Baryogenesis through Leptogenesis

Mu-Chun Chen, University of California at Irvine

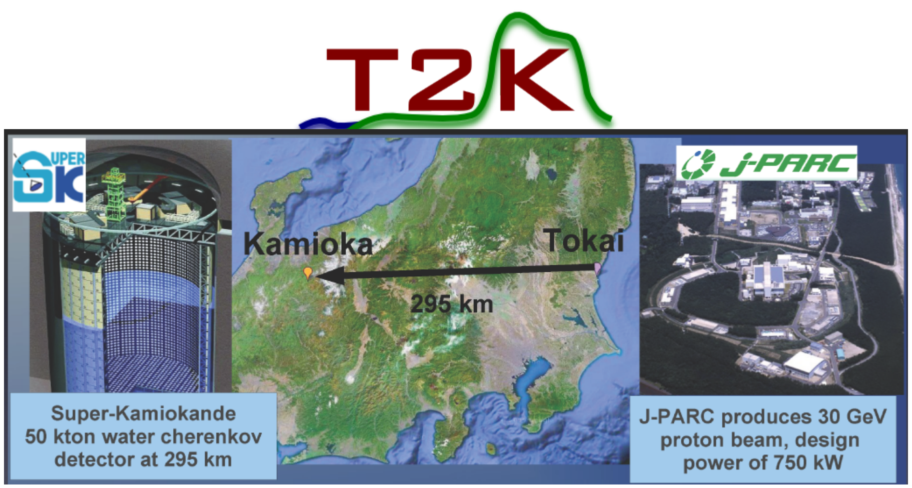
International Neutrino Summer School 2023, Fermilab, 8/15/2023

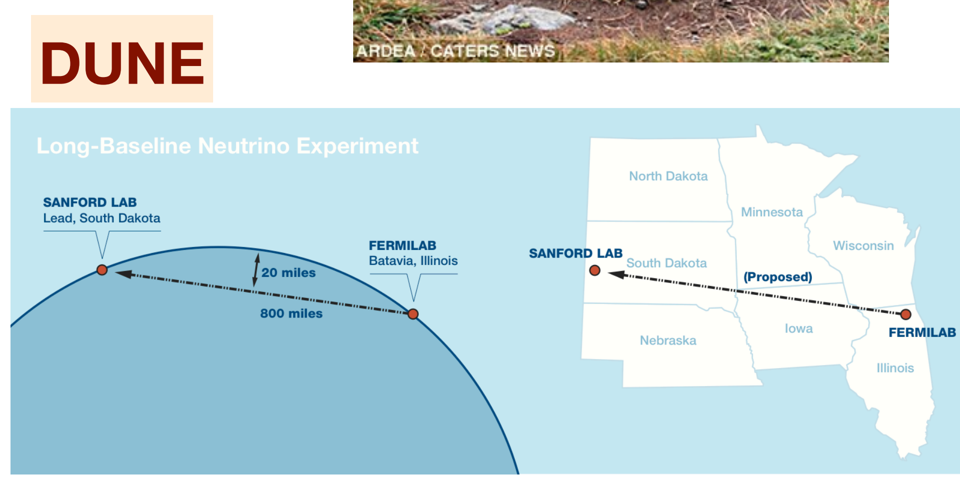
CP Violation in Neutrino Oscillation

- With leptonic Dirac CP phase $\delta \neq 0$ ➜ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

$$P\,(\nu_\alpha \rightarrow \nu_\beta) \neq P\,(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta})$$

- One of the major scientific goals at current and planned neutrino experiments





Connection to Low Energy Observables

- Lagrangian at high energy (in the presence of RH neutrinos)

$$\mathcal{L} = \overline{\ell}_{L_i} i\gamma^\mu \partial_\mu \ell_{L_i} + \overline{e}_{R_i} i\gamma^\mu \partial_\mu e_{R_i} + \overline{N}_{R_i} i\gamma^\mu \partial_\mu N_{R_i}$$
$$+ f_{ij}\overline{e}_{R_i}\ell_{L_j} H^\dagger + h_{ij}\overline{N}_{R_i}\ell_{L_j} H - \frac{1}{2} M_{ij} N_{R_i} N_{R_j} + h.c.$$

in f_{ij} and M_{ij} diagonal basis →

h_{ij} general complex matrix:

Group Work

How many mixing angles and CP phases does h_{ij} have at high energy?

