Leptogenesis - 
Connection to Neutrino Oscillation, and other 
Low Energy CP/Flavor Violating Processes

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Standard Leptogenesis

- Implemented in the context of seesaw mechanism
- out-of-equilibrium decays of RH neutrinos produce primordial lepton number asymmetry

\[ \epsilon_1 = \frac{\sum_\alpha [\Gamma(N_1 \rightarrow \ell_\alpha H) - \Gamma(N_1 \rightarrow \ell_\alpha \bar{H})]}{\sum_\alpha [\Gamma(N_1 \rightarrow \ell_\alpha H) + \Gamma(N_1 \rightarrow \ell_\alpha \bar{H})]} \]

- sphaleron process convert \( \Delta L \rightarrow \Delta B \)
- the asymmetry

\[ Y_B \simeq 10^{-2} \epsilon \kappa \quad \kappa : \text{efficiency factor} \sim (10^{-1} - 10^{-3}) \quad Y_B = \frac{n_B - n_{\bar{B}}}{s} \sim 8.6 \times 10^{-11} \]

(k: inverse decay \( \Delta L=1 \), scattering processes \( \Delta L=1, 2 \))
Bound on Light Neutrino Mass

- sufficient leptogenesis requires
  \[ M_1 \geq 3 \times 10^9 \text{ GeV} \]
- upper bound on light neutrino mass
  \[ m_1 < 0.12 \text{ eV} \]
- incompatible with quasi-degenerate spectrum
- constraints slightly alleviated with flavored case

\[ \Rightarrow T_{\text{reh}} \geq 10^9 \text{ GeV} \]

P. Di Bari, 2012

Mu-Chun Chen, UC Irvine

Leptogenesis

Snowmass 2013, 08/02/2013
Gravitino Problem

For light gravitino mass, BBN constraints

\[ T_{RH} < 10^{(5-6)} \text{ GeV} \]

tension! (if SUSY)

Sufficient leptogenesis \[ \Rightarrow \]

\[ T_{RH} > M_R > 2 \times 10^9 \text{ GeV} \]
Alternatives: “Non-standard” Scenarios

- Possible ways to avoid the tension:
  - resonant enhancement in self-energy diagram $\Rightarrow$ lowering $M_R$, thus $T_{RH}$
    $\Rightarrow$ resonant leptogenesis (near degenerate RH neutrinos) Pilaftsis, 1997

Recall: in standard leptogenesis:

![Diagram of standard leptogenesis]

- self-energy diagram dominate for near degenerate RH neutrino masses, $M_{1,2}$
- enhanced O(1) asymmetry possible if
  \[
  M_1 - M_2 \approx \frac{1}{2} \Gamma_{N_{1,2}}, \quad \text{assuming} \quad \frac{\text{Im}(h_{\nu}h_{\nu}^\dagger)_{12}}{(h_{\nu}h_{\nu}^\dagger)_{11}(h_{\nu}h_{\nu}^\dagger)_{22}} \approx 1
  \]

- possible collider test

Pilaftsis, Underwood, 2003
Dirac Leptogenesis

- Leptogenesis possible even when neutrinos are Dirac particles
- small Dirac mass through suppressed Yukawa coupling
- Characteristics of Sphaleron effects:
  - only left-handed fields couple to sphalerons
  - sphalerons change (B+L) but not (B-L)
  - sphaleron effects in equilibrium for \( T > T_{\text{ew}} \)
- If L stored in RH fermions can survive below EW phase transition, net lepton number can be generated even with \( L=0 \) initially

Late time LR equilibration of neutrinos making Dirac leptogenesis possible

\( \text{N}_{\text{eff}} > 3 \) (enhanced by \( \sim 10\% \))

[thanks to Michael Ratz]

K. Dick, M. Lindner, M. Ratz, D. Wright, 2000;
H. Murayama, A. Pierce, 2002

Diagram from K. Dick, M. Lindner, M. Ratz, D. Wright, 2000
Dirac Leptogenesis

- for neutrinos: LH equilibration at late time \( T_{eq} \ll T_{EW} \) because of their much suppressed masses \( m_D < 10 \text{ keV} \)
- Naturally small Dirac neutrino mass?
- Two examples:
  - non-anomalous U(1) family symmetry M.-C.C., J. Huang, W. Shepherd (2011)
    - gives realistic quark and lepton masses and mixing patterns
    - naturally small Dirac neutrino masses due to higher dimensional operators
    - primordial asymmetry by U(1) flavor Higgs decay
  - discrete R-symmetries M.-C.C., M. Ratz, C. Staudt, P. Vaudrevange (2012)
    - satisfy all anomaly cancellation conditions a la Green-Schwarz mechanism
    - automatically suppressed the mu term, thus solving the mu problem in MSSM
    - automatically suppressed the Dirac neutrino masses
    - Lepton Number Violation: \( \Delta L = 4 \)
Testing Leptogenesis?

