A Natural Mechanism for Resonant Leptogenesis

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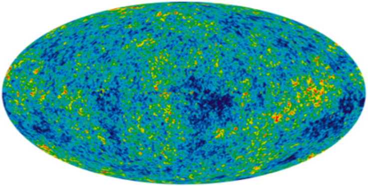
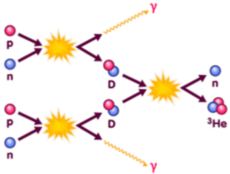
Baryon Asymmetry of the Universe (BAU)

- Cosmological Puzzle: Why is there more matter than antimatter?
- Actual measurement of the asymmetry is the BAU [4][1].

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \approx \frac{n_B}{s} = (8.72 \pm 0.08) \times 10^{-11} \quad (1)$$

- Measured from CMB and BBN seperately [6][2].





- Leptogenesis is an elegant solution to this problem that has its roots in neutrino physics.

The Sakharov Conditions

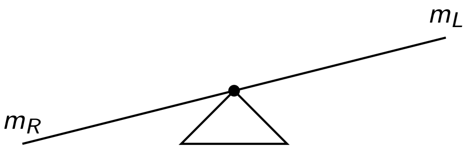
- In the 1960s Andrei Sakharov came up with three (really four) conditions for a baryon asymmetry to be produced [11].
    1. Violation of Baryon Number
    $$X \to Y + B$$
    2. Thermal Inequilibrium
    $$\Gamma(X \to Y + B) \neq \Gamma(Y + B \to X)$$
    3. C violation
    $$\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$
    4. CP violation
    $$\Gamma(X \to B_L) + \Gamma(X \to B_R) \neq \Gamma(\bar{X} \to \bar{B}_L) + \Gamma(\bar{X} \to \bar{B}_R)$$

Type-1 Seesaw Mechanism

- Add right-handed neutrinos to the SM Lagrangian [9]. Two terms are allowed.
  1. Dirac Mass Term: $-m_D \bar{\nu}_L \nu_R + h.c.$
  2. Majorana Mass Term: $-M_m \bar{\nu}_R^c \nu_R + h.c.$
- See-Saw Mechanism is the limit $M_m >> m_D$:

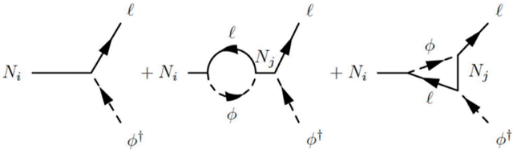
$$m_L \approx \frac{m_D^2}{M_m}, \quad m_R \approx M_m \tag{2}$$

explains the smallness of left-handed neutrino masses.



Leptogenesis

- At one loop, we find that the probability of $N \to H^\dagger L$ is greater than $N \to H\bar{L}$. Lepton asymmetry is produced by sterile neutrino decays at one-loop [3]:



- Leptogenesis can then satisfy the Sakharov conditions,

Sakharov Condition	Leptogenesis Answer
B Violation	Sphaleron Processes
Thermal Inequilibrium	Thermal inequilirbium of RHNs
C Violation	Majorana Term
CP Violation	Majorana or Dirac Terms

Figure: Sakharov Conditions and Leptogenesis Answers

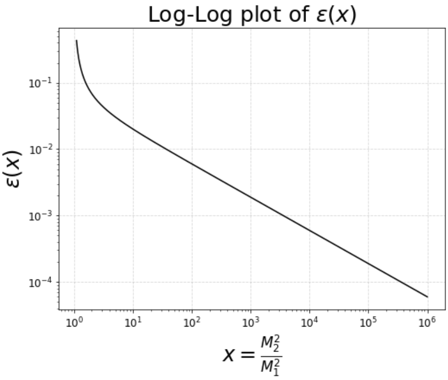
Resonance

- The CP violation parameter is defined as

$$\epsilon = \frac{\Gamma(N \to LH^\dagger) - \Gamma(N \to \bar{L}H)}{\Gamma(N \to LH^\dagger) + \Gamma(N \to \bar{L}H)} \tag{3}$$

