmetry
γ_W dissipation at $T \lesssim M$

- N decays and inverse-decays
- $\Delta L = 1$ scatterings
- $\Delta L = 2$ scatterings

γ_D, γ_a control departure from thermal equilibrium

- for non-singlet decaying particles must include annihilations through gauge interactions

Flavoured vs Unflavoured

Barbieri et al, Endoh et al, Pilaftsis Underwood, Vives, Abada et al, Nardi et al

Intuitively what should be important is the direction in flavour space into which N_1 decays.
Given that h_e, h_μ, h_τ are small and the lepton asymmetry is obtained from a trace in flavour space how can flavour matter?
Flavour distinguishes mass eigenstates.....

- So, consider temperatures where $\Gamma_\tau, \Gamma_\mu \gg H$
  $\rightarrow$ charged lepton Yukawas have no effect of the CP asymmetry BUT
- the dynamical process of RH neutrinos decay and production and the corresponding lepton asymmetry is distributed among distinguishable flavours.
- charged lepton Yukawa interactions have the effect of projectors, asymmetries in each flavour are washed out differently, contributing with different weights in the expression for the total asymmetry.

Flavoured vs. Unflavoured

$$\mathcal{L}_{yukawa} = \lambda^*_{\alpha 1}\bar{\ell_\alpha} N_1 \phi + h_{\alpha\beta}\bar{\ell_\alpha} e_\beta \phi + h.c.$$

Different basis give different results:

$$\mathcal{L}_{yukawa} = \lambda^*_{1}\bar{\ell_1} N_1 \phi + h_{i\beta}\bar{\ell_i} e_\beta \phi + h.c.$$

$$\mathcal{L}_{yukawa} = \lambda^*_{\alpha 1}\bar{\ell_\alpha} N_1 \phi + h_{\alpha}\bar{\ell_\alpha} e_\alpha \phi + h.c.$$

One-flavour

$$Y_B \approx \frac{1}{g^*}\sum \eta_\alpha \sum \epsilon_\alpha = \frac{1}{g^*}\eta\epsilon$$

Flavoured

$$Y_B \approx \frac{1}{g^*}\sum \eta_\alpha \cdot \epsilon_\alpha$$

Decay rate and CP revisited

Unflavoured	Flavoured
$\epsilon, \tilde{m}_1, M_1, \bar{m}^2.$	$\epsilon_\alpha, \tilde{m}_{1\alpha}$
$\Gamma = \frac{1}{8\pi}(\lambda\lambda^\dagger)_{11} M_1 = \frac{\tilde{m}_1 M_1^2}{8\pi v^2}$	$\Gamma_\alpha = \frac{1}{8\pi}\|\lambda_{1\alpha}\|^2 M_1$
$K \equiv \frac{\Gamma}{H}\|_{T=M_1} = \frac{\tilde{m}_1}{\tilde{m}_*} < 1$	$\Gamma_\alpha/\Gamma = K_\alpha = K\frac{\tilde{m}_\alpha}{\tilde{m}_*} < 1$
$\eta(\tilde{m}_1, \bar{m}^2)$	$\eta_\alpha(\tilde{m}_{1\alpha})$
$\eta \propto \frac{H}{\Gamma}$	$\eta_\alpha \propto \frac{H}{\Gamma_\alpha}$
$M_1 \gtrsim 10^9\, GeV(\frac{2.5\times10^{-3}\mathrm{e}V^2}{\Delta m^2_{atm}})^{1/2}$	decreases bound M_1
$\epsilon \leq \epsilon_{max} = \frac{3}{16\pi}\frac{M_1}{v^2}\frac{(\Delta m^2_{atm}+\Delta m^2_{sol})}{m_3}$	$\epsilon_\alpha = \leq \frac{\sqrt{3}M_1\bar{m}}{8\pi v^2}$
$\bar{m} < 0.15eV$	increases $\bar{m}$

Consequences of Flavour

- Trivial enhancement when $\epsilon_\alpha = \epsilon/3, \Gamma_\alpha = \Gamma/3$
- weaker bound than in unflavoured case, valid for degenerate light neutrinos.
- So there is an enhancement in the CP asymmetry, which grows as the scale of the heaviest ν. $\rightarrow Y_L = 3 Y_L^{one-flavour}$
- Much larger enhancements are possible when $\Gamma_\ell \neq \bar{\Gamma}_\ell$.

$$\epsilon_\alpha \sim \epsilon_1 K_\alpha + \Delta K_\alpha$$

Purely Flavoured Leptogenesis

Consider first the SM + seesaw, using the Casas-Ibarra parametrization:

$$\lambda_{\alpha k} = \frac{1}{v}\left[U^\dagger \sqrt{m_\nu} \cdot R\sqrt{M_N}\right]_{\alpha k}$$