Connection to Low Energy Observables

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in f_{ij} and M_{ij} diagonal basis →

h_{ij} general complex matrix: $\left\{ \begin{array}{l} \text{9-3 = 6 mixing angles} \\ \text{9-3 = 6 physical phases} \end{array} \right.$

- Low energy effective Lagrangian (after integrating out RH neutrinos)

$$\mathcal{L}_{eff} = \overline{\ell}_{L_i} i\gamma^\mu \partial_\mu \ell_{L_i} + \overline{e}_{R_i} i\gamma^\mu \partial_\mu e_{R_i} + f_{ii}\overline{e}_{R_i}\ell_{L_i} H^\dagger + \frac{1}{2}\sum_k h^T_{ik} h_{kj} \ell_{L_i}\ell_{L_j} \frac{H^2}{M_k} + h.c.$$

in f_{ij} diagonal basis →

h_{ij} symmetric complex matrix:

Group Work

How many mixing angles and CP phases does h_{ij} have at low energy?

Connection to Low Energy Observables

- Lagrangian at high energy (in the presence of RH neutrinos)

$$\mathcal{L} = \overline{\ell}_{L_i} i\gamma^\mu \partial_\mu \ell_{L_i} + \overline{e}_{R_i} i\gamma^\mu \partial_\mu e_{R_i} + \overline{N}_{R_i} i\gamma^\mu \partial_\mu N_{R_i}$$
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in f_{ij} and M_{ij} diagonal basis →

h_{ij} general complex matrix: $\left\{ \begin{array}{l} \text{9-3 = 6 mixing angles} \\ \text{9-3 = 6 physical phases} \end{array} \right.$

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in f_{ij} diagonal basis →

h_{ij} symmetric complex matrix: $\left\{ \begin{array}{l} \text{6-3 = 3 mixing angles} \\ \text{6-3 = 3 physical phases} \end{array} \right.$

- **high energy → low energy:**
  numbers of mixing angles and CP phases reduced by half

Observation of Neutrino Oscillations

$\Rightarrow$ CP violation in lepton sector

$\Rightarrow$ Leptogenesis

Standard Leptogenesis

- observation of neutrino oscillation
- SO(10) GUT:

$$\psi(16) = (q_L,\ u_R^c,\ e_R^c,\ d_R^c,\ \ell_L,\ \nu_R^c)$$

- hierarchical fermion masses:

$$M_N \ll M_{B-L} \sim M_{GUT}$$

- N: Majorana fermion
- RH neutrino decays → lepton number asymmetry

$$N \to \ell H, \quad N \to \overline{\ell}\,\overline{H}$$

Standard Leptogenesis

- most general Lagrangian in lepton sector

$$\mathcal{L}_Y = f_{ij}\overline{e}_{R_i}\ell_{L_j}H^\dagger + h_{ij}\overline{\nu}_{R_i}\ell_{L_j}H - \frac{1}{2}(M_R)_{ij}\overline{\nu}^c_{R_i}\nu_{R_j} + h.c.$$

- mass generation

$$m_\ell = fv, \quad m_D = hv \ll M_R$$

- see-saw mechanism in neutrino sector $\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$
- resulting effective masses

$$\nu \simeq V_\nu^T \nu_L + V_\nu^* \nu_L^c, \quad N \simeq \nu_R + \nu_R^c$$

$$m_\nu \simeq -V_\nu^T m_D^T \frac{1}{M_R} m_D V_\nu, \quad m_N \simeq M_R$$

- basic idea:
  - T < M_R: out-of-equilibrium decays of N → ΔL
  - sphaleron processes: ΔL → ΔB