- Its value is given by,

$$\epsilon = \frac{Im(Y^\dagger Y)^2_{21}}{(Y^\dagger Y)^2_{11}} \frac{1}{8\pi} \sqrt{x} \left[(1+x) \log\left(\frac{1+x}{x} \right) - \frac{2-x}{1-x} \right], \quad x = \frac{M_2^2}{M_1^2} \tag{4}$$



Thermal Masses

- Thermal Masses are a consequence of Thermal Field Theory [8].
- Calculations of this are most easily done using the Imaginary Time Formalism [5].

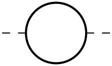
Feynman Rule	QFT	Imaginary Time
Scalar Propagator	$\frac{i}{p^2 - m^2}$	$\frac{1}{\omega_n^2 + \vec{\gamma} \cdot \vec{p} + m^2}$
Fermionic Propagator	$\frac{i}{\not{p} - m}$	$\frac{1}{i\omega_n \gamma_0 - \vec{\gamma} \cdot \vec{p} - m}$
Momentum Integral	$\int \frac{d^4 p}{(2\pi)^4}$	$\frac{1}{\beta} \sum_n \int \frac{d^3 p}{(2\pi)^3}$

Table: Thermal Field Theory: Imaginary Time Formalism

Finding Scalar Thermal Masses

- Scalar thermal masses are found from calculating self-energy loop diagrams.

$$\Sigma =$$



$$= cg^2 T^2 \tag{5}$$

where g is the coupling and c is a constant specific on the interaction and diagram.

- These self energies are renormalised into mass terms.

$$\frac{1}{\omega_n^2 + p^2 + m^2} \rightarrow \frac{1}{\omega_n^2 + p^2 + m^2 + \Sigma} \tag{6}$$

So we interpret an effective mass,

$$m_{eff}^2 = m^2 + \Sigma = m_0^2 + m_{th}^2 \tag{7}$$

and we can just write our thermal mass as,

$$m_{th}^2 = cg^2 T^2 \tag{8}$$

Finding Fermionic Thermal Masses

- For Fermionic Thermal Masses, Σ isn't a number.

$$\Sigma(p^0, p) = \gamma^0 \Sigma_0(p^0, p) + \gamma^i \cdot \hat{p} \Sigma_p(p^0, p) \tag{9}$$

- Modify the fermion propagator so that,

$$S^{-1}(p^0, p) = \gamma^0 (p^0 - \Sigma_0) - \gamma \cdot \hat{p}(1 + \Sigma_p / p) \tag{10}$$

- The dispersion relation for the fermion is then given by

$$det[S^{-1}(p^0, p)] = 0 \tag{11}$$

so to find the thermal mass, we need to compute the value of p^0 when $p \rightarrow 0$. This is because the dispersion relation changes $p^0 = \sqrt{p^2 + m_{th}^2} \rightarrow m_{th}$.

- This is equivalent to solving

$$m_{th} = lim_{p \rightarrow 0} \Sigma_0(m_{th}, p) \tag{12}$$

Table of Thermal Masses

- Evaluating a fermion loop diagram with a symmetry factor s. The thermal masses are given by,

Yukawa	$U(1)$	$SU(N)$
$m_{\text{th}}^2 = s\frac{y^2T^2}{16}$	$m_{\text{th}}^2 = s\frac{g^2T^2}{8}$	$m_{\text{th}}^2 = s\frac{g^2(N^2-1)}{16N}T^2$

Table: The table provides the thermal masses for fermions with various interactions.

- Our case, we gauging fermions under the same $U(1)_{B-L}$. As they are leptons, both RHNs are charged g_{B-L}=-1.
- This means sterile neutrinos gain the same thermal mass of $\frac{g^2T^2}{8}$.
- This gives us our mechanism for resonance.....

