Present understanding of solution to baryonic asymmetry of the Universe

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Motivation for Baryogenesis

Types of Baryogenesis
- Grand Unified Theory (GUT) baryogenesis
- Leptogenesis
- Electroweak Barogenesis
- Affleck-Dine Mechanism

Leptogenesis

Soft Leptogenesis

Conclusion

- Observations indicate that the number of baryons (protons and neutrons) in the Universe in unequal to the numbers of anti-baryons (anti protons and anti- neutrons).

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  1. If baryon asymmetry had been an initial condition, it would have been a highly fined tuned one. For every 6000000 anti-quarks there should be 6000001 quarks.
  2. And more importantly, we have a good reason to believe from the CMB that there was an era of inflation during early history of the Universe. So, any primodial asymmetry would have been exponentially diluted away by the required amount of inflation.

The baryon asymmetry of the Universe can be defined in two equivalent ways.

$$Y_{\Delta B} = \left.\frac{n_B - n_{\overline{B}}}{s}\right|_0 = (6.21 \pm 0.16) \times 10^{-10}$$

$$\eta = \left.\frac{n_B - n_{\overline{B}}}{n_\gamma}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

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- All of the above ingredients are there in Standard Model. But still it does not generates enough asymmetry.

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  2. It must either provide a departure from thermal equilibrium in addition to the electroweak phase transition (EWPT) or modify the EWPT itself.

Some new physics mechanisms for baryogenesis are as follows:

1. Grand Unified Theory (GUT) baryogenesis
2. Leptogenesis
3. Electroweak baryogenesis
4. Affleck-Dine mechanism

It generates the baryon asymmetry in the out-of-equilibrium decays of heavy bosons in GUT. The GUT baryogenesis has difficulties with the non-observation of proton decay, which puts a lower bound on the mass of the decaying boson, and therefore on the reheat temperature after inflation.

It was first proposed by Fukugita and Yanagida [1]. New particles-singlet neutrinos- are introduced via the see saw mechanism. Their couplings provide the necessary new source of CP violation. The rate of these Yukawa interactions can be slow enough that departure from thermal equilibrium occurs. Lepton number violation comes from the Majorana masses of these new particles, and the SM sphaleron processes still play a crucial role in partially converting the lepton asymmmtry into baryon asymmetry.

[1] M. Fukugita and T. Yanagida. "Baryogenesis Without Grand Unification". In: *Phys.Lett.* B174 (1986), p. 45. DOI: 10.1016/0370-2693(86)91126-3

Its a class of models where the departure from thermal equilibrium is provided by the electroweak phase transitions. In principle, Standard Model belongs to this class, but the phase transition is not strongly first order and the CP violation is too small. Thus, viable models of electroweak baryogenesis need a modification of the scalar potential such that the nature of the EWPT changes, and new sources of CP violation.

The asymmetry arises in classical scalar field, which later decays to particles. In a SUSY model, this field could be some combination of squark, Higgs and slepton field. This field starts from a large expectation value then starts to roll down to the origin. While starting from large initial value and rolling down to origin, there can be contribution from baryons and leptons violating interactions. These impart a net asymmetry from the rolling field.

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- This bound might be in conflict with an upper bound on the reheat that applies in supersymmetric models with a "gravitino problem".
- After inflation, the universe thermalizes to a reheat temperature T_{reheat}. Gravitinos are produced by thermal scattering in that bath, and the rate is higher at higher temperatures. The gravitinos are long-lived; if there are lighter SUSY particles (the gravitino is not the LSP), the decay rate can be estimated to be

$$\Gamma \sim \frac{m_{grav}^3}{m_{pl}^2} \simeq \left(\frac{m_{grav}}{20\text{TeV}}\right)^3 s^{-1}$$

- If too many gravitinos decay during or after Big Bang Nucleosynthesis ($t \sim s$), the resulting energetic showers in the thermal bath destroy the agreement between predicted and observed light element abundances.