Luty, 1992; Covi, Roulet, Vissani, 1996; Flanz et al, 1996; Plumacher, 1997; Pilaftsis, 1997;

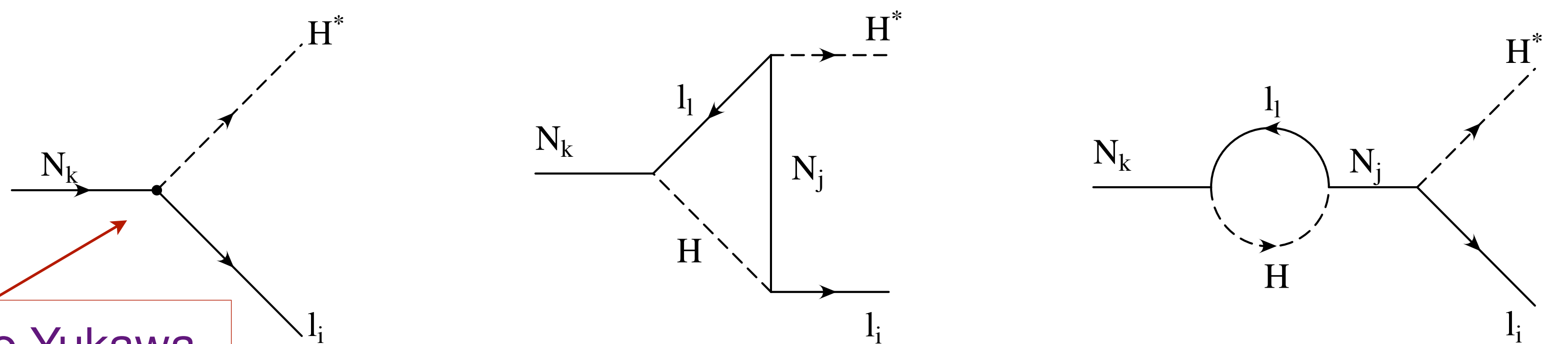
Buchmuller, Plumacher, 1998;
Buchmuller, Di Bari, Plumacher, 2004

Standard Leptogenesis

Fukugita, Yanagida, 1986

- CP asymmetry in RH heavy neutrino decay:
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry

ΔL



Neutrino Yukawa coupling

leptons   antileptons

$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}$$

Leptonic CP violation ⇒ ΔL ∝ $\left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]$ ≠ 0

Standard Leptogenesis- Asymmetry

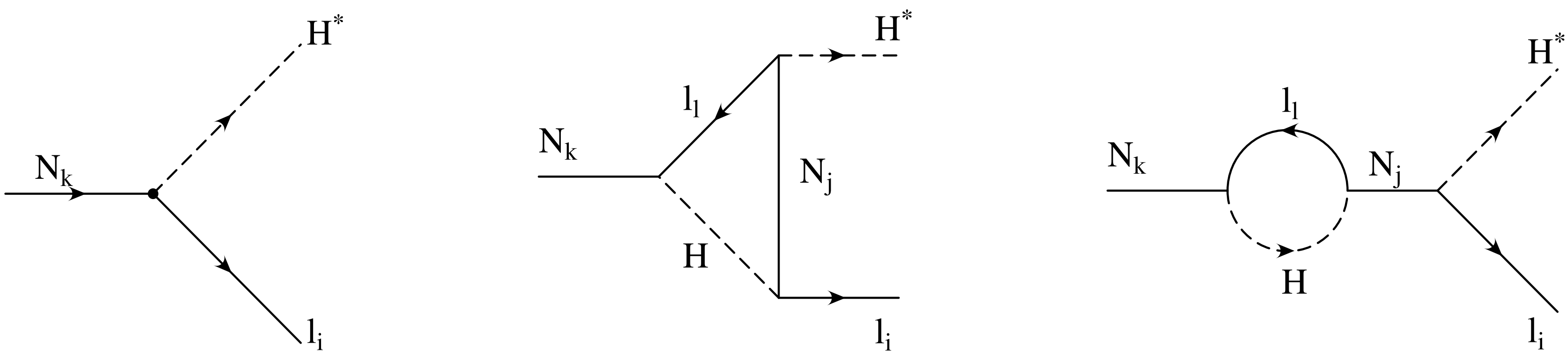
- Tree-level: $N_i \rightarrow H + \ell_\alpha$, where $\alpha = (e,\ \mu,\ \tau)$
  - total decay width