Flavour CP asymmetries:

Davidson et al, 07,08

$$\epsilon_\alpha = Im\left(F[m_\nu, M, R]_{ji} \times U_{j\alpha} U^*_{i\alpha}\right)$$

Total CP asymmetries:

$$\epsilon = \frac{M_1 M_k}{v^4} Im\left(\left(\sum_i m_{\nu_i} R^*_{i1} R_{ik}\right)^2\right)$$

PFL

- In the generic case it is very difficult to separate CP violating sources and it is not possible to infer in the see-saw the value of the CP asymmetry from low energy observables.
- Specific models can find some correlations by minimizing the number of parameters through: family symmetries, textures, 2RHN, etc

Assuming that R is real. We see,

- ϵ_α will depend only on the neutrino mixing matrix U
- $Y_B \neq 0$ even with $\epsilon = 0$ as long as $\epsilon_\alpha \neq 0$.

$\rightarrow$ A real R matrix implies that there is no CP violation from RH sector AND also that possible CP violation at low energy could be correlated to the CP violation that produced the BAU!! VERY MODEL DEPENDENT STATEMENT!!!!!

Purely Flavored Leptogenesis

In this type of models it is possible to generate the baryon asymmetry even in the case in which $\sum_\alpha \epsilon_\alpha = 0$ without lepton number violation in decay.

- The BE for lepton flavour asymmetries in general present different washouts in the different flavours so.....
  $Y_{B-L} \propto \sum \eta_\alpha \epsilon_\alpha \neq 0$
- Rely on the condition that the dynamics of the different lepton flavors are decoupled at the leptogenesis temperature.
- CP violation can originate from the non leptonic sector/lepton number conserving loop
- Nice check that in the single flavour approximation $Y_{B-L} \to 0$
- Case with lepton flavour violation (LFV). No need to have lepton number violation in the loop, lepton number violation only via the washout processes.

Consequences of Purely Flavor Leptogenesis

- In this type of models one can have enhancements in the CP asymmetry originating from the introduction of additional scales or couplings.
- The additional coupling can decouple the neutrino mass dependence from the out of equilibrium condition and CP-asymmetry such that leptogenesis can occur at much lower scales.

$$\epsilon \sim \frac{h^\dagger h \lambda\lambda}{h^\dagger h} \tag{1}$$

This implies that either:

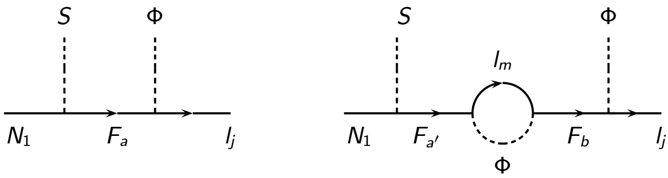
- Relax the tension between the neutrino masses and large enough CP violation allowing a smaller T (M_1) for leptogenesis
- decouple the neutrino masses, out of equlibrium constraint and CP violation

However, these were precisely the issues that motivated leptogenesis!!!!

Symmetries and Lepton number violation

D.Aristizabal, ML, E. Nardi 08, D. Aristizabal, L. Muñoz, E. Nardi 08

Take a flavour symmetry $U(1)_F$ such that the coupling $\bar{\ell}NH$ is not allowed.



For $M_F \gg M_N$: $\tilde{\lambda}_{\alpha k} = \left(h \frac{<S>}{M_F} \lambda^\dagger\right)_{\alpha k}$. So $m_\nu \sim \mathcal{O}(\tilde{\lambda}^2)$.
CP asymmetries:

$$\epsilon = \sum_\alpha \epsilon_\alpha = 0; \qquad \epsilon_\alpha \neq 0 \sim \mathcal{O}(h^2) \tag{2}$$

Decoupling ϵ_α from $\tilde{m}_\alpha, m_\nu$ allows to lower $T_{LG} \sim$ TeV.