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- One of the plausible solution is to have small reheating temperature $T_{reh} < 10^6 - 10^{10}$ GeV so that the gravitino density is small. Which is provided by "Soft Leptogenesis".

- In the framework of supersymmetric see saw models, new leptogenesis mechanism become plausible, Soft leptogenesis.

[2] Rathin Adhikari and Raghavan Rangarajan. "Baryon number violation in particle decays". In: *Phys.Rev.* D65 (2002), p. 083504. DOI: 10.1103/PhysRevD.65.083504. arXiv: hep-ph/0110387 [hep-ph]

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- Super symmetry must, however, be broken. In the framework of the supersymmetric standard model extended to include singlet neutrinos (SSM+N), there are, in addition to the soft supersymmetry breaking terms of the SSM, terms that involve the singlet sneutrinos $\widetilde{N}$, in particular biliniear (B) and the trilinear (A) scalar couplings.

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- It has been argued earlier[2] that to create a baryon asymmetry there should be net $\Delta B \neq 0$ violation to the right of the "cut" in the loop diagram.

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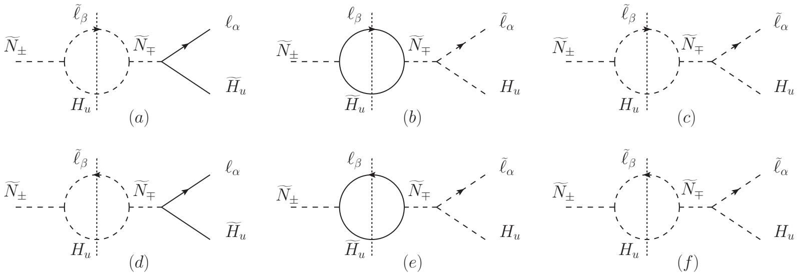
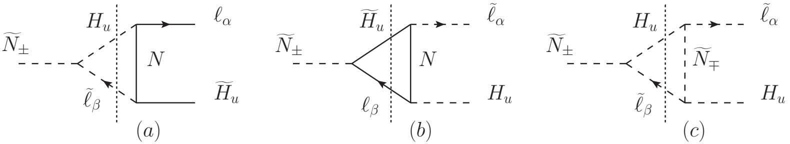
- We showed that the diagrams which can be achieved while incorporating the above condition in the context of Soft leptogenesis are

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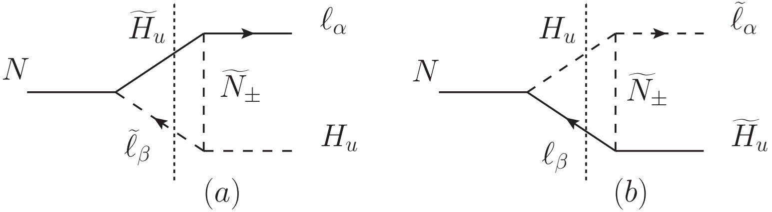
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1. The relevant new sources of CP violation and lepton number violation appear generically in this framework. In this sense, soft leptogenesis is qualitatively unavoidable in SSM+N framework, and the question of its relevance is a quantitative one.
2. If $M < 10^9$ GeV (in the supersymmetric framework, this range is preferred by the gravitino problem), then standard leptogenesis encounters problems, while softleptogenesis can be significant.

Now after considering the $\Delta L \neq 0$ to the right of the "cut", we showed that with generic soft trilinear A couplings there are two interesting consequences

3 One can realize non thermal CP violation where the CP asymmetries in the decays of heavy sneutrinos to lepton and sleptons do not cancel at zero temperature resulting in an enhanced efficiency in generating baryon asymmetry.

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3. One can realize non thermal CP violation where the CP asymmetries in the decays of heavy sneutrinos to lepton and sleptons do not cancel at zero temperature resulting in an enhanced efficiency in generating baryon asymmetry.
4. The dominant CP violation from self-energy corrections is sufficent even far away from the resonant regime and the relevent soft parameters can assume natural values at around the TeV scale.

THANK YOU!