$$\Gamma_{D_i} = \sum_\alpha \left[\Gamma(N_i \rightarrow H + \ell_\alpha) + \Gamma(N_i \rightarrow \overline{H} + \overline{\ell}_\alpha) \right] = \frac{1}{8\pi}(hh^\dagger)_{ii} M_i$$

- ΔL from $N_{2,3}$ decays at $T >> M_1$: wash out by L-violating interactions of $N_1 \Rightarrow N_1$ decay dominate
- out-of-equilibrium condition $\Gamma_{D_1} < H \Big|_{T=M_1}$
  - heavy neutrinos not able to follow equilibrium particle distribution @ T < M1
  - N1 decay → ΔL

Standard Leptogenesis- Asymmetry

- CP Asymmetry from interference of tree and 1-loop diagrams



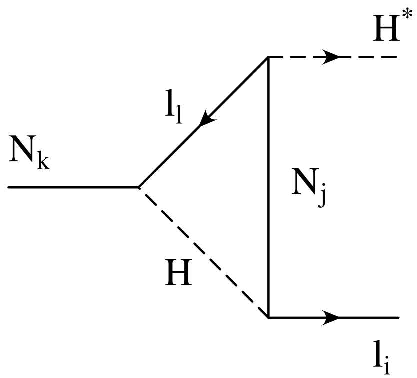
- Total Asymmetry

$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}$$

$$\simeq \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu)_{11}} \sum_{i=2,3} \mathrm{Im}\left\{ (h_\nu h_\nu^\dagger)^2_{1i} \right\} \cdot \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right) \right]$$

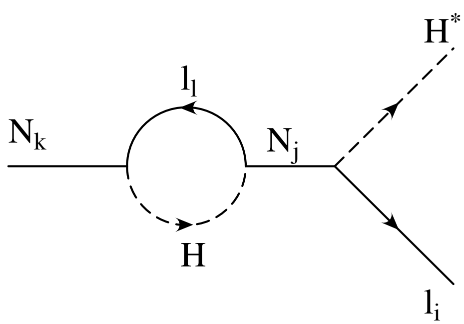
Standard Leptogenesis- Asymmetry

- vertex corrections



$$f(x) = \sqrt{x}\left[1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right]$$

- wave function renormalization



for $|M_i - M_1| \gg |\Gamma_i - \Gamma_1|$:

$$g(x) = \frac{\sqrt{x}}{1-x}$$

Standard Leptogenesis- Asymmetry

- Hierarchical RH neutrino masses: $M_1 \ll M_2, \; M_3$
  - total asymmetry

$$\epsilon_1 \simeq -\frac{3}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left\{(h_\nu h_\nu^\dagger)^2_{1i}\right\}\frac{M_1}{M_i}$$

  - near degenerate N_i and N_j: enhancement from self-energy diagram resonant leptogenesis
    - allowing low M1
    - solving gravitino over-production problem

Standard Leptogenesis - Washout

- asymmetry can be washed out by inverse decays and scattering processes
- out-of-equilibrium condition

$$r \equiv \frac{\Gamma_1}{H|_{T=M_1}} = \frac{M_{pl}}{(1.7)(32\pi)\sqrt{g_*}} \frac{(h_\nu h_\nu^\dagger)_{11}}{M_1} < 1$$