A Natural Mechanism for Resonance

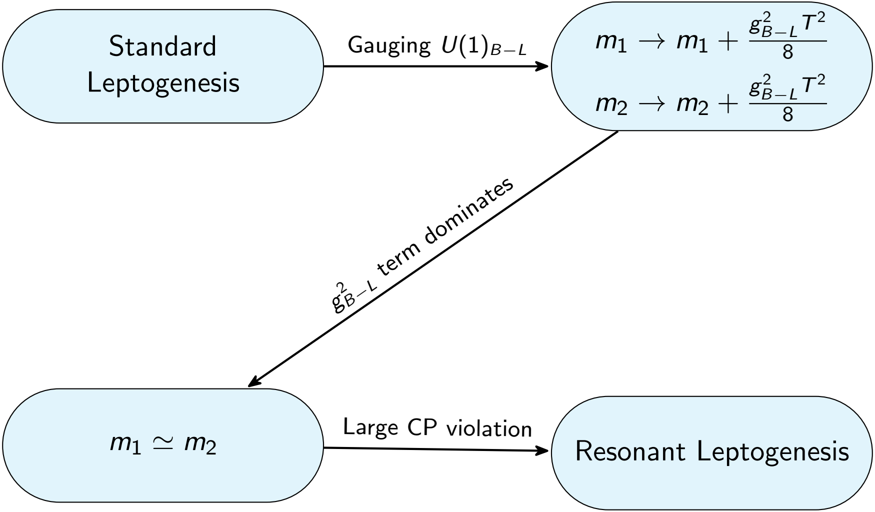


Figure: Flowchart of Resonant Leptogenesis with Gauged $U(1)_{B-L}$

Gauging $U(1)_{B-L}$

- B-L symmetry is a natural extension to the standard leptogenesis regime and one that has been studied extensively.

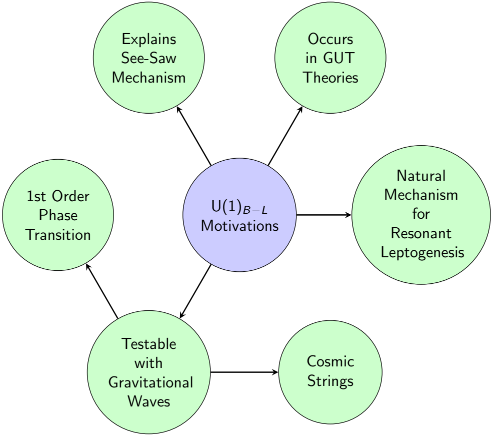


Figure: Motivations for Gauging $U(1)_{B-L}$

Our Model

- Our Lagrangian is,

$$\mathcal{L}_{\text{model}} = \mathcal{L}_{\text{SM}} - \frac{1}{4} F^{\mu\nu}_{B-L} F^{B-L}_{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4}\phi^4 + \sum_{i,j}^{2} \left(i\bar{N}_i \not{D} N_i - y_D^{ij} \bar{l}_L^i \tilde{H} N^j - \frac{1}{2} y_M^i \phi N_i N_i \right) + \text{h.c.}, \tag{13}$$

- Now have $M_m = y_m \langle v \rangle_\phi$ and $m_D = y_D \langle v \rangle_H$. This explains why $M_m >> m_D$ in the see-saw mechanism.
- We can now see that gauging under $B - L$ has given us,
  1. The scalar field required for non-thermal leptogenesis
  2. An explanation for why $M_m >> m_D$ with being proportional to a heavy scalar vev.
  3. The mechanism for resonance from thermal masses for a very large part of the parameter space

$$g_{B-L} T >> y_{m2} v_\phi \implies \textit{Resonance}! \tag{14}$$

- Our Thermal Masses:

	RH Neutrino	Higgs	Lepton
Dominant Thermal Mass	$\frac{g_{B-L}^2 T^2}{8}$	$\frac{y_t^2 T^2}{4}$	$\frac{g_{B-L}^2 T^2}{8}$

- For any g_{B-L} at high temperatures $M_N < M_H + M_L$ and Neutrino decay is not allowed. Instead most interesting parameter space is,

$$y_t > g_{B-L},\ g_{B-L} T > y_{m2} v_\phi \tag{15}$$

and we have resonant Leptogenesis from Higgs Decays.