• Sakharov Conditions:
  • out-of-equilibrium
    ➡ expanding Universe
    ➡ smallness of neutrino masses
  • Baryon Number Violation
    ➡ abound in many extensions of the SM
    ➡ neutrinoless double beta decay
      ‣ Leptogenesis with Majorana (if observed) or Dirac (if not observed) neutrinos
        ‣ if Dirac: $N_{\text{eff}}$ enhanced
  • CP violation
    ➡ Long baseline neutrino oscillation experiments

Leptogenesis with Majorana neutrino: out-of-equilibrium heavy field decay

Dirac Leptogenesis: late equilibration temperature
Connection to Low Energy Observables

- Seesaw Lagrangian at high energy (in the presence of RH neutrinos)
  6 mixing angles + 6 physical phases

- Low energy effective Lagrangian (after integrating out RH neutrinos)
  3 mixing angles + 3 physical phases

  presence of low energy leptonic CPV
  (neutrino oscillation, neutrinoless double beta decay)

- No model independent connection

- Statement is weakened when the so-called flavor effects are taken into account
  (relevant if leptogenesis at $T < 10^{12}$ GeV)

- BUT, in certain models, connection can be established even without the flavor effects

high energy $\rightarrow$ low energy: numbers of mixing angles and CP phases reduced by half

leptogenesis $\neq 0$
Connection in Specific Models

- models for neutrino masses:
  - additional symmetries
  - reduce the number of parameters $\Rightarrow$ connection can be established
- rank-2 mass matrix (may be realized by symmetry)
  - models with 2 RH neutrinos (2 x 3 seesaw)  
  - sign of baryon asymmetry $\leftrightarrow$ sign of CPV in $\nu$ oscillation
- all CP come from a single source
  - models with spontaneous CP violation:
    - SM + vectorial quarks + singlet scalar  
    - minimal LR model: only 1 physical leptonic CP phase
    - SCPV in SO(10): $<126>_{B-L}$ complex
  - SUSY SU(5) x T’ Model:  
    - group theoretical origin of CP violation $\Rightarrow$ only low energy lepton phases $\neq 0$
Example: Minimal LR Model w/ Spontaneous CPV

- minimal LR symmetric Model:
  - matter content
    \[
    Q_{i,L} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,L} \sim (1/2, 0, 1/3), \quad Q_{i,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,R} \sim (0, 1/2, 1/3) \\
    L_{i,L} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,L} \sim (1/2, 0, -1), \quad L_{i,R} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,R} \sim (0, 1/2, -1) 
    \]
  - Higgs content
    \[
    \Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (1/2, 1/2, 0) \\
    \Delta_L = \begin{pmatrix} \Delta_L^+ / \sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+ / \sqrt{2} \end{pmatrix} \sim (1, 0, 2) \\
    \Delta_R = \begin{pmatrix} \Delta_R^+ / \sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+ / \sqrt{2} \end{pmatrix} \sim (0, 1, 2)
    \]
- Two physical CP phases
  \[
  < \Phi > = \begin{pmatrix} \kappa \\ 0 \\ \kappa' e^{i\alpha_{\kappa'}} \end{pmatrix}, \quad < \Delta_L > = \begin{pmatrix} 0 \\ 0 \\ e^{i\alpha_L} \end{pmatrix}, \quad < \Delta_R > = \begin{pmatrix} 0 \\ 0 \\ v_R \end{pmatrix}
  \]

\[ \alpha_{\kappa'} \Rightarrow \text{all CPV in quark sector} \]
\[ \alpha_L \Rightarrow \text{all CPV in lepton sector} \]

(contributions to lepton sector negligible for high seesaw scale)
Example: Minimal LR Model w/ Spontaneous CPV

- correlations: lepton number asymmetry, neutrinoless double beta decay matrix element, leptonic Jarlskog invariant

\[ \Delta \epsilon ' \]

\[ J_{CP} \]

\[ \langle m_{ee} \rangle \ (eV) \]

\[ \Delta \epsilon ' \]

\[ J_{CP} \]

\[ \langle m_{ee} \rangle \ (eV) \]

M.-C.C, Mahanthappa, 2005
Connection to Other B/L Violating Processes

- e.g. n-nbar oscillation searches → complementarity test of leptogenesis (baryogenesis) mechanisms
  - constrain the scale of leptogenesis

- observation of neutron antineutron oscillation
  - new physics with $\Delta B = 2$ at $10^{5-6}$ GeV
  - erasure of matter-antimatter generated at high scale, e.g. standard leptogenesis

- Low scale leptogenesis scenarios preferred:
  - Dirac Leptogenesis
  - Resonance Leptogenesis
  - Soft leptogenesis; ...

[Animation Credit: Michael Ratz]
Conclusions

• origin of matter: one of the great mysteries in particle physics and cosmology
• leptogenesis: appealing mechanism connected to neutrino physics
• various leptogenesis realizations:
  • standard leptogenesis: gravitino problem, tension with SUSY
  • Low scale alternatives:
    • resonance leptogenesis
    • Dirac leptogenesis
  • Soft leptogenesis (CP phases in soft SUSY sector; decouple from neutrino physics; require small B term)
Conclusions

• tested by “archeological” evidences

• model-independent ways:
  • Kinematic test, Cosmology (absolute neutrino mass bound, N_{eff})
  • Neutrino-less double beta decay (Majorana vs Dirac leptogenesis)

• Leptonic CP violation:
  • important fundamental property of neutrinos, independent of leptogenesis

• model-dependent connections to CPV in other sectors possible
  • correlations: models with single source of CPV (J_{cp}, \langle m_{\beta\beta} \rangle, EDM, etc)
  • searches at neutrino experiments (leptonic CPV, mixing parameters)
  • complementarity test from other B or L violating processes
    • e.g. N-Nbar oscillation \Rightarrow constraint scale of leptogenesis