  - expansion rate of the Universe $H \simeq 1.66\, g_*^{1/2} \frac{T^2}{m_p}$
- constraint on effective mass

$$\widetilde{m}_1 \equiv (h_\nu h_\nu^\dagger)_{11} \frac{v^2}{M_1} \simeq 4\sqrt{g_*} \frac{v^2}{M_{pl}} \frac{\Gamma_{D_1}}{H}\bigg|_{T=M_1} < 10^{-3}\ \mathrm{eV}$$

  - g_* : # of relativistic dof (SM: 106.75 ; MSSM: 228.75)

Standard Leptogenesis - washout

- final amount of asymmetry $$Y_L \equiv \frac{n_L - \overline{n}_L}{s} = \kappa \frac{\epsilon_1}{g_*}$$
- k: parametrizing washout effects
  - out of equilibrium condition $\Gamma_{D_1} < H\Big|_{T=M_1}$
  - asymmetry can be washed out by inverse decays and scattering processes
    - Boltzmann equations
- EW Sphaleron effects ΔL → ΔB
  - final B asymmetry

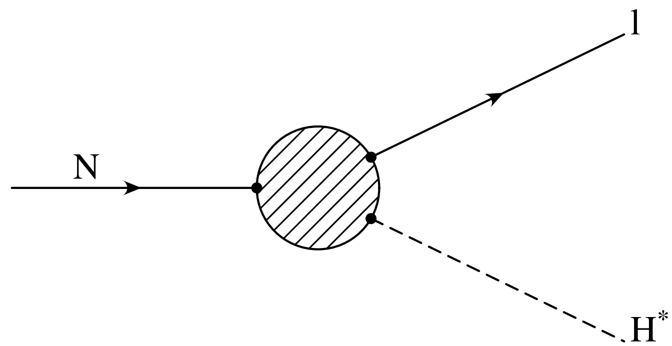
$$\boxed{Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} = cY_{B-L} = \frac{c}{c-1} Y_L}$$

$$c_s = \frac{8N_f + 4N_H}{22N_f + 13N_H}$$

Standard Leptogenesis - Washout

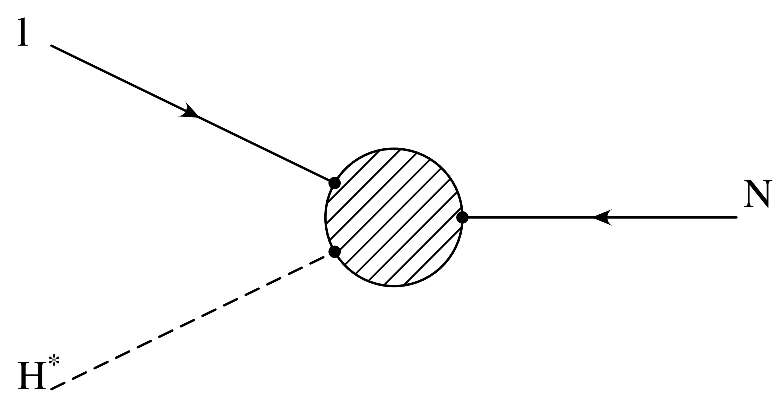
- Precise value for k: Boltzmann equations
- Main relevant processes in thermal bath
  - decay of N:

$$N \to \ell + H, \qquad N \to \overline{\ell} + \overline{H}$$



  - inverse decay of N:

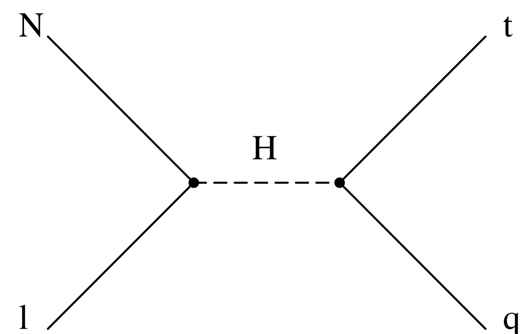
$$\ell + H \to N, \qquad \overline{\ell} + \overline{H} \to N$$