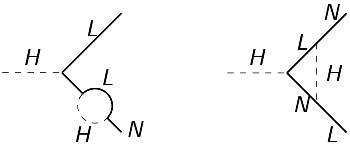


Figure: CP-Violating Higgs Decays

From Particle Physics to Cosmology

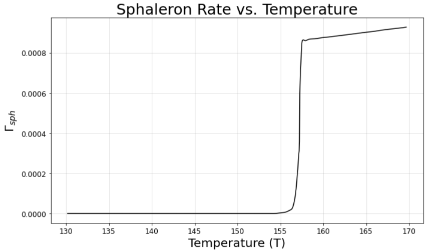
- To get from this epsilon to cosmology we would normally solve the Bolztamnn equations...

$$
\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi(\rho_\phi - \rho_\phi^{\text{eq}}), \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi(\rho_\phi - \rho_\phi^{\text{eq}}) - \Gamma_N(\rho_N - \rho_N^{\text{eq}}), \\
\dot{\rho}_R &= -4H\rho_R + \Gamma_N(\rho_N - \rho_N^{\text{eq}}), \\
\dot{n}_{B-L} &= -3Hn_{B-L} - \epsilon\Gamma_N(n_N - n_N^{\text{eq}}) - W_{ID}n_{B-L},
\end{aligned}
\tag{16}
$$

- But Resonance means we need to be more careful and instead use density matrix formalism.
- Results coming soon in early 2025!

A Potential Issue and Resolution

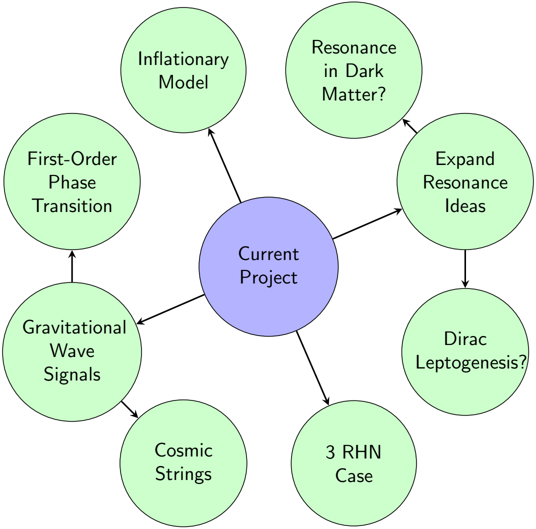
- Problem: After being in the resonant regime the extra baryon asymmetry appears to be washed out.
- Resolution: Electroweak symmetry breaking comes to the rescue!



- For sterile neutrinos under $m_{th}(T_{EW})$ we will always be in resonance.
- We predict that our model will have successful leptogenesis for all of the parameter space non-thermal leptogenesis is.....PLUS neutrinos masses below electroweak scale as well. Thus extending the parameter space for successful leptogenesis.

Where Next?

- We have a plethora of extensions to this project!



Conclusions

- We have introduced the framework of leptogenesis and resonant leptogenesis.
- We have introduced the concept of thermal masses and how to calculate them for scalars and fermions.
- We have shown how to gauge leptogenesis under $U(1)_{B-L}$.
- We have shown that for a large parameter space resonant leptogenesis is achieved from Higgs decays.
- We have teased future work in this area applying the general mechanism for resonance in other fields and predicting gravitational wave background from this model.

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