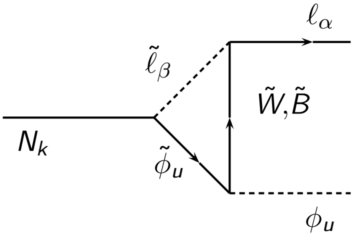
Lepton Flavour Equilibration

D. Aristizabal, ML, E. Nardi 09

- In the presence of LFV, fast $\ell_\alpha \to \ell_\beta$ transitions effectively eliminate all dynamical flavor effects.
- If at T_{LG} the LFV processes are in chemical equilibrium then there are no flavour effects and the one-flavour approximation correctly describes the production of the lepton asymmetry.
- Must be included in the chemical equilibration/BEs and Spectator processes become more relevant.
- In general, models of new physics have new sources of LFV, so it is not immediate that flavour effects will survive.
- Some interesting examples

LFE effects in SUSY

Model with soft $m^2_{\alpha\beta}$ gives rise to new diagrams that could contribute to a lepton asymmetry via PFL à la soft leptogenesis.



- Flavour CP asymmetries which are enhanced as $\propto g^2\lambda$, but $\epsilon = \sum_\alpha \epsilon_\alpha = 0$.
- Ineffective because lepton flavour densities equilibrate very fast, so ...LG described by single flavour approximation, which cannot be sourced by the type of diagram above.

Spectators again

- $T > 10^{13}$ GeV:
  Higgs asymmetry enhances washout-effects $\rightarrow$Suppression of Y_{B-L} by ~ 0.4
- $T < 10^{8}$ GeV: Lepton asymmetry transferred into baryons and into SU(2)-singlets $\rightarrow$ Enhancement of Y_{B-L} by ~ 0.2

Buchmuller, Plumacher; Nardi, Nir, Racker, Roulet

- $T \lesssim 100$ TeV: With lepton flavor equilibration, in SUSY models via soft leptogenesis, $\rightarrow$ possible large enhancements (~ 5) of Y_{B-L} when strong washout dependence exists.

Aristizabal, Losada, Nardi

Dimension six operators and the seesaw

Antusch,Blanchet,Blennow,Fernandez-Martinez 09

- L-violating dim 5: $(\ell\phi)^2 \rightarrow \epsilon_\alpha \propto \mathcal{I}m\left(\lambda_{j\alpha}\lambda^*_{i\alpha}\left[\frac{3}{\sqrt{2}x_j}(\lambda\lambda^\dagger)_{j1}\right]\right)$
- L conserving dim 6:
  $(\bar{\ell}\phi^*)\partial(\ell\phi) \rightarrow \epsilon_\alpha \propto \mathcal{I}m\left(\lambda_{j\alpha}\lambda^*_{i\alpha}\left[\frac{1}{x_j}(\lambda\lambda^\dagger)_{1j}\right]\right)$

Non-unitarity in lepton mixing through dimension 6 terms.

1. enforce global U(1) to suppress dim 5 terms but NOT dim 6.
2. so can have PFL, with $\epsilon_\alpha \neq 0$, but $\sum \epsilon_\alpha \sim 0$.
3. flavour asymmetries are not strongly correlated to ν masses so can be large.

Need hierarchy in RH ν to be small to produce a large enough Y_B.
This induces fast lepton flavour violating rates.
So for $M_1 \lesssim 10^8$, LFE does not allow a large enough baryon asymmetry. $\rightarrow$ LFE sets a lower bound on M_1.

Color Octet Leptogenesis

In Fileviez-Perez and Wise model for neutrino masses the SM is extended by the inclusion of

- $\mathcal{N}_S$ scalar fields S with quantum numbers (8,2,1/2),
- $\mathcal{N}_F$ fermions F with quantum numbers (8,1,0)

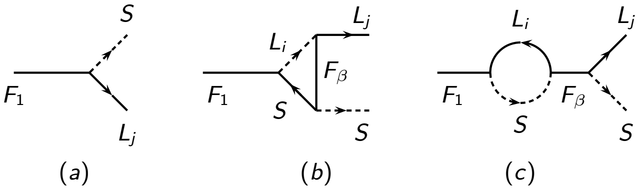
$$\mathcal{L} = \Big(y_{iab}\, L^i\, \epsilon\, F_a\, S_b + g^u_{ijb}\, u^{i\dagger}_R\, S_b \epsilon\, Q^j + g^d_{ijb}\, d^{i\dagger}_R S^\dagger_b\, Q^j + \mathrm{h.c.} \Big) - V(H,S)\,. \tag{3}$$

The left-handed neutrino Majorana mass matrix, arising at one-loop order, is

$$m^\nu_{ij} = \sum_{ab} \frac{1}{4\pi^2}\, y_{iab}\, y_{jab}\, \lambda_b\, v^2\, m_{F_a}\, \frac{m^2_{S_b} + m^2_{F_a}\left(\log(m^2_{F_a}/m^2_{S_b}) - 1\right)}{\left(m^2_{F_a} - m^2_{S_b}\right)^2}\,. \tag{4}$$