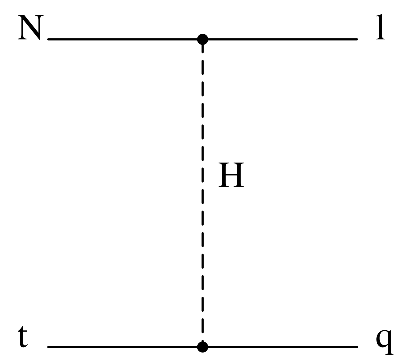
Standard Leptogenesis - Washout

- 2-2 scattering
  - ΔL = 1

$$[\text{s-channel}]: \qquad N_1\,\ell \leftrightarrow t\,\overline{q} \quad , \quad N_1\,\overline{\ell} \leftrightarrow t\,\overline{q}$$



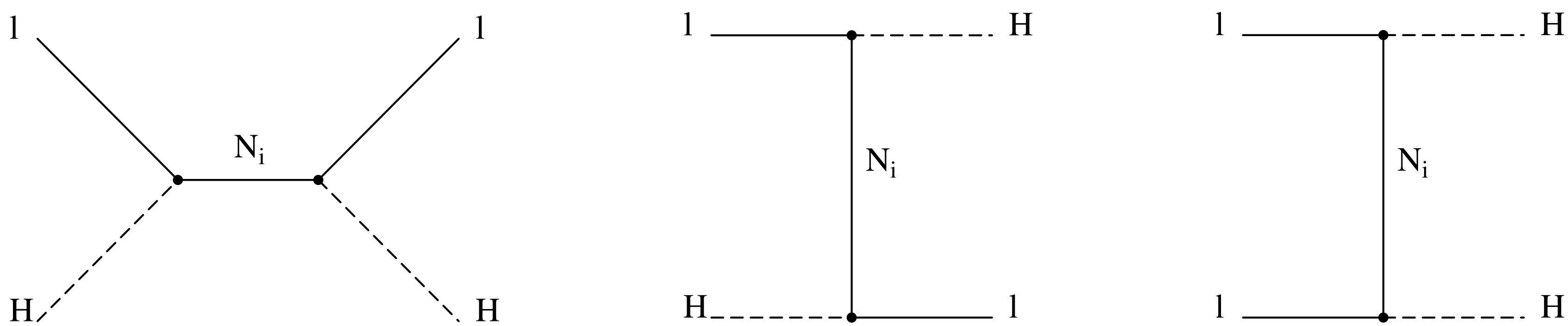
$$[\text{t-channel}]: \qquad N_1 t \leftrightarrow \overline{\ell}\,q \quad , \quad N_1\,\overline{t} \leftrightarrow \ell\,\overline{q}$$



Standard Leptogenesis - Washout

- 2-2 scattering
  - $\Delta L = 2$

$$\ell H \leftrightarrow \overline{\ell}\,\overline{H} \quad , \quad \ell\ell \leftrightarrow \overline{H}\,\overline{H}, \quad \overline{\ell}\,\overline{\ell} \leftrightarrow H\,H$$



- T > M1: strong enough to keep N1 in equilibrium
- T < M1: weak enough to allow asymmetry generation

Standard Leptogenesis - Washout

- Boltzmann equations → evolution of N1 density and (B-L) number density

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{eq})$$
$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L}$$

$$(D,S,W) \equiv \frac{(\Gamma_D, \Gamma_S, \Gamma_W)}{Hz}, \quad z = \frac{M_1}{T}$$

  - D: decay and inverse decays
  - S: $\Delta L = 1$ scatterings
  - W: inverse decays + $\Delta L = 1, 2$ scatterings

Standard Leptogenesis - Washout

- strongly hierarchical RH neutrino masses, $M_1 << M_2$:
  - Davidson-Ibarra bound

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1(m_3-m_2)}{v^2} \equiv \epsilon_1^{DI}$$

  - exp constraint $|m_3 - m_2| \leq \sqrt{\Delta m_{32}^2} \sim 0.05 \text{ eV}$
    - lower bound on M1:

$$M_1 \geq 2 \times 10^9 \text{ GeV}$$

$\Rightarrow$ lower bound on reheating temperature (gravitino problem)

    - equivalently, $m_1 \lesssim \; \tilde{m}_1 \lesssim 0.1 - 0.2 \;\; \text{eV}$

Is Leptogenesis Possible without LNV?

Group Work

What characteristics do you find in sphaleron processes discussed this morning?

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000;
Murayama, Pierce, 2002; ...

- Leptogenesis possible 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 > Tew
- If L stored in RH fermions can survive below EW phase transition, net lepton number can be generated even with L=0 initially
- for SM quarks and leptons: rapid left-right equilibration through large Yukawa

no net asymmetry
if B = L = 0 initially

Dirac Leptogenesis

- LR equilibration for neutrinos:
  - neutrino Yukawa coupling $\lambda \bar{\ell}_L H \nu_R$
  - rate for conversion $\Gamma_{LR} \sim \lambda^2 T$
  - for LR conversion not to be in equilibrium

$$\Gamma_{LR} \lesssim H \,, \quad \text{for} \quad T > T_{eq} \qquad\qquad H \sim \frac{T^2}{M_{\text{Pl}}}$$

  - Thus LR equilibration occur at much later time

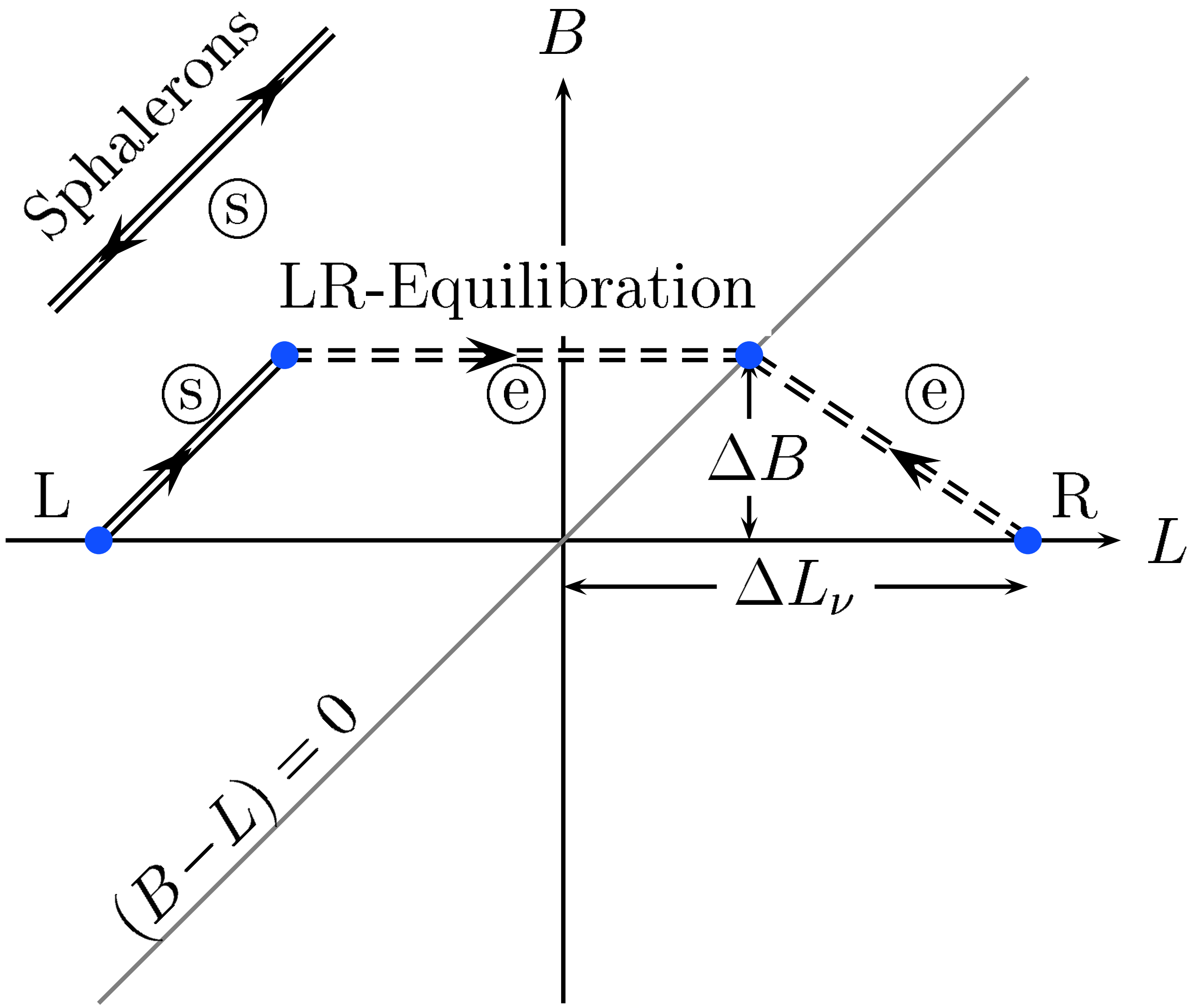
$$T \lesssim T_{eq} \ll T_{EW} \quad \Rightarrow \quad \lambda^2 \lesssim \frac{T_{eq}}{M_{\text{Pl}}} \ll \frac{T_{EW}}{M_{\text{Pl}}}$$