Color Octet Leptogenesis

ML, S. Tulin 09



- LG from decay of heavy (fermion/scalar) octet
- some three body decays can also occur for given mass hierarchies
- ϵ can be $\mathcal{O}(1)$ and still fit neutrino data
- LFV processes are fast at T_{LG} so appropriate to use single-flavor approximation.

$$\epsilon_{F_1} = \frac{3}{8\pi} \frac{\sum_{i,j} \mathrm{Im}[y_{i1} y_{i2}^* y_{j1} y_{j2}^*]}{\sum_i |y_{i1}|^2} \frac{(m_{F_1}^2 - m_S^2)^2}{m_{F_1}^3 m_{F_2}} f(m_{F_1}, m_{F_2}, m_S) \; ,$$

Signatures

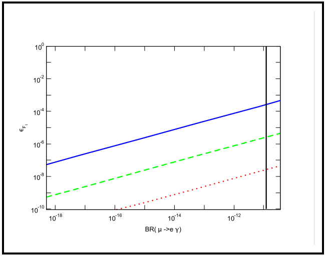
Most general form for y that gives the correct light neutrino masses and mixing angles is $y = U \cdot X$,

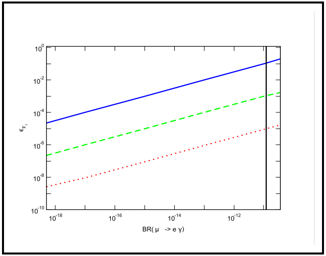
$$\sum_{i,j} \mathrm{Im}[y_{i1} y^*_{i2} y_{j1} y^*_{j2}] = \sum_{i,j} \mathrm{Im}[X_{i1} X^*_{i2} X_{j1} X^*_{j2}] \ ,$$

- F_1 production at colliders would occur as for gluino pair production
- Decay of fermion octet would produce a same-sign lepton signature
- EW precision constraints from scalar octets to gauge boson vacuum polarizations
- Corrections to $Z\ell\ell$ vertex through F and S loops

Low energy constraints

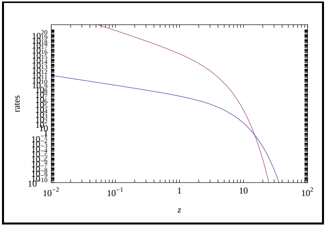
- LFV processes can provide strong constraints on values of parameters
- Still, large values of the CP asymmetry are possible, depending on the neutrino mass hierarchy.

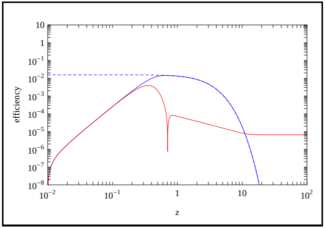


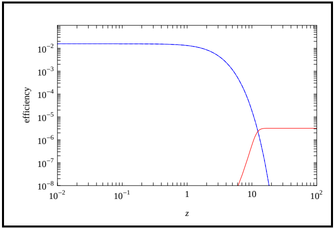


Efficiency including scattering

- Annihilation rate can be much larger that decay rate
- In some regions of parameter space can still produce the BAU







Recent Highlights/Questions in Leptogenesis

- Validity of kinetic equilibration assumption requires use of full BE $\rightarrow$ effects can enhance/suppress Y_{B-L} in different scenarios
- Quantum effects can be relevant e.g. resonant leptogenesis with MLFV
- Possible signatures at colliders from decay of (particles with additional interactions to) heavy particle, e.g.triplet scalar: double charged Higgs decay to same sign leptons or Z's from additional U(1)
- Separation of CP violation and lepton number violation in the decay is now possible. Lepton number violation can be introduced purely through washout effects: PFL
- Possible relevance of symmetries to induce correlations between low energy observables and LG parameters.

Summary

- Non-zero ν masses can be explained via the see-saw mechanism $\rightarrow$ has all necessary ingredients for LEPTOGENESIS
- For $T < 10^{12}$GeV the flavour basis is fixed! $\rightarrow$ can enhance significantly the value of Y_{B-L}
- Possible mechanisms to enhance CP asymmetry with implications on LH and RH neutrino mass bounds
- Many more detailed and precise analysis have been made recently: finite T, spectators, kinetic equilibrium, flavor, non hierarchical N's, $\rightarrow$ reducing the predictive power
- Many corrections can significantly affect the importance of the washout processes
- Many interesting models are viable: soft, Dirac, resonant, electromagnetic, PFL
- Indirect support from neutrinoless double beta decay or CPV in neutrinos is detected
- Direct tests are extremely hard.
- Leptogenesis is STILL interesting.