$$M_{\text{Pl}} \sim 10^{19} \text{ GeV} \qquad T_{EW} \sim 10^2 \text{ GeV} \qquad \lambda < 10^{-(8\sim9)}$$

$$m_D < 10 \text{ keV}$$

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000



Dirac Leptogenesis

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

- Leptogenesis possible even when neutrinos are Dirac particles **(no $\Delta L = 2$ violation)**
- 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 > Tew

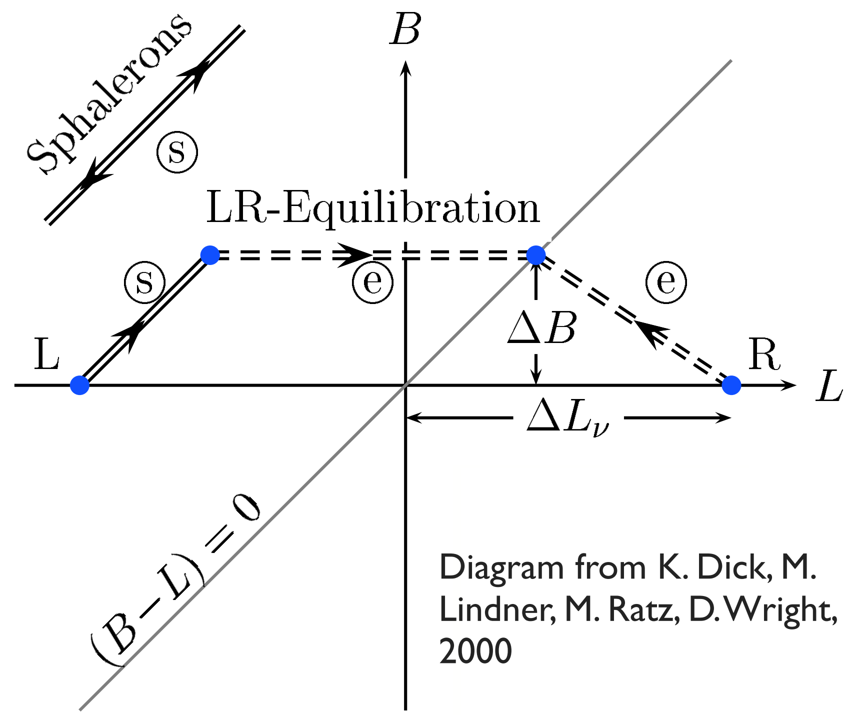


Diagram from K. Dick, M. Lindner, M. Ratz, D. Wright, 2000

late time LR equilibration of neutrinos making Dirac leptogenesis possible with primordial **$\Delta L = 0$**